The science of lighting

A guide about nature and behavior of light

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Revealing
the secrets
of lighting

The science of lighting is based upon human reactions to technical lighting products. It is this connection between technical and human aspects that makes lighting such a special and interesting subject, and makes it relevant to people across widely different professions.

Everyone who works in a profession related to lighting, be it in technical, artistic, commercial or administrative capacities, will benefit from a basic knowledge of light and lighting.

This book will explain what light is, how vision works, how artificial light is produced and how optical phenomena can be used to direct light to where we need it. The book then goes on to elaborate on how typical light units are defined in terms of how the eye sees things, as well as the relationships between light on the one hand, and vision, color and health on the other. Finally, the book discusses how the quality of lighting installations can be described so that lighting results in good visual performance, increased visual comfort, well-being and health, without negatively impacting the environment. These topics are dealt with as simply as possible and are suitable for beginners who are new to the world of lighting.

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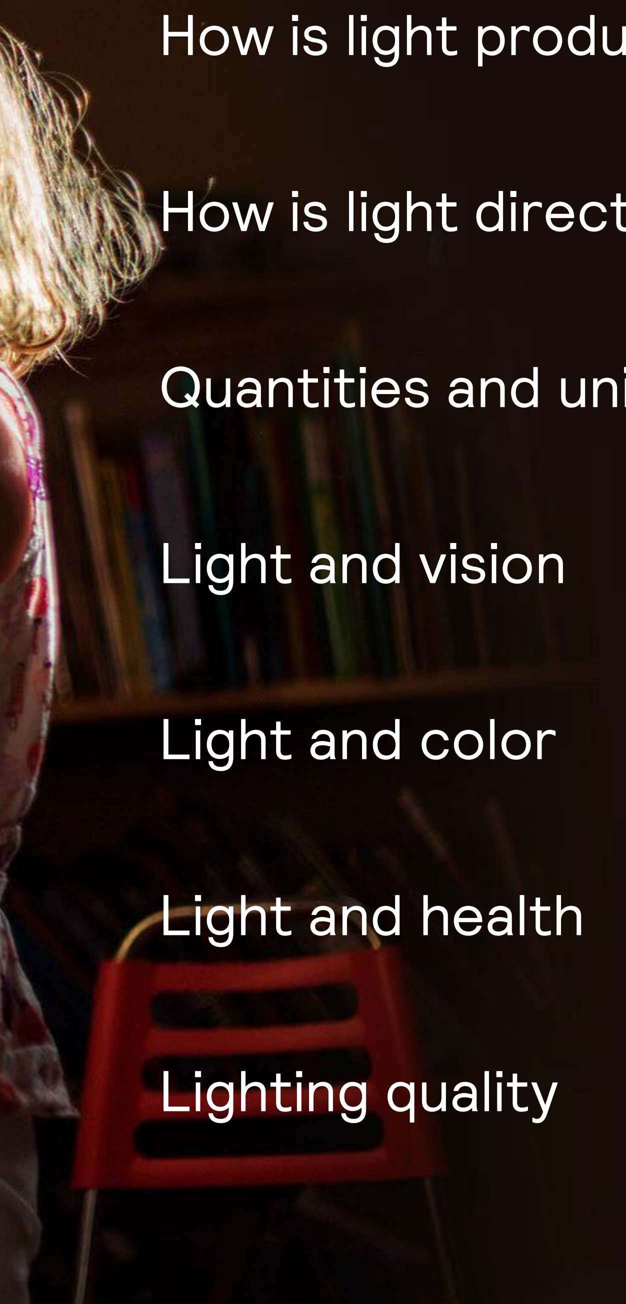


Light and radiation

1

It took scientists a long time to formulate a well-founded theory about the nature and behavior of light. Two theories emerged that together describe all aspects of light in a satisfactory manner: the electromagnetic wave theory and the quantum or photon theory.

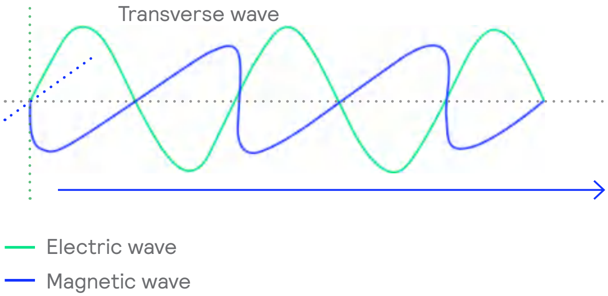
Electromagnetic wave theory

The simplest definition of light is given by Maxwell who describes it as electromagnetic radiation that consists of waves that travel from its source in all directions. Light waves do not consist of material particles, as in sound waves, but of electric and magnetic field waves. Unlike sound, where the particle vibration is in line with the direction of travel (Fig. 1.1), light is a transverse vibration perpendicular to the direction of travel (Fig. 1.2). The electric and magnetic waves travel mutually perpendicular to each other. Since they do not consist of particles they can, in contrast to sound waves, travel through a vacuum.

Only light can travel through vacuum. Imagine what would happen if sound could travel through vacuum? Deafening noise would be audible on Earth from sun and star eruptions.

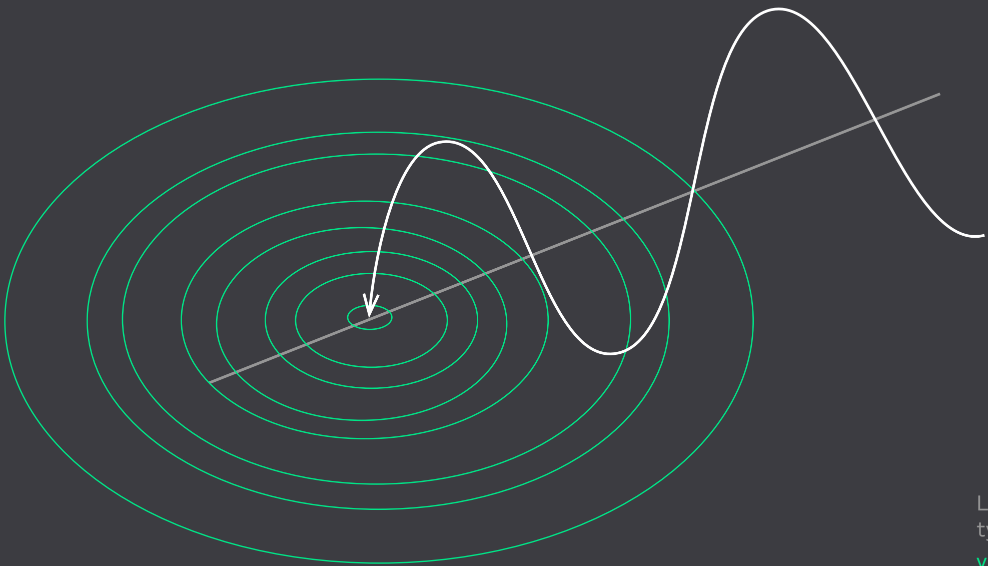
Fig. 1.1. Longitudinal sound waves.

Fig. 1.2. Transverse electromagnetic waves.



The transverse vibration is most easily demonstrated by throwing a stone into a pool of water.

Fig. 1.3. Transverse wave in water.



Learn more about the different types of light waves.
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Characteristics of electromagnetic waves

The distance between one top of the wave to the next one is called the wavelength (λ). Many different properties of electromagnetic radiation are explained by their difference in wavelengths.

The number of vibrations per second is called the frequency (f). Frequency is expressed in Hertz (Hz), or cycles per second. There exists a direct relation between the frequency and the wavelength of electromagnetic waves:

$$C = \lambda \cdot f$$

In his theory of relativity, Albert Einstein found that the speed of electromagnetic radiation, and thus of light, in a vacuum is not only the highest possible velocity, but also the only true constant in the universe. The speed of light (c) is very close to 300,000 km per second.

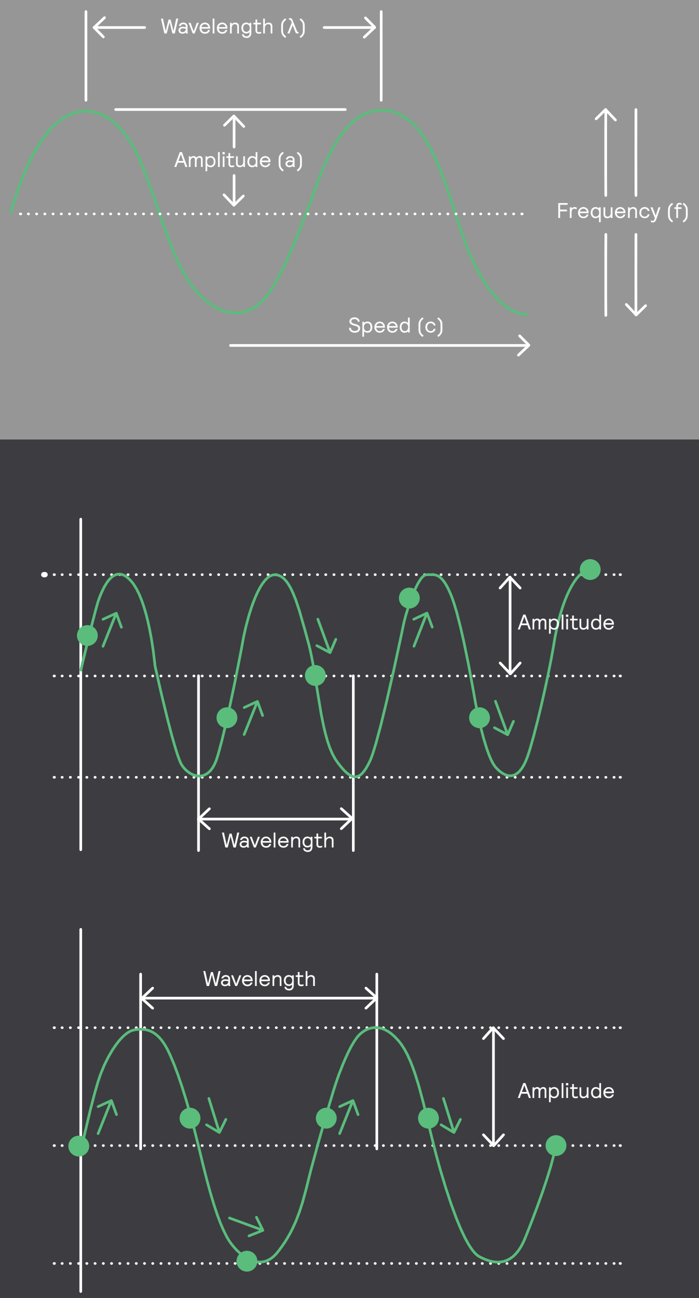

Fig. 1.4. Characteristics of waves.

The electromagnetic spectrum

The spectrum of electromagnetic radiation is extremely wide. Ranging from the wavelengths of long-wave radio transmissions (up to 2,000 meters) to short-wave AM and FM radio, microwave, TV broadcastings, and radar transmission waves (wavelengths of 1 meter and less). We then arrive at the wavelength of heat, or infrared radiation, at wavelengths of less than one thousandth of a millimeter. Now, we have radiation with a wavelength between 780 and 380 nanometers (millionth of a millimeter, or 10^{-9} meters), which is the visible part of the electromagnetic spectrum and therefore referred to as light.

Different wavelengths in the visible part of the spectrum result in different color impressions as wavelength decreases. At shorter wavelengths we have the ultraviolet region: the longer wavelengths in this UV range are part of the radiation we receive from the sun and are considered beneficial (UVA). They result in tanning of the skin. Shorter-wave ultraviolet radiation (UVB), on the other hand, is potentially dangerous to the skin and eyes, although we need it in small quantities because UVB produces vitamin D. The shortest ultraviolet radiations (UVC) are used as disinfectants since they kill bacteria. Still shorter wavelengths bring us first to X-rays, which penetrate the body, and then to the highly- dangerous gamma-rays, emitted as a result of nuclear decomposition. Finally, we come to the cosmic rays, which result from collisions between extremely-fast- moving particles travelling from the outposts of the universe. Cosmic rays have wavelengths down to 10^{-18} meter.

Learn more about the spectrum of electromagnetic radiation.

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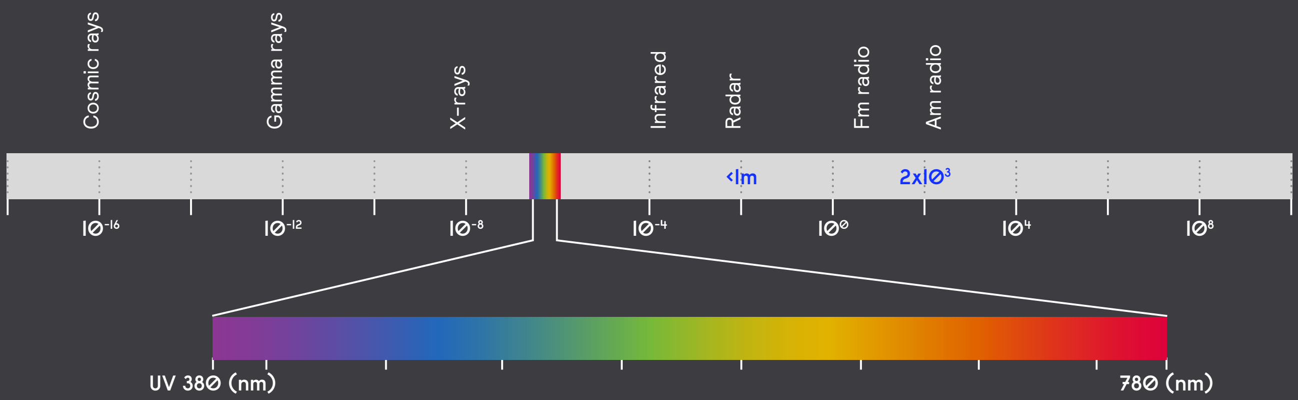

Fig. 1.5. The electromagnetic spectrum.

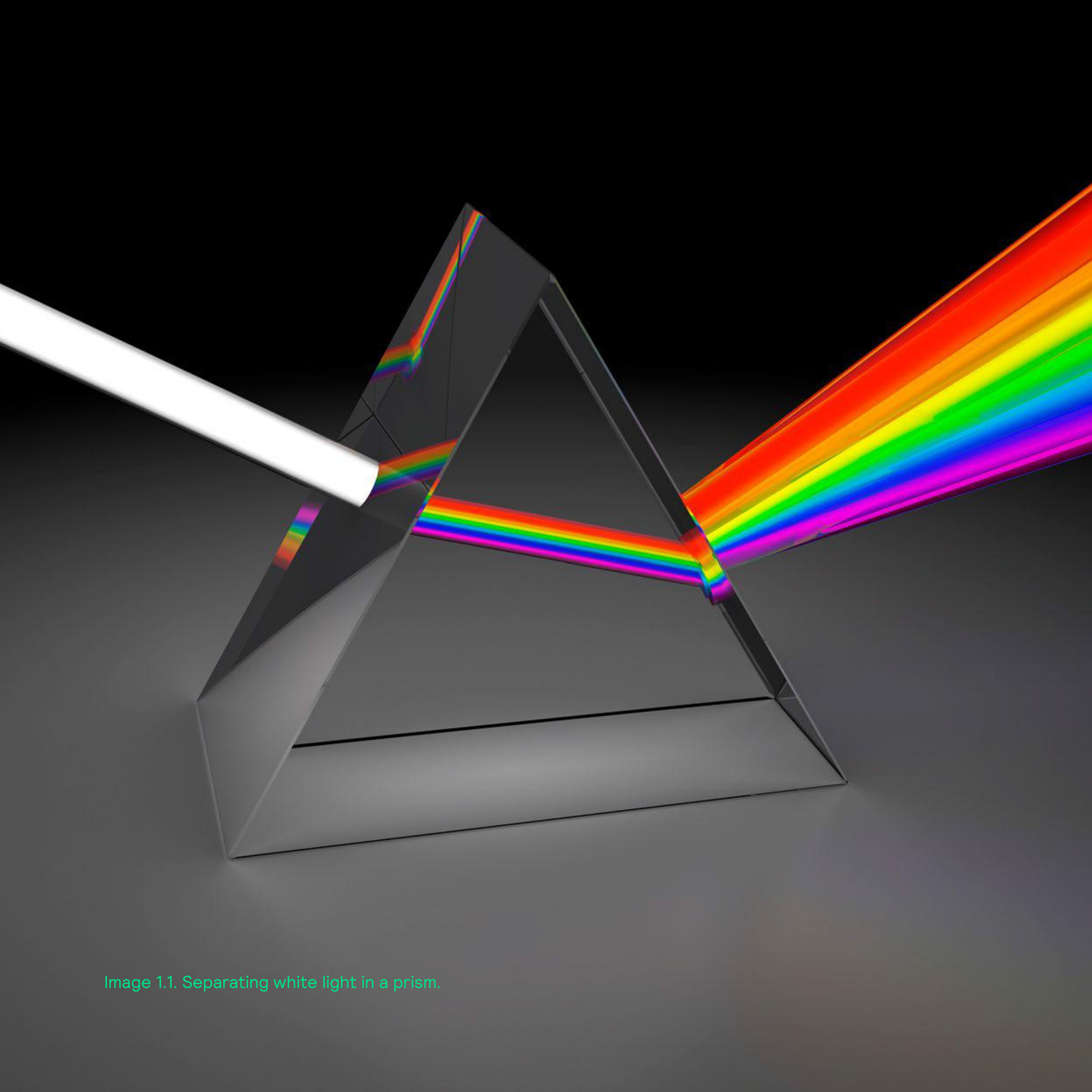

Image 1.1. Separating white light in a prism.

White light, emitted by the sun or an incandescent lamp, is a mixture of all wavelengths in the visible spectrum. Its spectrum also contains radiation from the adjacent infrared and ultraviolet regions. A well-known way of separating white light into its component wavelengths is by means of a prism (Image 1.1). The spectrum obtained in this way exhibits the familiar colors of the rainbow, violet, blue, green, yellow, orange and red.

The corresponding wavelengths are:

Violet	380	–	435 nm
Blue	435	–	500 nm
Green	500	–	565 nm
Yellow	565	–	600 nm
Orange	600	–	630 nm
Red	630	–	780 nm

Not all wavelengths produce the same impression of brightness on the human eye. The highest eye sensitivity lies in the green region at 555 nm. This phenomenon will be dealt with in some detail in Chapter 4 “Quantities and units”.

Using the electromagnetic wave theory, it is possible to calculate and predict not only the speed of light but also aspects such as reflection, absorption, transmission, refraction, interference and polarization of light. However, the calculation of energy of radiation for different wavelengths is not possible with the wave theory. For this purpose we have to apply the theory in which light is seen as a quantum or photon phenomenon.

Learn more about the function of prism.
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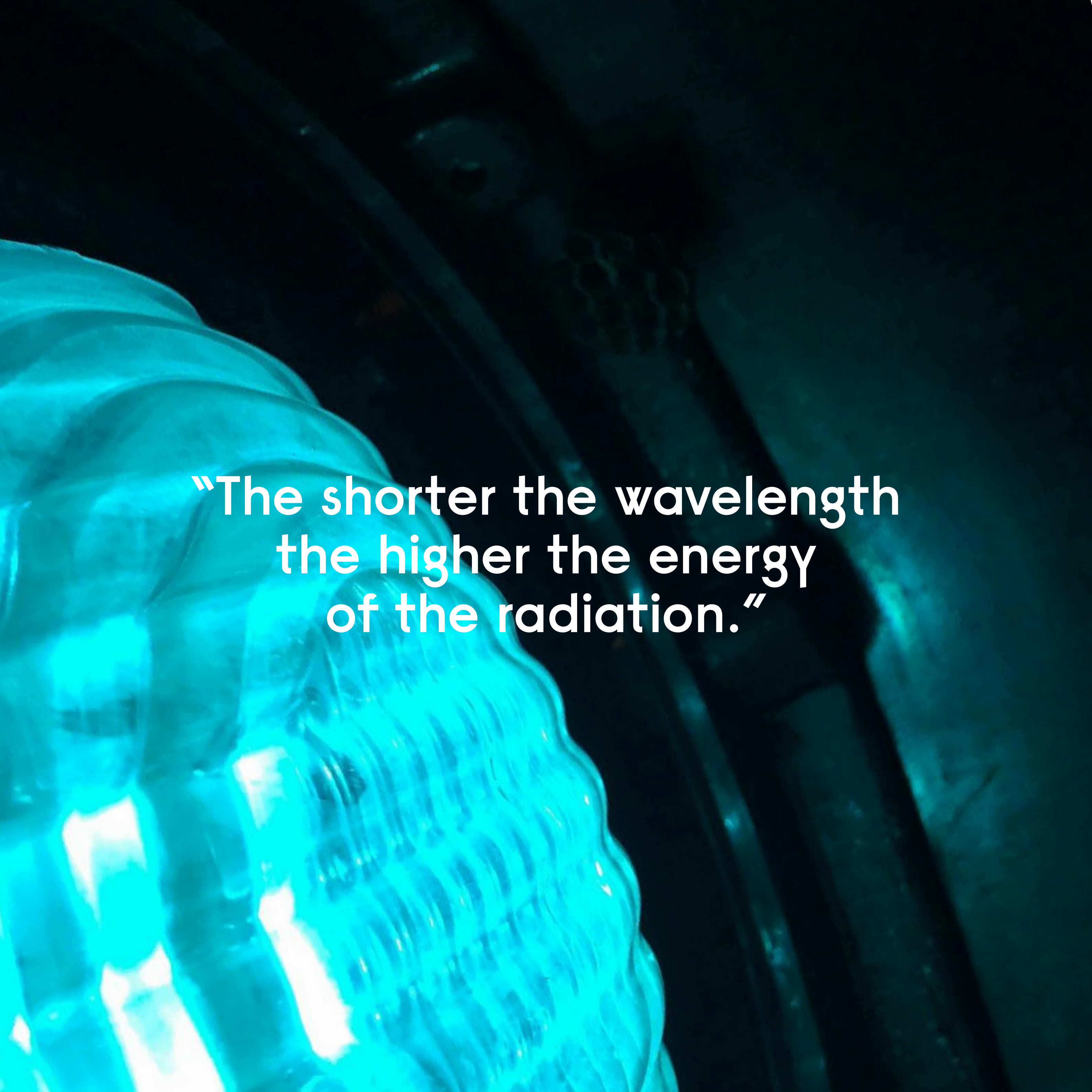
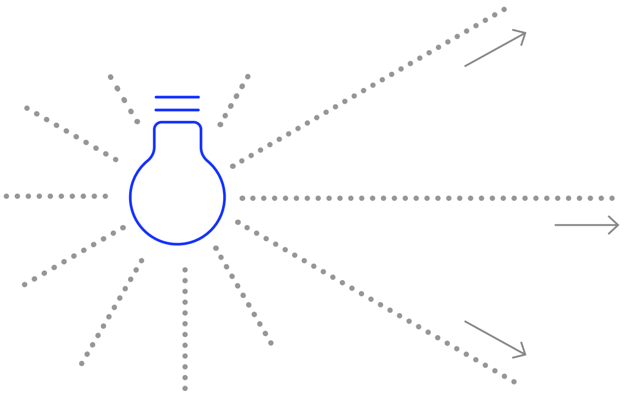

"The shorter the wavelength
the higher the energy
of the radiation."

Electromagnetic quantum theory

Max Planck assumed in 1900 that the energy of radiation is emitted in discrete indivisible portions, which he called quanta. For visible radiation (light) the term photons is used.



E = h.f or E = h.c/ λ

Fig. 1.6. Light treated as quanta or photons.

The energy content of a quantum of radiation is directly related to its frequency or wavelength:

where:
E = energy (Joule)
f = frequency (Hz)
h = Planck's constant (6.626×10^{-34} J.sec)
c = speed of light in vacuum (2.998×10^{8} m/sec)
λ = wavelength (m)

So from Max Planck's quantum theory we learn that the shorter the wavelength the higher the energy of the radiation. This explains why we have no problems with radio waves: they have long wavelengths and thus low energy. It also explains why we have to be very careful with the powerful (energy-rich) short wavelengths of UV rays, X-rays and gamma rays.


How is light produced?

2

Light can be generated in different ways

Lamps are the biggest source of artificial light today. Lamps are of three fundamentally different types:

- Thermal radiators
- Gas-discharge radiators
- Solid-state radiators

Thermal radiators

Bodies that emit electromagnetic radiation as a result of their increased temperature are called thermal radiators. Typical examples of thermal radiators are the sun and incandescent lamps.

If a solid body is heated to a temperature of about 525 °C, it will begin to emit a dull-red light. If the temperature increases, the color will change from dull-red to bright red, orange, yellow, white and finally to bluish-white as it approaches melting point.

Black-body radiator
The exact properties of the radiation from a heated body depend to some extent on the type of body (type of material) being heated. So, for the reliable analysis of these properties an unambiguous definition of the type of heated body is needed. For this purpose an idealized body, that is a perfect light absorber, is used: the so-called "black-body radiator". At temperatures too low for emission of visible radiation, it will look perfectly black, hence the description black-body radiator.

Light spectrum
The composition of light emitted by a light source is called a spectrum. In other words, the light spectrum shows the composition of the various colors or wavelengths of the emitted light. Within the visible wavelength range, all wavelengths, in different proportions, are present in the spectrum of a thermal radiator. Such a spectrum is called a continuous spectrum.

Color temperature
The temperature of a black-body radiator exactly determines the spectrum of the radiation and thus the perceived color of the light. To characterize the color of thermal radiators we therefore use the expression "color temperature", which is the temperature of the heated body. It is customary to express the color temperature in K (Kelvin) with:

$K = °C + 273$
$K = (°F + 460) \times 5/9$

Learn more about color temperature.

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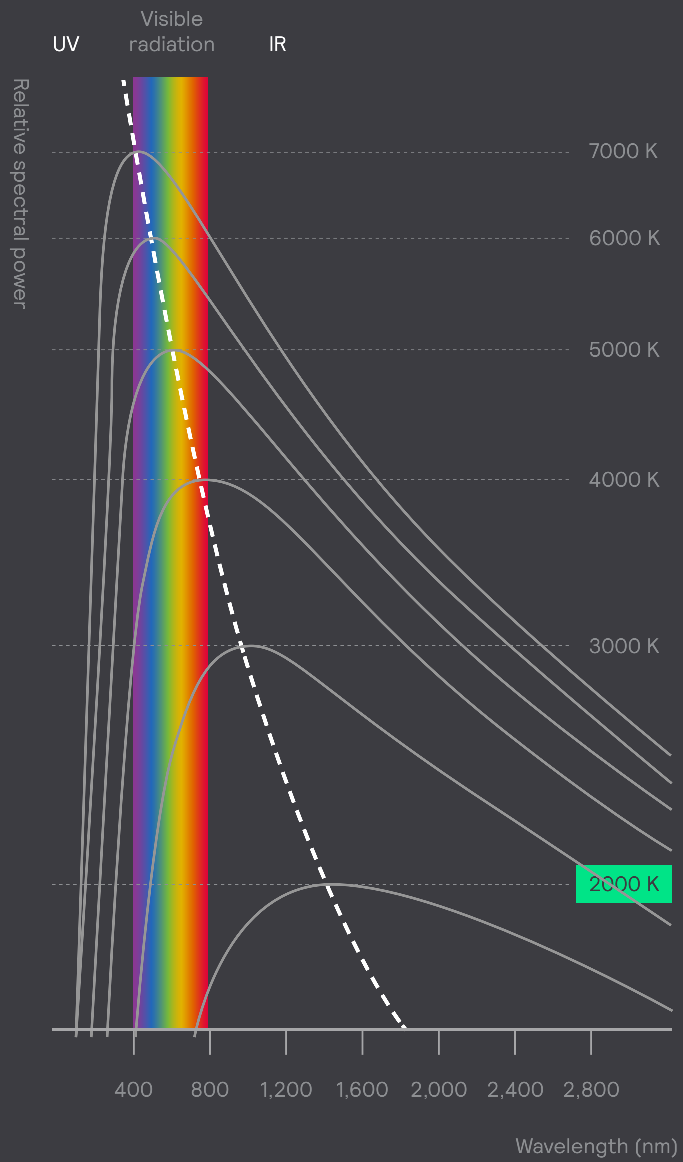
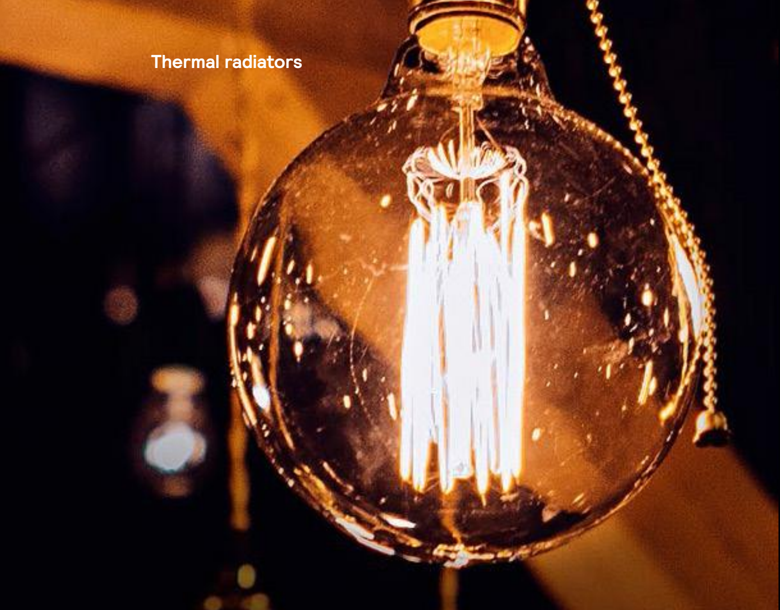


Fig. 2.1. Energy distribution curves for black-body radiators of different color temperatures.

The flame of a candle (consisting of glowing carbon particles at a temperature of around 2,000 K) emits a yellow light. The filament of an incandescent lamp (temperature around 2700 K to 2800 K) is yellowish-white, and the sun at noon (temperature around 5000 K) is white. The lower the color temperature the warmer (more reddish) the color of the light and the higher the amount of infrared radiation produced. On the other hand, the higher the color temperature, the cooler (more bluish) the color of the light, and the higher the amount of ultraviolet radiation produced.

Spectral power distribution

The spectral power distributions of black-body radiators of different color temperatures, as illustrated in Fig. 2.1, give the energy proportions for a range of wavelengths. They show that energy is radiated not only in the visible region but also in the infrared and, for temperatures higher than 3000 K, in the ultraviolet range as well. With increasing temperature, the peak of radiant energy shifts to shorter wavelengths (the blue region of the spectrum). Between 3700 K and 7600 K, the peak lies in the visible region.



Incandescent lamps

Incandescent lamps are the only available light sources generating light as a result of heating a filament. For a practical analysis of the properties of incandescent lamps, we can usually use the theoretical black-body concepts dealt with above.

This means that we learn from Fig. 2.1 that an incandescent lamp with a color temperature of 2700 K to 2800 K, emits most of its energy in the form of infrared radiation, or heat. This is why incandescent lamps are so inefficient in terms of the amount of light emitted compared to the energy consumed. Only roughly 5% of the energy consumed by an incandescent lamp is converted into visible radiation or light.

Because the filament of an incandescent lamp must have a very high temperature in order to give light, the material of the filament evaporates relatively quickly. As a consequence, incandescent lamps have a relatively short lifetime: 1,000 hours.

Halogen incandescent lamps

In a halogen incandescent lamp the temperature of the filament is increased to 3000 K.
As a result, its efficiency is indeed 2 to 3 times more than that of normal incandescent lamps. Halogen lamps can be brought to this higher temperature without the filament evaporating faster by introducing halogen gas into their bulbs.

The evaporated filament material (tungsten) chemically reacts with the halogen in such a manner that an important part of the evaporated filament material returns to the filament. This process is called the halogen cycle. Thanks to this process, the lifetime of the halogen lamp can be considerably longer than that of a normal incandescent lamp: up to 1,000 - 6,000 hours.

Learn more about the characteristics of incandescent and halogen lamps.

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Gas discharge radiators

Unless under extremely high pressure (as in the core of the sun), a gas will not light up when heated in the same way as an incandescent body does.

Nevertheless, gases can be made to emit electromagnetic radiation. The most effective way of making gas emit light is by sending a stream of electrons through it. This happens, for example, in our familiar fluorescent and other gas discharge lamps. In nature we see a similar electric discharge, only shorter, for example when there is lightning.

Principle of gas discharge

The reason why a stream of electrons travelling through a gas produces light is that the free-running electrons interact with the gas atoms. To get free-running electrons in a gas, the gas is "put" into a transparent tube with a so-called electrode sealed into each end. The positive electrode, or anode, is given a positive charge while the negative electrode, or cathode, receives a negative charge (see Fig. 2.2). The transparent tube is called the discharge tube. When a voltage difference is applied between the electrodes, free electrons are pulled out of the negatively-charged electrode and move to the positively-charged anode. Each gas atom consists of a positively-charged core (the nucleus) and a number of negatively-charged electrons orbiting around the core. If an atom is hit by a fast-moving free electron, three things may happen, depending on the relative speed of the colliding particles:

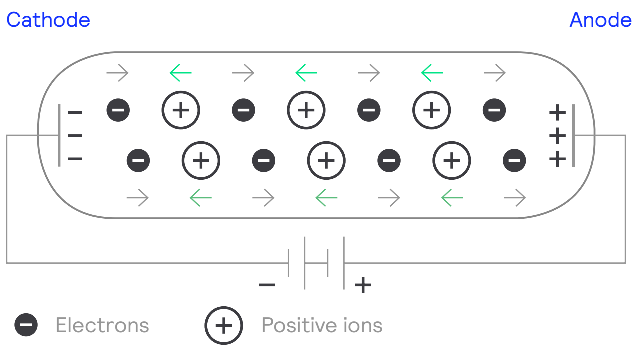

Fig. 2.2. Stream of electrons and ions in a gas discharge tube moving at high speed to the electrodes viz. anode and cathode respectively.

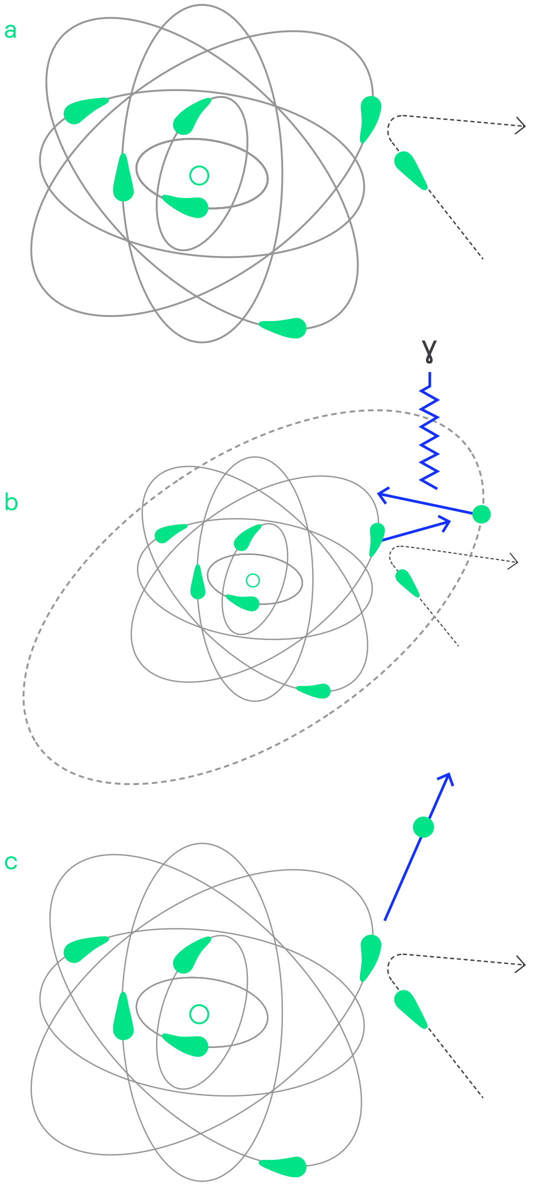

Fig. 2.3a, b and c. Elastic, exiting and ionizing collision of a free-running electron with a gas atom.

Fig. a. If the speed is relatively low, the atom will absorb some of the kinetic energy of the electron, but remain structurally unchanged. This is called “elastic collision” and results in an increase of the gas temperature.

Fig. b. If the speed is moderate, the collision will eject one of the electrons of the gas atom temporarily into a higher orbit of higher energy. This is called “exciting collision”. The excited electron very quickly falls back into its original orbit of lower energy. The difference in energy is emitted as electromagnetic radiation. The wavelength of the radiation depends on the type of gas atom and the pressure of the gas. This wavelength might fall in the infrared, the visible or the ultraviolet part of the spectrum, leading to the generation of heat, visible light or ultraviolet radiation, respectively.

Fig. c. If the speed is high, it is possible that an outer electron of the gas atom will be completely ejected. This is called “ionizing collision”. The effect is that new free particles are generated: positively-charged ions and negatively-charged electrons. The positive ions and negative electrons resulting from the ionisation process will move toward the cathode and anode respectively (see Fig. 2.2). On their way they may collide with neutral atoms in the gas, themselves contributing to the discharge process.

Learn more about the basic concepts of gas discharge lamps.

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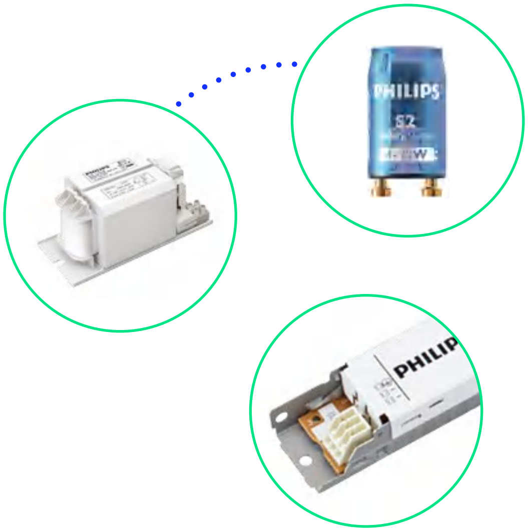
Electrical gear

As described on the previous page, the ionization process increases the number of free-moving electrons. With this increase the electric current through the discharge tube increases as well. A current-limiting device is needed to avoid an unlimited increase of this current. Such a device is called, depending on its way of operation, a resistive, inductive, or electronic ballast (pictures below).

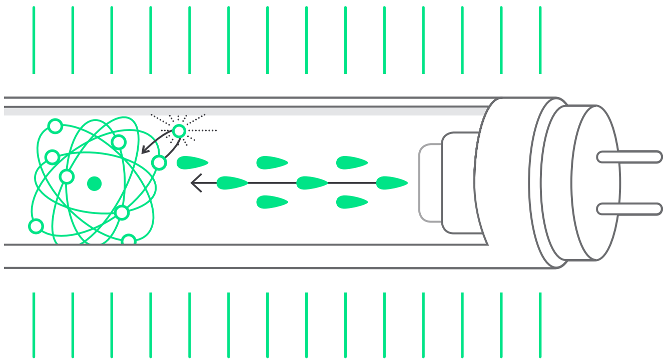
With most gas-discharge lamps the voltage difference between the electrodes alone is not enough to start pulling free electrons out of the cathode. The lamp needs an ignition device that temporarily gives a higher voltage peak to help it start. Starters may be separate items or (in more-advanced cases) the function can be incorporated in the electronic ballast.



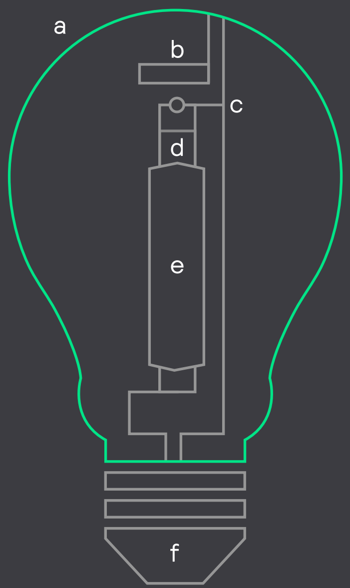
Low-pressure gas discharge lamps

In low-pressure gas discharge lamps the gas pressure inside the discharge tube is close to vacuum (about 10^{-5} of an atmosphere). The operating temperature is relatively low and the lamp is relatively long (compact low-pressure lamps are folded a few times). Low pressure gas-discharge lamps employed in lighting use either mercury or sodium gas: the low-pressure mercury and low-pressure sodium lamps. A more common name for the former is “fluorescent lamps”.

Low-pressure neon lamps, sometimes mistakenly thought to be low-pressure mercury lamps, are generally not used for illumination, but for other applications such as signage advertising.



a. Outer bulb
b. Getter
c. Discharge or Arc tube support
d. Electrode
e. Discharge or Arc tube
f. Lamp cap



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Gas discharge lamps are far more efficient than incandescent lamps: low-pressure mercury lamps up to 8 times more efficient and low-pressure sodium lamps, with their typical yellowish light, are up to 15 times more efficient. As gas discharge lamps do not employ a heated filament to give light, they have a much longer life than incandescent lamps: low-pressure lamps can have a lifetime from 10,000 to more than 25,000 hours.

High-pressure gas discharge lamps

In high-pressure gas discharge lamps the working gas pressure inside the discharge tube is around 1 atmosphere. The temperature of the gas may reach 4,000 to 6,000 degrees centigrade. Compared to low-pressure lamps, high-pressure lamps are much more compact. As in low-pressure gas discharges, either mercury or sodium gas is used in high-pressure mercury and high-pressure sodium lamps. Common lamp types using mercury are, in addition to high-pressure mercury lamps, metal halide lamps. Lamp types using sodium are the high-pressure sodium SON and white SON lamps. The group of high-pressure gas discharge lamps is sometimes referred to as HID (High Intensity Discharge) lamps.

As already mentioned, gas discharge lamps are far more efficient than incandescent lamps: high-pressure lamps up to 10 times more. Also the lifetime is much longer: high-pressure lamps have a lifetime of 10,000 to more than 25,000 hours.

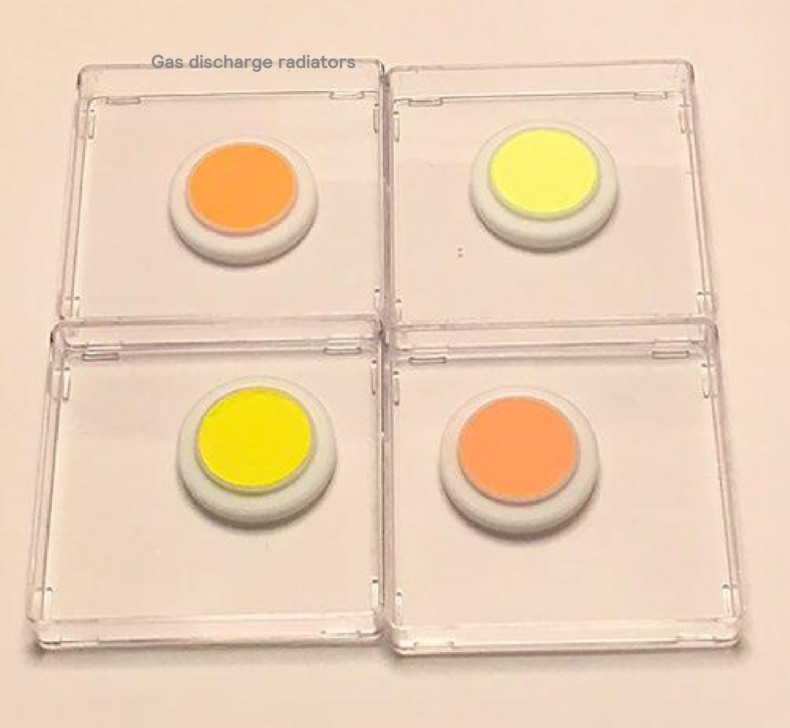
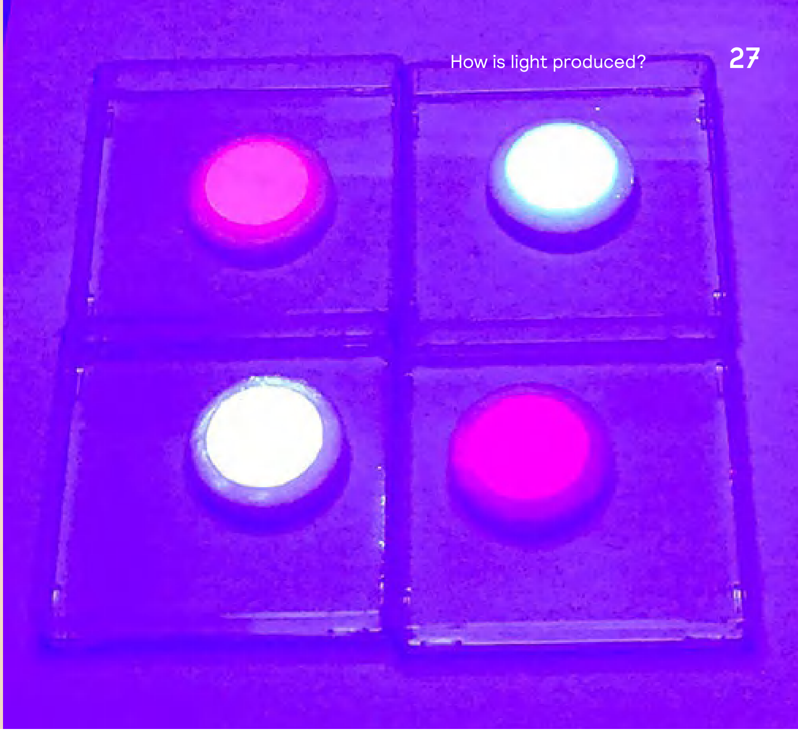


Fig. 2.3. Four different types of fluorescent powder under white light.



The same fluorescent powders under UV radiation.

Fluorescence

In some gas discharge lamps not all the radiation produced is in the visible range. In the case of low-pressure mercury lamps, for example, the most important part of the radiation is in the ultraviolet range, combined with just a little bit of blue visible light. By coating the inside of the discharge tube with fluorescent powder, the ultraviolet radiation is converted into visible light (Fig. 2.3). This is the process employed in tubular low-pressure mercury lamps – hence the name fluorescent tubes.

Many different fluorescent powders are available to convert the ultraviolet radiation into visible light of different wavelengths (colors). By mixing different fluorescent powders in different proportions, lamps producing different tints of white light can be made. This is how the different fluorescent lamp colors are produced.

Learn more about fluorescent light and delivery system.

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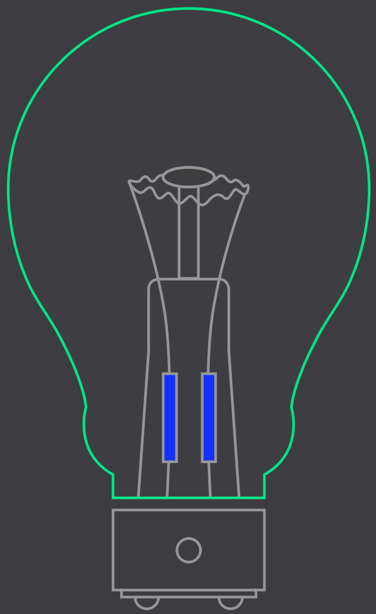
Correlated color temperature

In the beginning of this chapter, the concept of color temperature as a measure for the color impression of the light emitted has been explained. This concept cannot be used for gas discharge lamps because the temperature of the gas in the discharge has no relation to the color of the light. The concept of correlated color temperature was therefore introduced to quantify the color characteristics of gas discharge lamps. The idea behind this concept is that we compare the color of the light of the discharge lamp with the color of a black-body radiator, the temperature of which can be changed.

The color temperature of a gas discharge lamp is defined by adjusting the temperature of a black body radiator until its color closely matches that of the discharge lamp we wish to evaluate. In practice there is no need to repeat this “test” for each new lamp, because the correlated color temperature can be calculated from the spectral power distribution of the discharge lamp. More details on this are given in Chapter 6 “Light and color”.

Spectral power distribution

As was explained earlier, a heated filament produces a continuous spectrum: that is to say, all wavelengths are present in the spectrum. Fig. 2.4a. shows the spectral power distribution of an incandescent lamp. Gas discharge lamps, on the other hand, have a discontinuous spectrum. A somewhat extreme example is shown in Fig. 2.4b. The “peaks and gaps” in the spectrum of a gas discharge lamp have consequences on the color properties of its light, details of which are dealt with in Chapter 6 “Light and color”.



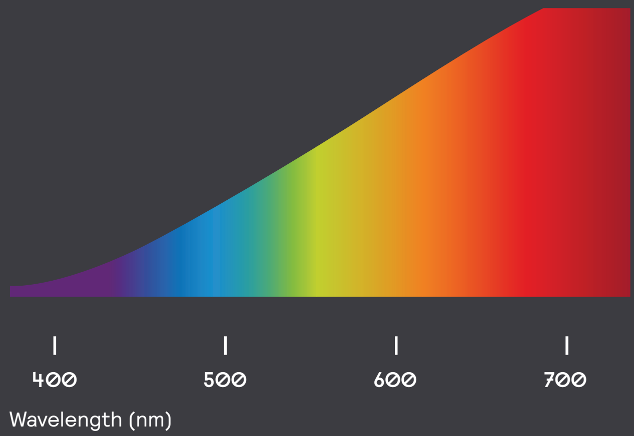
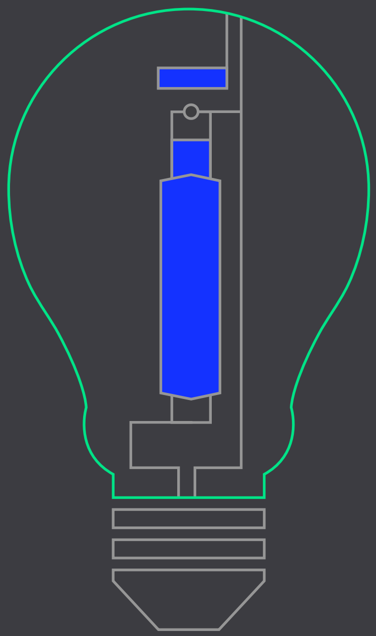


Fig. 2.4a. Example of a spectral power distribution of an incandescent lamp



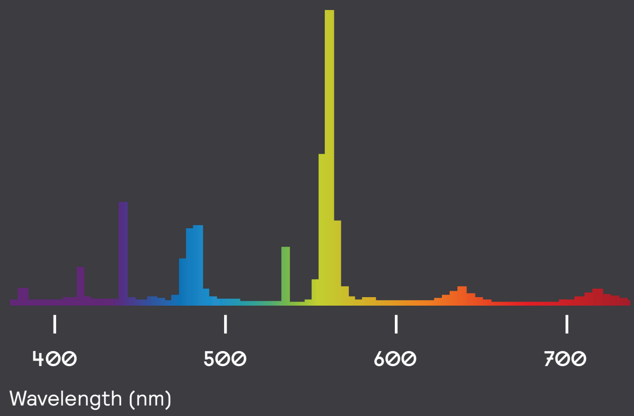


Fig. 2.4b. Example of a spectral power distribution of a gas discharge lamp.


Solid

Solid-state radiators

As the term suggests, solid-state radiators are light sources where the light is created inside solid-state materials.

Principle of operation

The phenomenon was discovered as early as 1907. The first practical product based on it was developed in 1962. The solid material used is semiconductor material which, like in common diode chips, is layered as a so-called p-n junction, hence the name Light-Emitting Diode or LED. The n-material has an excess of electrons whereas the p-material has electrons missing i.e. electron holes.

Applying a voltage across the p-n junction pushes electrons towards the junction of the two materials, where electrons from the n-material fall into the holes of the p-material. In so doing, the electron moves from a high energy level to a lower one, and the energy difference is emitted as light (Fig. 2.5).

All diodes emit electromagnetic radiation. The semiconductor material used in LEDs is selected so as to emit in the visible range. Different materials produce light with different wavelengths and thus different colors. It is, of course, essential to get the light out of the solid state material without too many absorption losses. This is one of the fields where important improvements have been made. Until the mid-nineties of the last century, LEDs had a low lumen output and low efficiency, making them only suitable as signal lamps. Today, the efficiency of LEDs is comparable to that of gas discharge lamps.

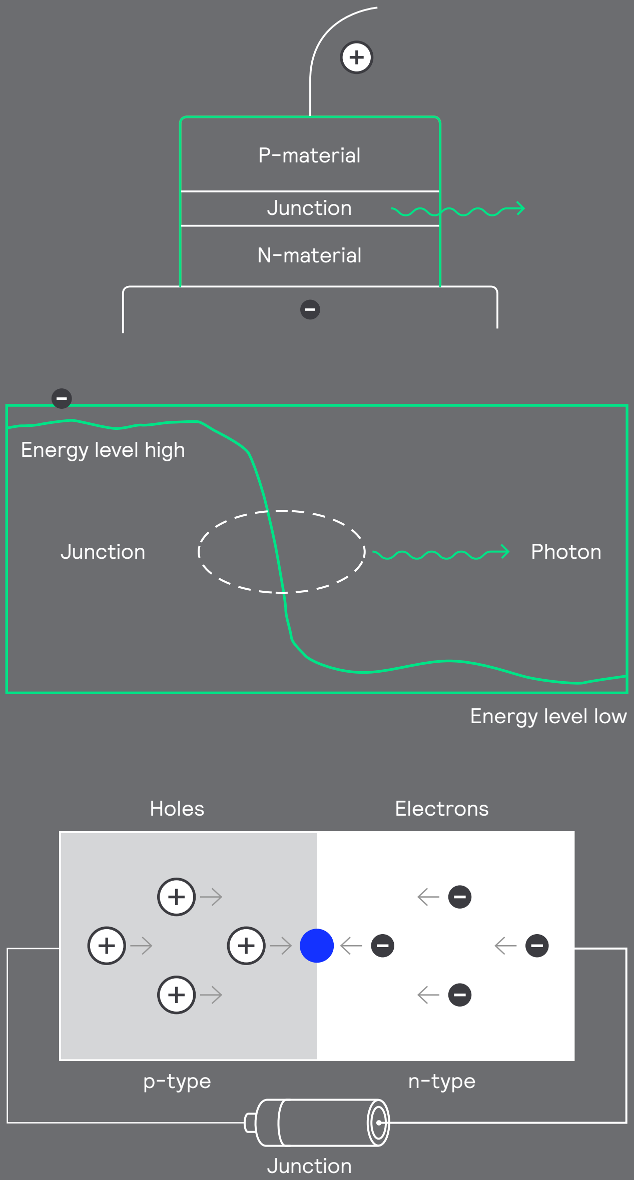


Fig. 2.5. Principle of operation of solid-state radiators.

Electrical drivers

In LEDs, current increases very quickly as voltage increases. Small fluctuations in voltage can therefore damage them. A so-called “driver” must therefore be employed to control the input power to the LED. The LED driver is an electronic circuit that keeps the current constant despite fluctuations in voltage so that the LED can be operated from any normal power supply. Drivers can also incorporate a dimming function so that a LEDs light output can be controlled to between 0% and 100%.

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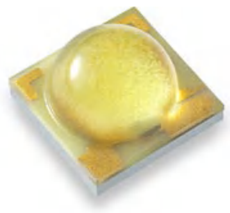
LEDs

LED-chips are small, point light sources that can be used singly or in a cluster of more than one chip. Around the LED chip or cluster all kinds of optical materials can be used to direct and screen the light (Fig. 2.7). If the LED chip or cluster, with its driver, is encapsulated in a bulb with a conventional lamp base, we have a direct replacement for an incandescent lamp: the so-called LED lamp.



Spectral power distribution

Different semiconductor materials give different spectra. The materials today available make it possible to produce LEDs in all colors. The spectral power distribution is always narrow.

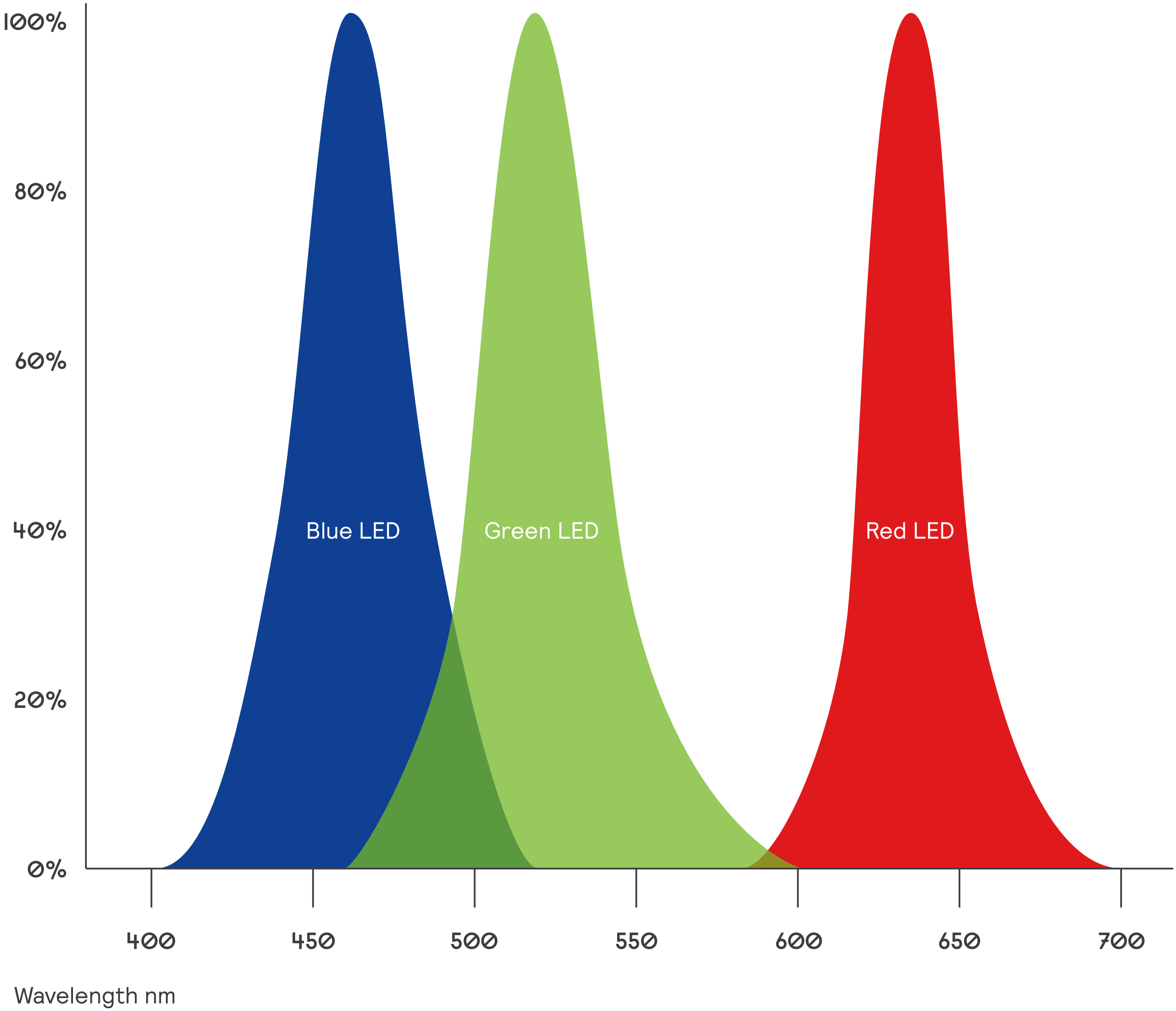


Fig. 2.6. The spectral power distributions of typical blue, green and red LEDs.

White LEDs

Since the spectrum of a single LED is always narrow, white LED chips cannot yet be produced. But white LED light can nevertheless be obtained by combining three (or more) differently-colored LED chips. A common method is to combine red, green and blue LED chips into a single module or system to give white light. However, the color rendering of such an “RGB white light” system is not good, since large areas of the full color spectrum are not included. Research is underway to produce single, multi-layer LED chips, each layer producing a specific color of light. A single LED producing red, green and blue light would therefore result in white light. Good-quality white light, which is especially important when it comes to providing good color rendering, is obtained by using a blue LED chip in combination with fluorescent material that converts much of the blue light into light of different wavelengths spread over almost the whole visible spectrum. In LED technology, such a fluorescent material is called a phosphor: hence the white LED based on this principle is called a “phosphor-converted white LED”. Figure 2.8 shows the spectral power distribution of such a white phosphor LED, from which it can be seen that now light is emitted over almost the whole of the visible spectrum.

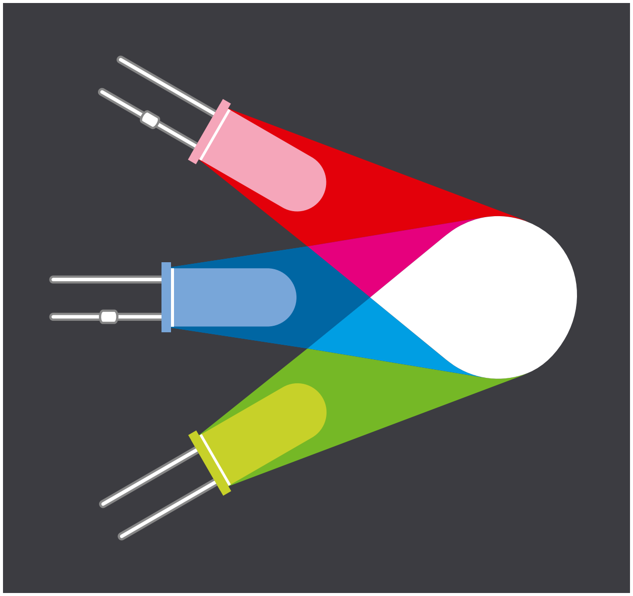


Fig. 2.7. White light by combining red, green and blue LED light.

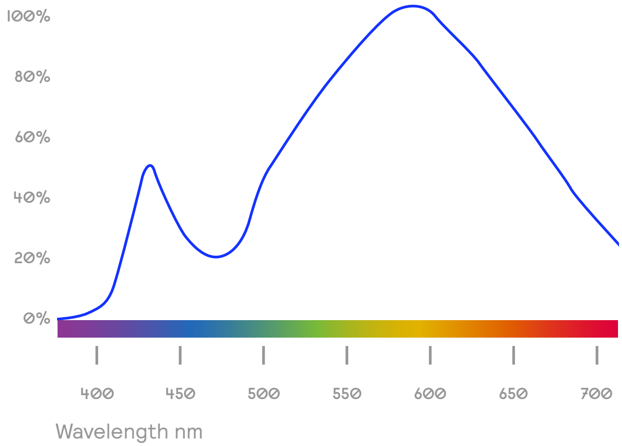


Fig. 2.8. The spectral power distribution of a typical white-phosphor LED.

Learn more about how LED works.

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Lamp types

We will explain why there are so many different lamp types and what the “family relationship” between these many different types is.

Why so many lamp types?

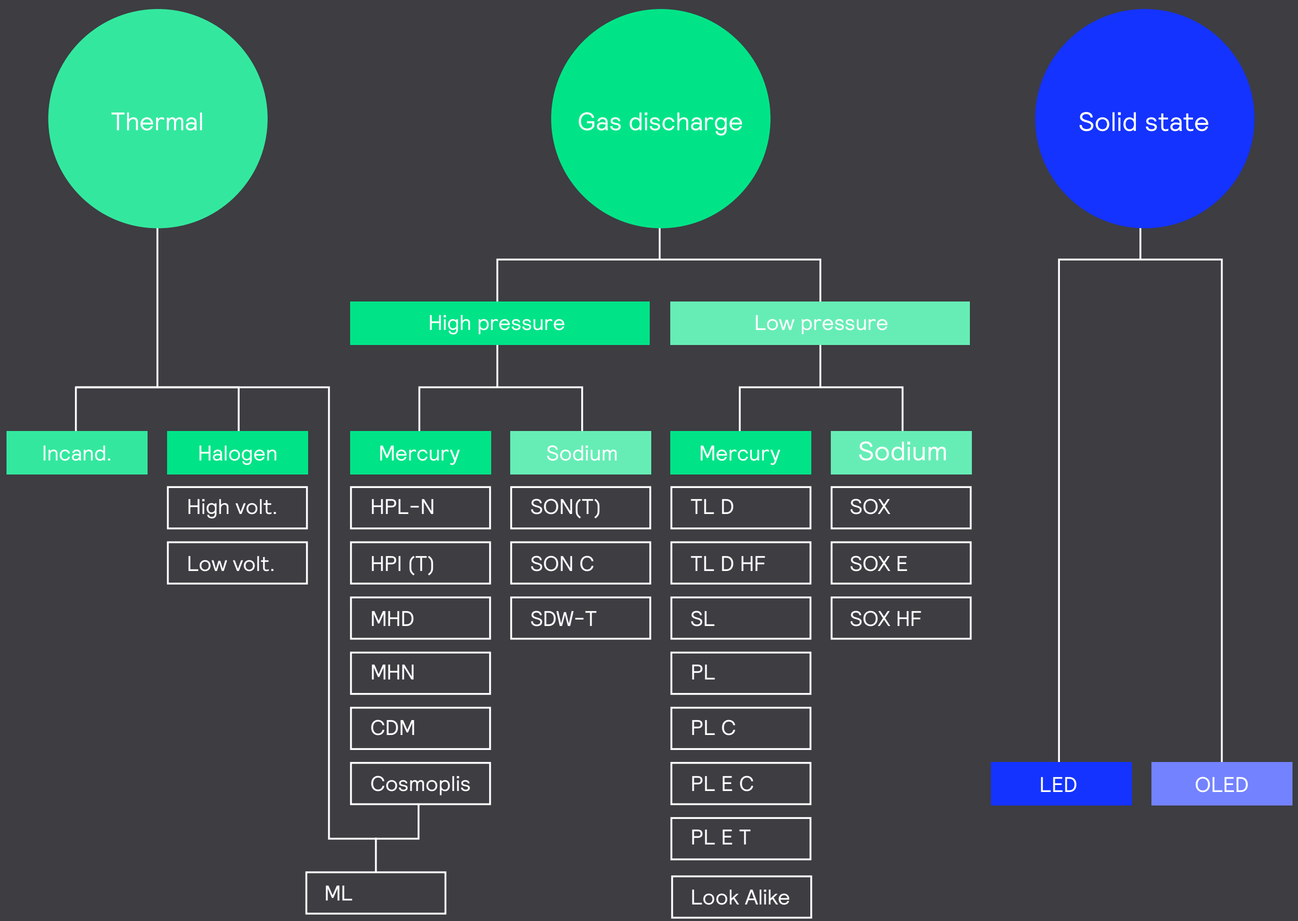
In the past we talked about lamps and luminaires optics within the lighting system separately, but nowadays with LED technology, with very few exceptions, lamps and optics are combined. We will further discuss this in Chapter 3 “How is light directed and screened?” The catalogue of a lamp manufacturer lists a great number of different lamp types. The reason for this is that the ideal lamp simply does not exist. For one specific lighting application the properties of one specific lamp type may be very suitable, but that same lamp may be totally unsuited for another lighting application. Each lighting application calls for a lamp with a specific set of properties. Table 2.1 provides a description of some of the more important lamp properties, which can vary with different lamp types. It is the task of the lighting designer to choose the lamp properties best suited to a particular application.

Light output	Price
Efficacy	Shape and dimensions
Light color	Dimmability
Color rendering	Dimmability
Lifetime	Lamp temperature
Light depreciation	Temperature sensitivity
Ballast yes / no	Sensitivity
Ignitor yes / no	Burning position
Light distribution	Run-up time Environment-unfriendly materials

Table 2.1. Some of the more important properties of lamps.

Lamp pedigree

It is difficult to remember all the different properties of so many different lamp types. The following family tree, will help in this respect.



How is light directed and screened?

3

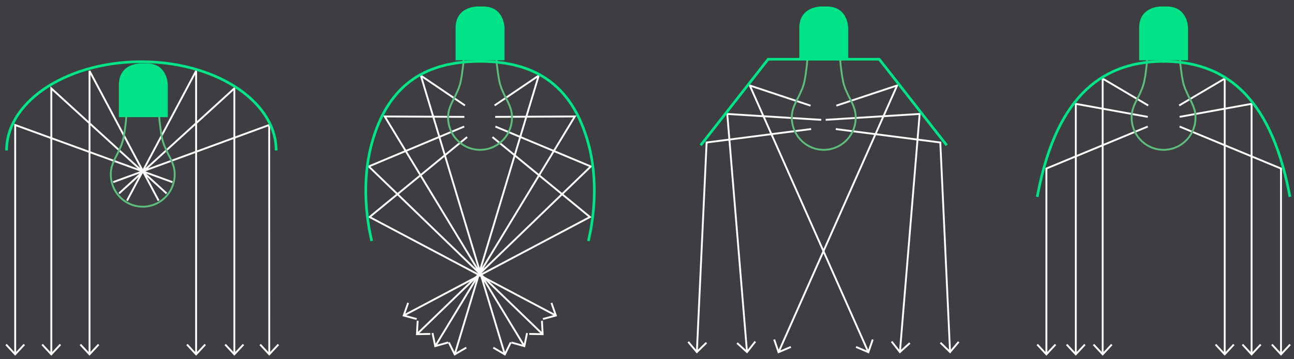


Fig. 3.2. Different light beams as a result of different mirror shapes.

Learn more about how Light absoprtion works.
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The light from a bare lamp has to be efficiently directed to where it is needed and also screened so that it does not create disturbing glare. For directing and screening light we use materials that reflect, refract, absorb or transmit the light. In luminaries, one or more of these effects are employed.

Reflection

Under normal conditions, only part of the light falling on a surface will be reflected. The amount reflected depends on the type of surface, the angle of light incidence, and the spectral composition of the light. Reflection ranges from less than a few percent for very dark surfaces, like black velvet, to over 90 per cent for aluminum, silver. and certain types of white paint. The ratio of the reflected to the incident light is called the reflectance of the surface. denoted by the symbol ρ. which can vary between 0% and 100%. Normally. the reflectance Is not the same for all spectral colors. A red surface, for example, will mainly reflect red light. This subject will be dealt with in Chapter 6 “Light and color”.

The way light is reflected also depends on the smoothness of the surface. Three types of reflection can be distinguished: specular, diffuse and mixed reflection. Specular reflection takes place on a smooth surface, like the surface of still water or polished glass. The angle of light incidence Is equal to the angle of refection (Fig. 3.1).

This type of reflection is called specular or mirror reflection. Reflectors, especially curved ones, are very popular when precise light control is required, as in floodlights, spotlights, road and indoor lighting luminaires. These reflectors may be part of the luminaire or integrated into the lamp itself. Depending on the shape of the mirror (spherical, elliptical, parabolic) and the position of the light source, divergent, parallel or convergent light beams can easily be produced (Fig. 3.2).

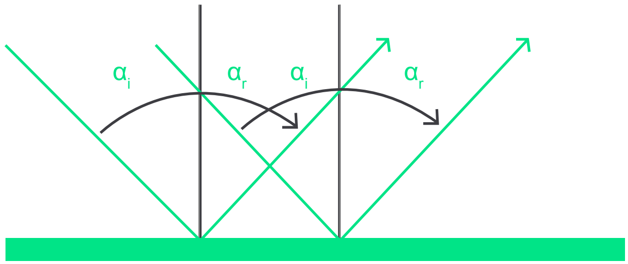


Fig. 3.1. Spectacular replection: angle of light incidence ą is equal to the angle of the reflection ą

Diffuse reflection

A different type of reflection occurs if the surface shows a certain degree of irregularity. The incident light will then be reflected in all directions. This type of reflection is called diffuse reflection.

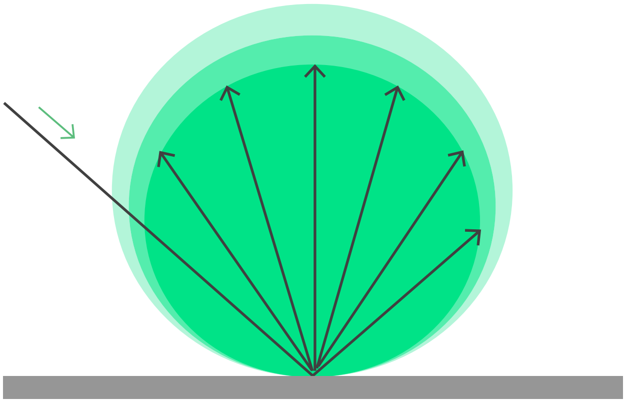
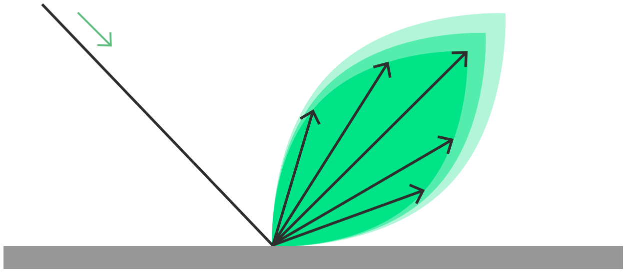


Fig. 3.3. Diffuse reflection

Mixed reflection

There are several mixed forms of reflection between specular and diffuse. One is spread reflection, which is essentially specular, but the reflected light forms a spreading beam (Fig. 3.4). A wet road surface is a familiar example. Spread reflection is also produced by a corrugated, hammered, etched or tarnished surface. Another form is compound reflection, which is diffuse reflection with a strong component in the specular direction. Matt-painted surfaces, stones, and dry road surfaces exhibit this form of reflection.



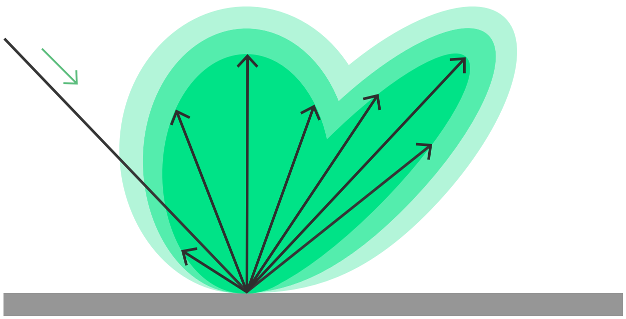


Fig. 3.4. Above: spread reflection and under: compound reflection

Total internal reflection

If light travels in a medium of greater optical density than that of the medium by which it is surrounded – for example, in a glass rod surrounded by air – it will be completely reflected from the boundary between the two media so long as the angle of incidence with respect to the normal exceeds a certain critical value. This phenomenon is called total internal reflection (Fig. 3.5).

The value of the critical angle for glass and air is 42°. If the glass rod mentioned above has no sharp curves, the light will be unable to leave it, except at the ends, and thus can be transmitted over long distances, with only small losses due to absorption. This phenomenon is widely used in glass fibres for digital data transmission, but in some cases also for (accent) lighting installations.

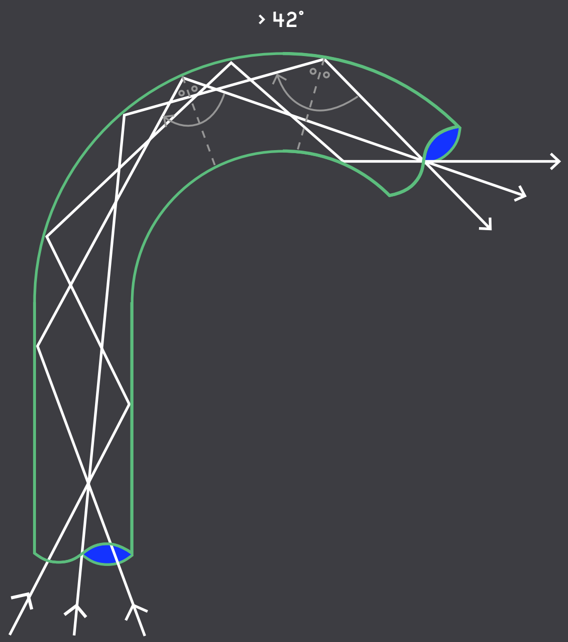


Fig. 3.5. Total internal reflection in a glass fibre.

Absorption

The light falling on a surface that is not reflected is either absorbed or transmitted. If the surface material on which the light falls is not transparent, the non-reflected light ‘disappears’ in the surface and is converted into another form of energy, ultimately heat.

The percentage of the light absorbed by a surface depends on both its angle of incidence and its wavelength. For example, a red surface reflects the red light but absorbs most of the other colors.

Transmission

If the material on which the light falls shows a certain degree of transparency, part of the light will pass through it. This is called transmission.

Some materials, such as clear water and clear glass, transmit almost all the light that is not reflected. Others, such as a sheet of paper, will only transmit a very small proportion of the incident light. The ratio of transmitted light to the incident light is termed the transmittance. The transmission is wavelength dependent: red-colored transparent material transmits only the red part of the spectrum while the remaining part is absorbed. Filters based on this effect are called absorption color filters.

Refraction

If a ray of light passes from one medium into another of different density, at an angle other than perpendicular to the medium, the ray will be broken or bent.

This phenomenon is called refraction, and has to do with the change of speed of light as it passes between media of different optical densities. The refractive properties of a medium are expressed by the refraction index n. This refractive index varies with the wavelength of the incident light, short wavelengths (e.g. blue light) being refracted more than long waves (e.g. red light). Refraction, like specular reflection, can be accurately calculated (Fig. 3.6).

$$\frac{\sin \alpha_1}{\sin \alpha_2} = \frac{n_1}{n_2}$$

with n_1 = refraction index of air (= 1)
n_2 = refraction index of glass (crown glass = 1,5)

This is of great value in the construction of refractors and mirrors, which are often used for directing and screening light in various types of luminaires.

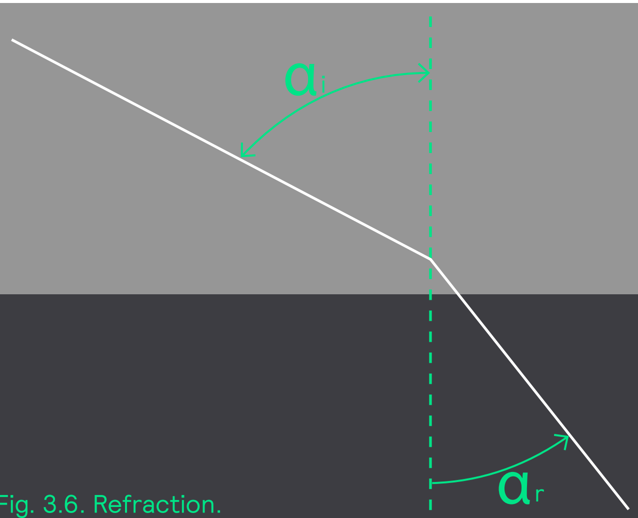


Fig. 3.6. Refraction.

Learn more about the refraction of light

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Interference

The wave nature of light can also lead to the interesting effect of interference. This can be seen, for example, on the surface of a CD or as the brilliant pattern of colors on soap bubbles.

It is in practice used to split transmitted and reflected light into light of different wavelengths. This is done by applying very thin, ¼ λ, coatings (also called dichroic coatings) on surfaces. This is how the anti-reflective glass used for VDU screens and spectacles is made: light with wavelengths in the visible range is transmitted but not reflected from the coated glass surface. The interference effect is also used to produce high-quality color filters. These interference, or dichroic, filters are more accurate than normal absorptive color filters and do not become hot because there is no light absorption in the glass. Interference or dichroic layers are also the basis for splitting radiation into an infrared (heat) part, which is reflected, and another part, the visible part, which is transmitted. Cool-beam halogen lamps and low-pressure sodium lamps use this technology.

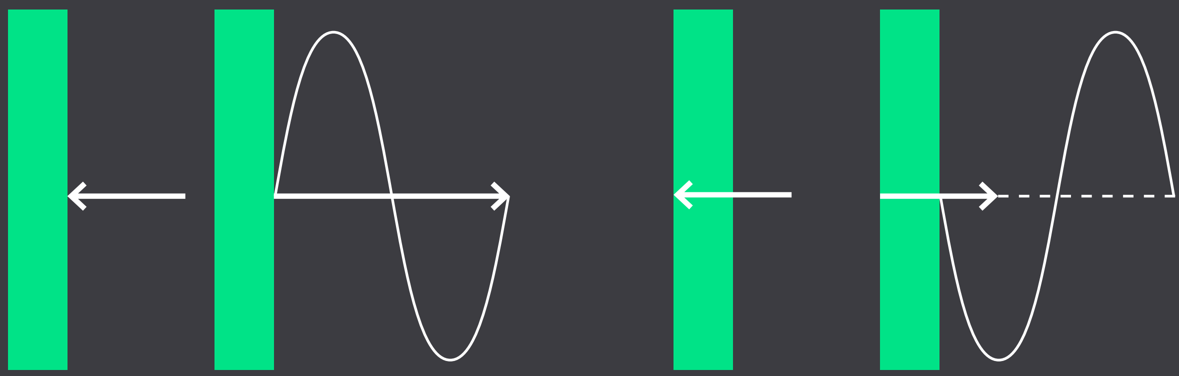

Fig. 3.7. Interference on a layer with a thickness of ¼ of the wavelength of light.


Brilliant

The interference effect can be compared with the effect of two waves on the water meeting and either amplifying each other, as when the tops of the two waves meet (waves are in phase), or weakening (or extinguishing) each other, as when the tops of one wave meet the valleys of the other wave (waves are out of phase). What is happening with the soap bubble is that light is reflected on the outside and on the inner side of the very thin film of soap. On their return path the two reflected waves meet and interact: the waves can be amplified, weakened or even extinguished. Extinguishment occurs when the thickness of the layer is equal to ¼ of the wavelength of the light.

This is because then the reflected wave on the inner side (lower part of Fig. 3.7.) has, relative to the reflected wave on the outer side (top part of Fig. 3.7), travelled an extra distance “up and down” the ¼ width of the layer. This means that the two reflected waves are out of phase (tops meet valleys). So, waves with this wavelength are extinguished and are not reflected but only transmitted through the layer while all other wavelengths are reflected.

For reasons of clarity, the effect of reflection on the outer side and inner side of the layer is drawn separately (top and bottom respectively). On the left the incident light and on the right the reflected light. The reflected wave on the inner side is ½ of a wavelength out of phase because it has travelled an extra distance “up and down” the ¼ width of the layer. The two out-of- phase waves cancel each other out.

Quantities and units

4


Sense

Why separate light quantities?

A special set of concepts and units has been adopted for lighting that bears no direct relationship to those used in other domains of physical science.

The principal reason for this is that lighting units must take not only the energy content of radiation into account, but also the sensitivity of the human eye to that radiation.

The spectral eye sensitivity and light units

In previous chapters we have seen that natural and artificial light can comprise different wavelengths.

Within the visible range of the electromagnetic spectrum the sensitivity of the eye varies strongly with different wavelengths of the same energy content. For example, at daylight levels the eye is about 20 times more sensitive to light with a wavelength of 555 nm (yellow-green) than it is to wavelengths of 700 nm (deep red) or 450 nm (violet-blue). As early as 1924, the international lighting commission CIE defined a standard eye sensitivity curve. This curve gives the relative eye sensitivity a function of wavelength and is called the V(λ) curve (Fig. 4.1). Note that at dim light levels (e.g. night time) the eye sensitivity curve is distinctively different.

In all light units the energy content of radiation is weighted against the spectral eye sensitivity V(λ). All light units therefore indeed take into account both the energy content of radiation and the sensitivity of the eye to the wavelengths contained in that radiation.

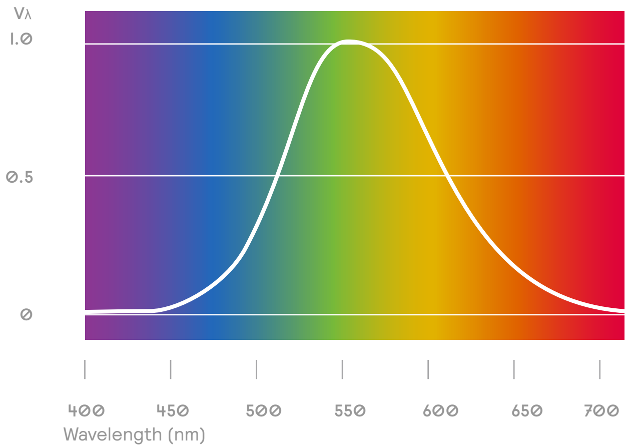

Fig. 4.1. Standard spectral eye sensitivity curve for photopic vision V(λ), according to CIE.


Spectral

Photometric quantities and units

Luminous Flux

Luminous flux (f) is the amount of light radiated by a light source per second. The unit of luminous flux is the lumen (lm) and the symbol is ϕ.

The luminous flux is used to specify the total amount of light emitted by a lamp or a luminaire – it does not specify the directions in which this light is radiated (Fig. 4.2).

It is often included in lamp specifications in catalogues, datasheets, and on the packaging of a lamp. By international agreement (IEC standards), the luminous flux (lamp-lumen) is measured when the lamp is operated under standard conditions.

The ratio between the luminous flux of a lamp and the power dissipated in that lamp is termed its 'luminous efficacy' and is expressed in lumen per watt (lm/W). It is a measure for how energy efficient the light is produced. Values range from something like 10 lm/W for an incandescent lamp to 100 lm/W for a fluorescent tube and 175 lm/W for a low-pressure sodium lamp, to over 120 lm/W for a high flux LED.

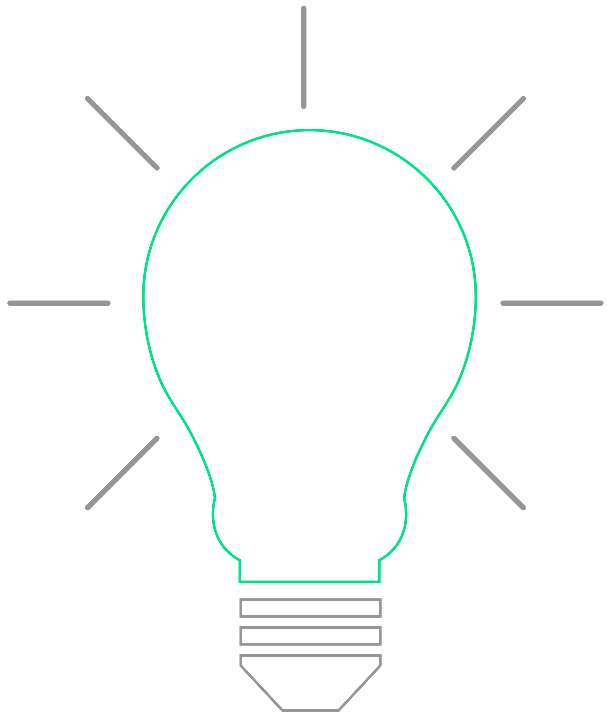

Fig. 4.2. Luminous flux: total amount of light emitted.

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Learn more about photometrics
view more >>

Learn more about luminous flux
view more >>

Luminous intensity

Luminous intensity I is the quantity of light emitted per second in a specific direction. The unit is the candela (cd). The intensity is thus a light unit that can be used to specify the amount, or concentration, of light in a specified direction. The luminous intensity is defined as the luminous flux in a specified direction, radiated per unit of solid angle ω (Fig. 4.3.)

Learn more about luminous intensity
view more >>

Illuminance

Illuminance E is the amount of light, or luminous flux Φ, falling on a unit area of a surface (Fig. 4.4). The unit is the lux. One lux equals one lumen of incident light per square meter of the light-receiving surface.

$$E = \Phi / A$$

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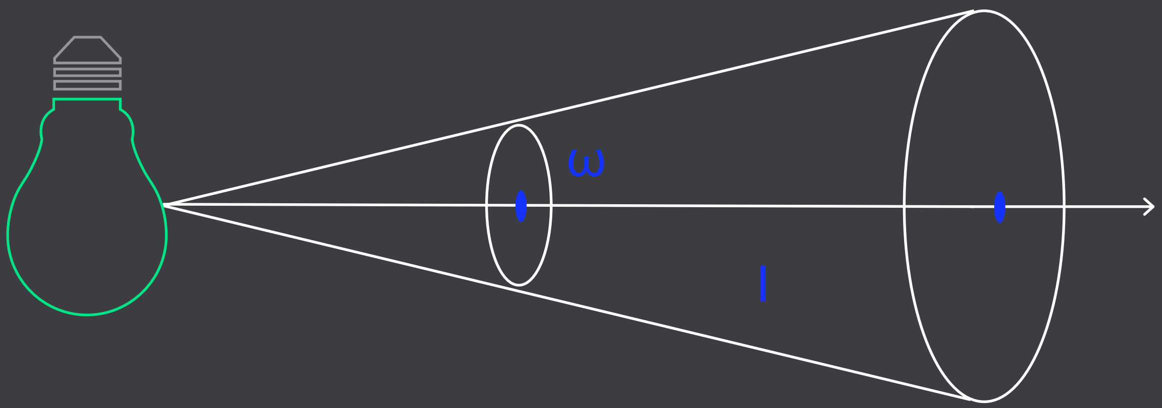


Fig. 4.3. Solid angle ω and intensity I. A solid angle can best be described as the opening angle of a cone. Intensity is the luminous flux contained in an infinitely small cone divided by the solid angle of that cone.

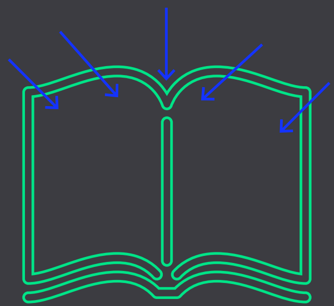
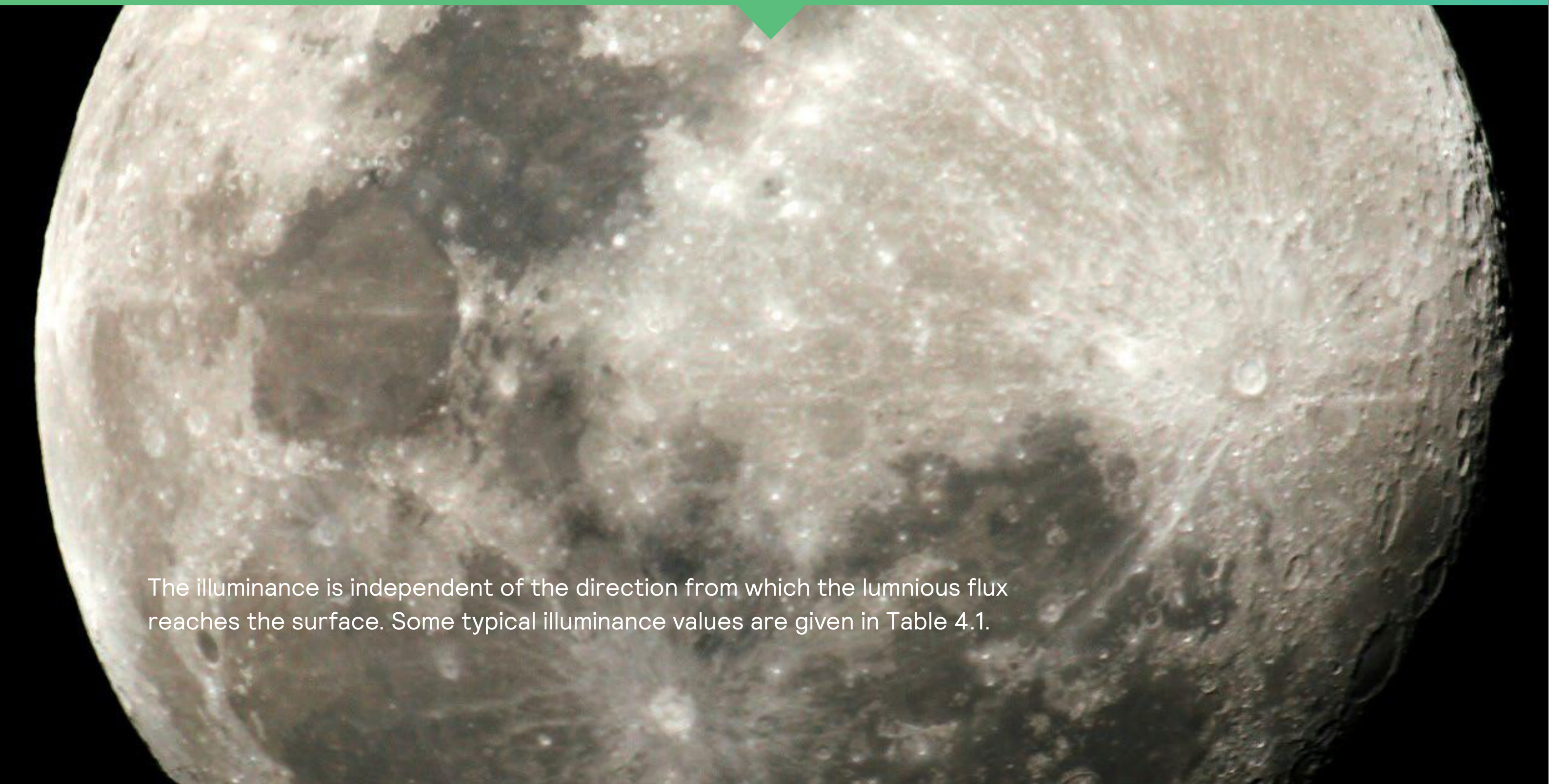


Fig. 4.4. Illuminance: flux falling on a unit area of surface.

Illuminance (lux) typical values

Summer - bright day	100,000 lux
Overcast sky	5,000 lux
Office, illuminated	500 lux
Living or hotel room	100 lux
Moonlight - clear sky	0.25 lux

Table 4.1. Typical illuminance values under different conditions



The illuminance is independent of the direction from which the lumnious flux reaches the surface. Some typical illuminance values are given in Table 4.1.

Luminance

The luminance L of a light-emitting object or surface is the luminous intensity (I) emitted per unit of (apparent) area of that surface Aa in a specific direction (Fig. 4.5). The unit is candela per square meter (cd/m²).

$$L = I \ / \ A_a$$

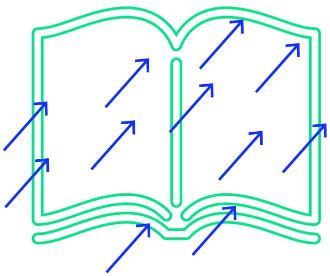
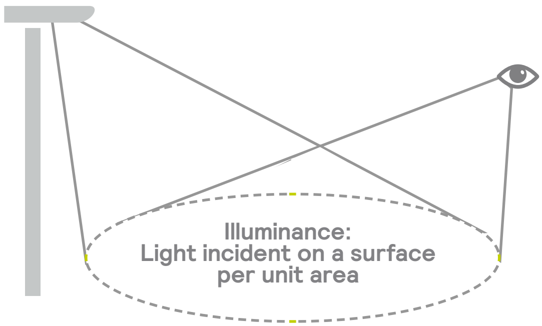


Fig. 4.5.Luminance: intensity emitted per unit of area from a surface.

Luminance: Light intensity per unit area of the surface emitting light as seen by our eyes



The surface can be the light-emitting part of a lamp or luminaire, but it can also be a surface from which light is reflected or transmitted, like a window. In the latter case we talk of a secondary light source. Examples of secondary light sources are a book or walls in a room lighted by the room lighting or a road surface lighted by a road-lighting installation. Normally we are interested in the luminance in the direction of an observer looking towards the light-emitting area or surface. What we see from lit surfaces such as books, walls and road surfaces is not the light falling on them but the light reflected from them. This means that we “see” not illuminances but luminances, or rather luminance variations in the field of view. It is therefore the most important quantity in lighting engineering, although the other three - luminous flux, luminous intensity and illuminance - are generally easier to work with when performing calculations or measurements.

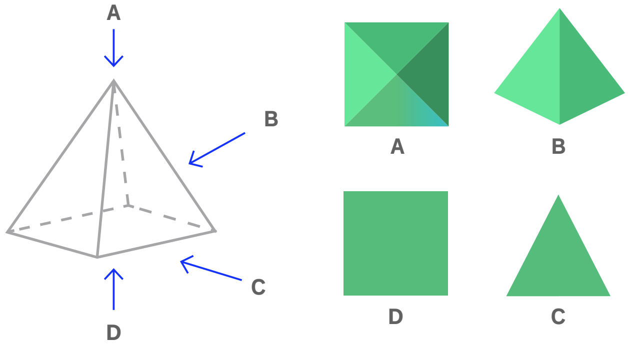
Some typical luminance values are given in Table 4.2.

Surface sun	1,650 M cd/m²
Filament incandescent lamp	7,000,000 cd/m²
Blue / overcast sky	2,000 / 80,000 kcd/m²
Fluorescent lamp	5,000 - 15,000 cd/m²
Office desk	100 cd/m²
Road surface (street lighting)	0.5 - 2.0 cd/m²

Table 4.2. Typical luminance values.

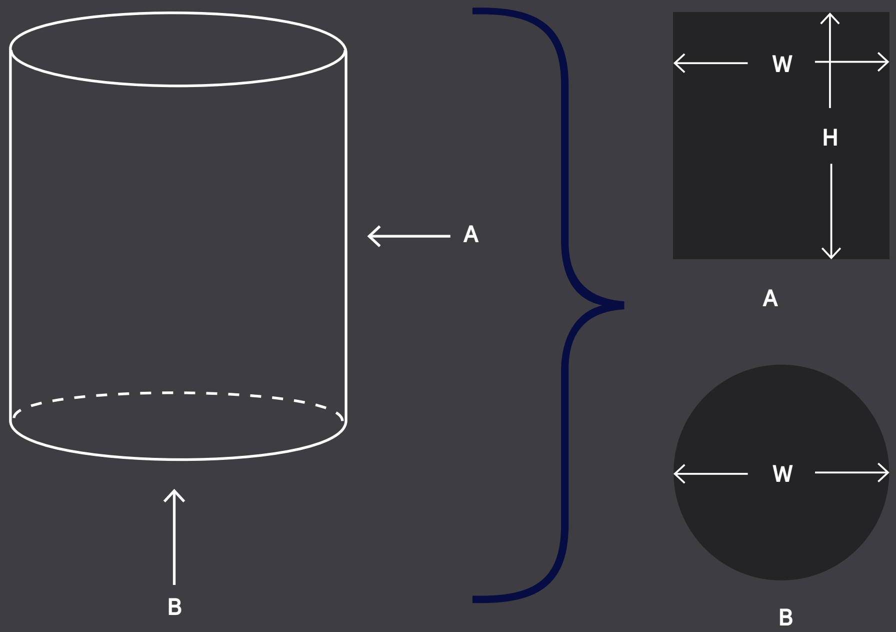
Apparent area

The apparent area is the projection of any area of the surface in question onto a plane that is at right angles to the direction of view (Fig. 4.6)



Even for homogeneous radiating surfaces of complex three dimensional form (same intensities in all directions) the luminance is very much dependent on the direction of observation. For a given direction, both the luminous intensity and the apparent area are independent of observation distance. This means that, in clear sky, the luminance is also independent of distance.

Fig. 4.6. Apparent areas (in greens) for different viewing directions towards the same shape.



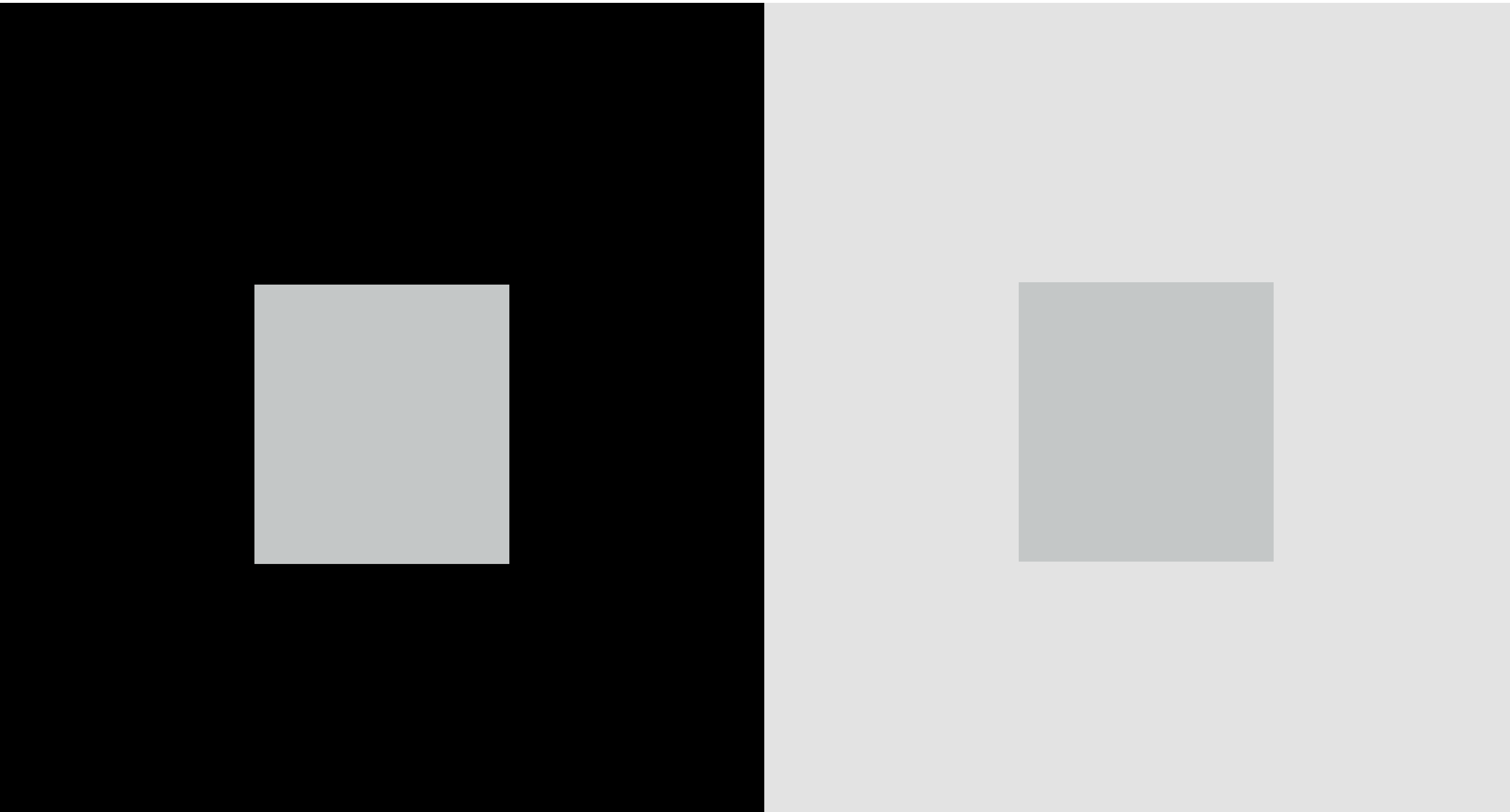
As seen from direction A, the source would appear as a flat rectangle.

As seen from direction B, it would appear as a disc (circle).

Brightness

Luminances of light-emitting surfaces evoke a sensation of brightness if we look towards them. Luminance is an objective measure, whereas brightness is a subjective evaluation made by the observer. The subjective evaluation is indeed largely dependent on the luminance of the surface, but also on other factors such as the overall luminance distribution in the field of view. Two surfaces of the same luminance may evoke different brightness impressions. The grey square in the illustration (Fig. 4.7) looks darker against the white background than against the black background, although the luminances are the same.

Fig. 4.7. Same tints of gret may appear different because of a different background.



Practical relations between light quantities

Luminous flux and average illuminance

The average illuminance on a surface is equal to the luminous flux (ϕ_inc) incident on that surface divided by the area (A) of that surface (Fig. 4.8).

Thus:

$$E_{av} = \frac{\Phi_{inc}}{A}$$

If a luminous flux of 10,000 lm falls on a surface with an area of 12 m², the average illuminance will be 10,000 / 12 = 833 lux.

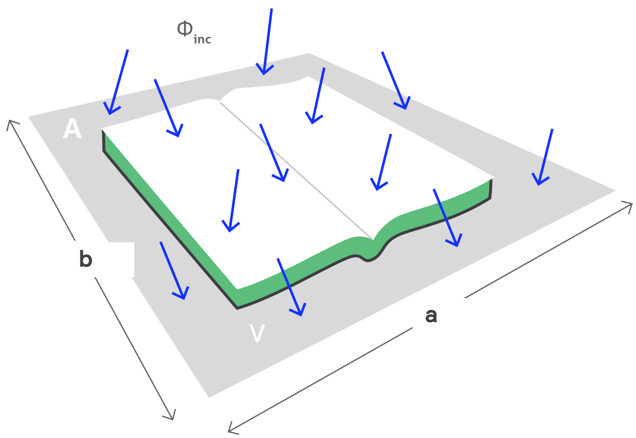


Fig. 4.8.Relation between average illuminance E_{av} and incident luminous flux Φ_{inc} on a surface with area A (a x b).

Luminous intensity and illuminance

Inverse square law

The illuminance on a point in a plane perpendicular to the direction of light incidence is equal to the luminous intensity in the direction of the point, divided by the square of the distance between the (point) light source and the point in question (Fig. 4.9). If we call the distance d, the following formula applies:

$$E = \frac{I}{d^2}$$

For example, if a point light source emits a luminous intensity of 1,200 cd in a direction perpendicular to a surface at a distance of 3 meters, the illuminance E at the point where the light strikes the surface will be 1,200 / 3² = 133.33 lux. If the surface is at a distance of 6 meters from the light source, the illuminance will be: 1,200 / 6² = 33.33 lux.

This relationship, called the 'inverse square law', is a very important law in lighting. It applies only to point sources.

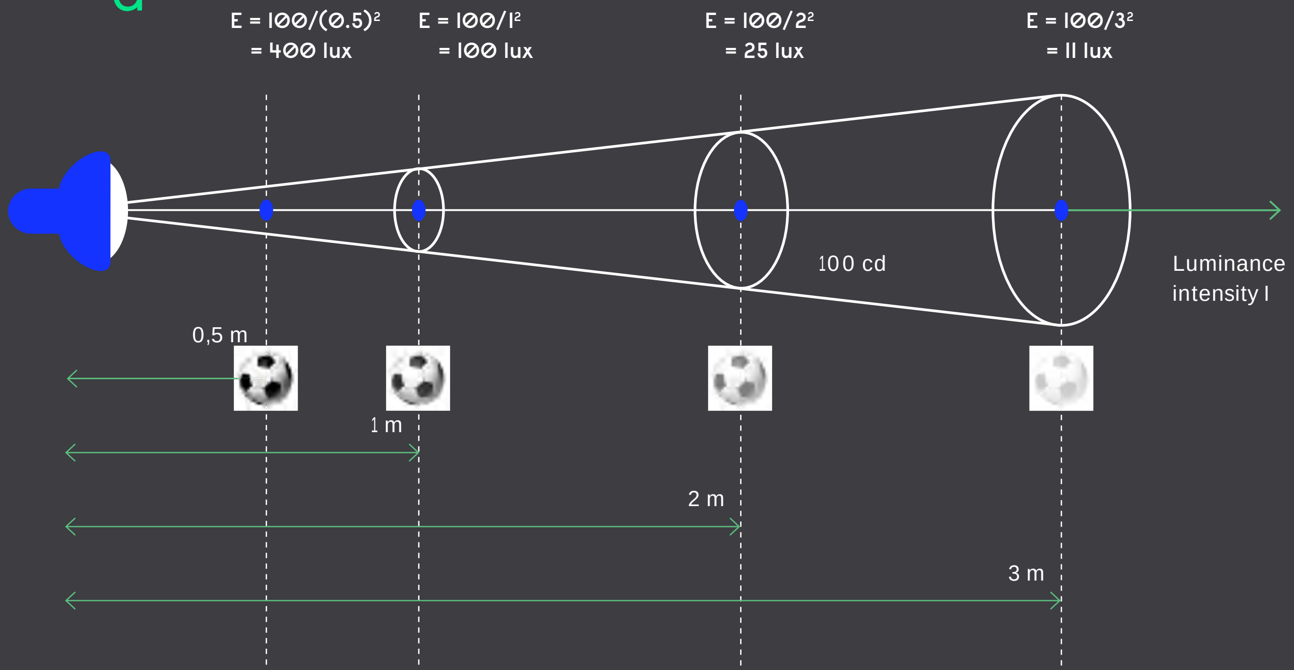


Fig. 4.9. Inverse square law.

The cosine law

The illuminance at a point in a plane not perpendicular to the direction of light incidence is equal to the luminous intensity in the direction of the point, divided by the square of the distance between the light source and the point in question, multiplied by the cosine of the angle that the direction of light incidence makes with the normal (i.e. perpendicular) to the plane (Fig. 4.10).

$$E_\gamma = \frac{I}{d^2} \cos\gamma$$

This is called the cosine law. For example, if a light source radiates a luminous intensity of 1,200 cd in the direction of a point on a surface at 3 meters distance, and the light strikes the surface at an angle of 60° to the normal to the surface, the illuminance at that point will be equal to:

$$(1{,}200 / 3^2) \times \cos 60° = 67 \text{ lux}$$

Horizontal illuminance

For horizontal surfaces, it will often be more practical to modify the above formula by replacing the distance (d) between the light source and the calculation point by the vertical height (h) of the light source above the surface (Fig. 4.11). For each different point on the horizontal surface the distance d is different, whereas the "mounting height" h is the same. The result is called the horizontal illuminance at the point, and the formula becomes:

$$E_{hor} = \frac{I}{h^2} \cos^3\gamma$$

The concept of horizontal illuminance is often used as a measure for the amount of light at the "working plane" as, for example, in an office (the desk area) or at a sports ground (the playing field).

Vertical illuminance

By rotating the system for horizontal illuminance through 90°, we obtain the illuminance on a vertical surface (Fig. 4.12). Thus:

$$E_{vert} = \frac{I}{d^2} \cos\gamma$$

This is called the vertical illuminance at a point. For practical reasons, this formula is often rewritten so as to substitute for the angle between the angle of light incidence and the normal to the vertical surface, the vertical angle between the direction of light incidence and the normal to the horizontal surface, and the horizontal angle indicating the orientation of the vertical surface with respect to the plane of light incidence (Fig. 4.13). Thus:

$$E_{vert} = \frac{I}{h^2} \sin\alpha \cos^2\alpha \cos\beta$$

Note: the values are typically calculated by computer.

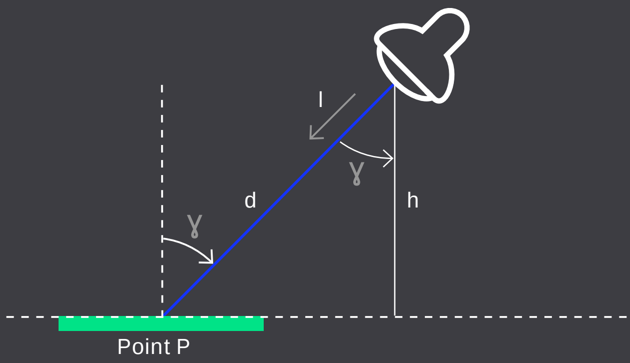


Fig. 4.10. Illuminance at a point P

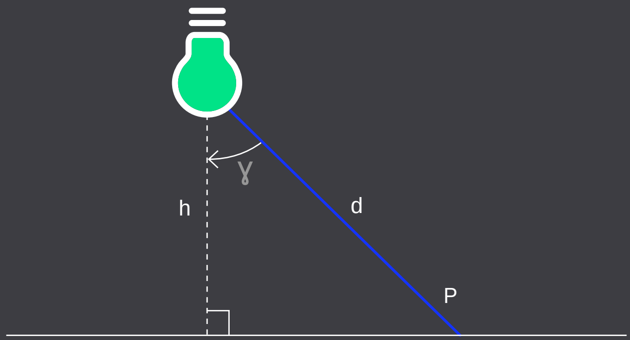


Fig. 4.11. Horizontal illuminance at point P.

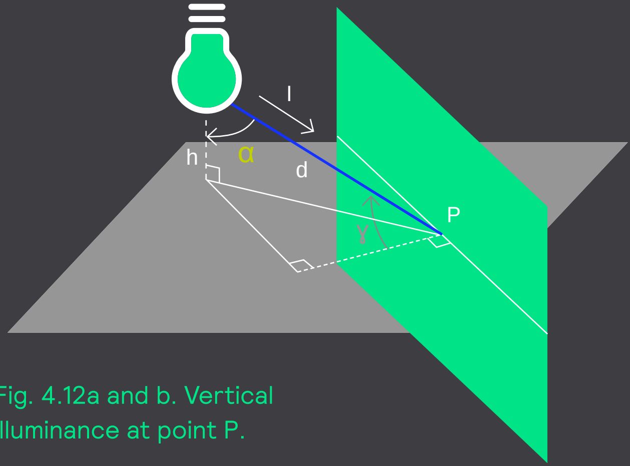


Fig. 4.12a and b. Vertical illuminance at point P.

Average cylindrical illuminance

The average cylindrical illuminance over an infinitely small cylinder (Fig. 4.14) can be expressed as:

$$E_{cyl,\,av} = \frac{I}{\pi h^2} \sin\alpha \cos^2\alpha$$

The concept of average cylindrical illuminance is sometimes used to check if in a room objects especially also persons and walls get enough light.

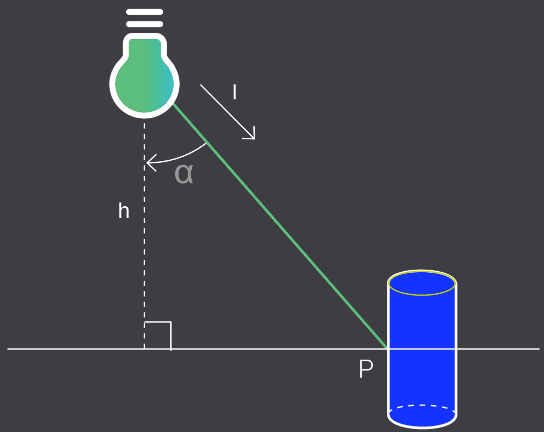


Fig. 4.14. Average cylindrical illuminance.

Hemispherical and semi-cylindrical illuminance

The illuminance on the curved surface of an infinitely-small hemisphere (Fig. 4.15) can be expressed as:

$$E_{hemisphere} = \frac{I}{4h^2} \cos^2\gamma\,(1+\cos\gamma)$$

Similarly, the illuminance on the curved surface of an infinitely-small vertical semi-cylinder (semi-cylinder) can be expressed as (Fig. 4.16):

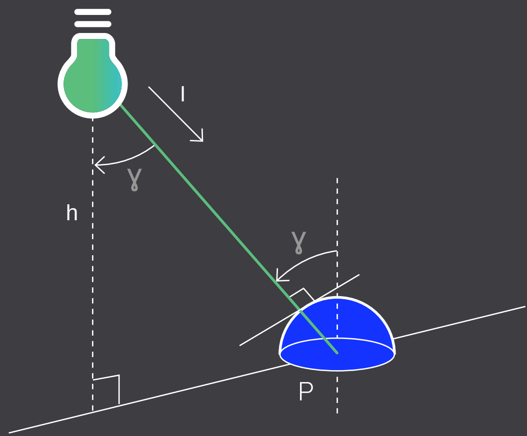


Fig. 4.15. Hemispherical illuminance.

The concepts of hemispherical and semi-cylindrical illuminance are relevant in street and residential-area lighting, where the illuminance on non-flat surfaces such as human faces is important for facial recognition purposes.

$$E_{semicyl} = \frac{I}{\pi h^2} \sin\alpha \cos^2\alpha (1+\cos\beta)$$

Note: the values are typically calculated by computer.

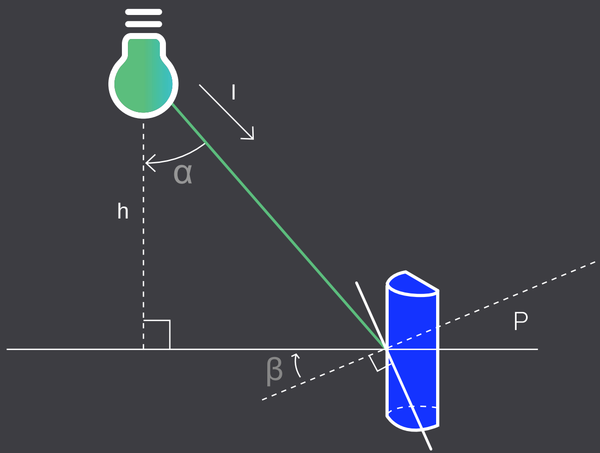


Fig. 4.16. Semi-cylindrical illuminance.

Illuminance and luminance

In the case of a light-reflecting surface, the luminous intensity that the surface emits is usually not known, but very often the illuminance on the surface is. Think, for example, of a road surface that is lit by a road-lighting installation, or a grass field lit by a floodlighting installation. For perfectly diffusing surfaces a relationship exists between the illuminance on the surface, the surface reflectance and the luminance L of the surface (Fig. 4.17):

$$L = \frac{\rho \cdot E}{\pi}$$

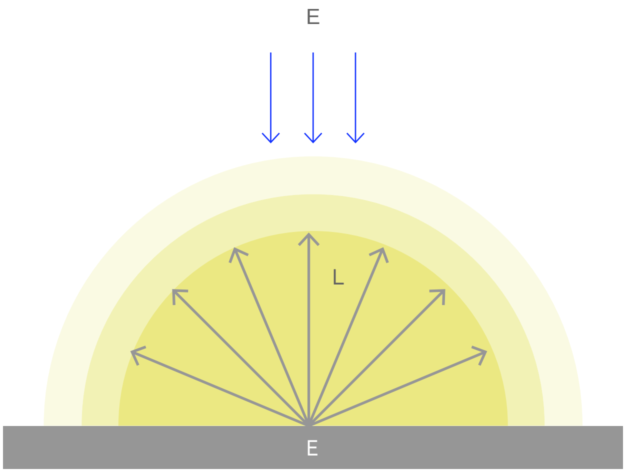


Fig. 4.17. Relation between illuminance and luminance of a diffuse reflecting surface.

For example, a sheet of matt paper is illuminated to a level of illuminance of 500 lux, and the reflectance of the paper is 0.7 (70%). The luminance of the sheet of paper in all directions then equals:

$$500 \times 0.7 / \pi = 111 \text{ cd/m}^2$$

The formula is not valid for specular surfaces or for surfaces exhibiting mixed reflections (see Chapter 3 “How is light directed and screened?”), such as road surfaces, when viewed in the direction of the specular component.

Luminous flux and luminous intensity

The luminous intensity I in any direction of a light source whose light distribution is uniform in all directions, is equal to the luminous flux divided by 4π.

$$I = \frac{\emptyset}{4\pi}$$

For example, an incandescent lamp of 1,000 lumen housed in a globe luminaire of opal glass with a transmittance of 0.9 will have a luminous intensity in any direction of: 1,000 x 0.9 / 4π = 72 cd.

This equation is only of limited practical importance, as it is only valid for light sources that radiate equal luminous intensities in all directions.

Measurement of light quantities

All light meters are equipped with a photocell that generates a small electric current or changes an electric current when light falls upon its surface (Fig. 4.18). Today, photovoltaic cells made of semiconductor material are most widely used for light measurements.

Basically all light measurements are illuminance measurements: the amount of light incident on the photocell is measured. If a quantity other than illuminance is needed, such as luminous flux, intensity or luminance, the illuminance measured by the photocell is converted into the quantity needed using the relationships given in the previous pages.

The response of most photocells to the various wavelengths of the spectrum is quite different from the standardized sensitivity of the eye V(λ), on which the lighting quantities are based.

The manufacturer of the meter corrects the color sensitivity of the cell by applying multiple layers of different color filters. The more filters used, the more accurate the meter but also the more expensive it will be.

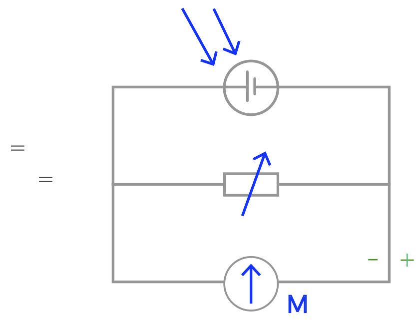


Fig. 4.18. Principle of a photocell.

Illuminance

The photograph in Image 4.1 shows a lux meter typically employed for making illuminance measurements “in the field” to check the quantity of illumination at specific locations.

Image 4.1. Example of a lux meter

Luminous intensity

Most luminous intensity measurements are made in the laboratories of luminaire manufacturers in order to obtain the luminous intensity, or light distribution, characteristics of a particular lamp-luminairecombination. The measurement involves measuring the illuminance on the photocell at various directions around the luminaire. For this work gonio-photometers are used (Fig. 4.19), in which either the luminaire, or a system of mirrors, (or both) is rotated with respect to a stationary photocell.

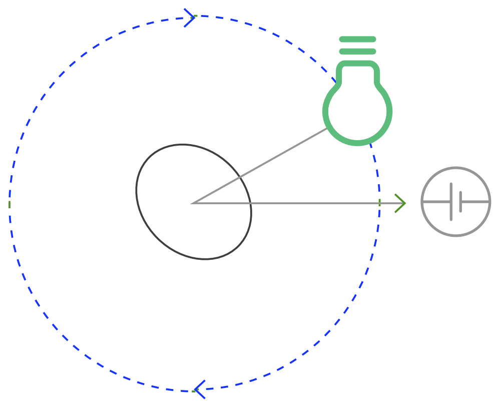


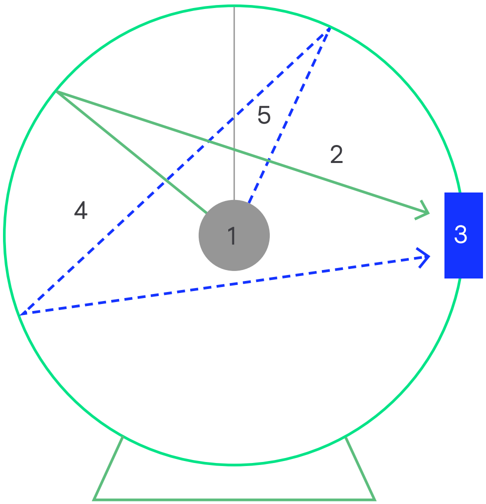
Fig. 4.19. Example of a gonio-photometer for the measurement of light distribution.

Image 4.2. Ulbricht sphere for the measurement of luminous flux.

Luminous flux

The luminous flux of a bare lamp or LED luminaire is usually measured in the so-called ‘Ulbricht sphere’ or “integrating sphere” photometer (Image 4.2). The lamp being measured is suspended at the center of a large hollow sphere, painted in matt-white to make it perfectly diffusing.

Owing to the uniform scattering or diffusing effect, the illuminance on any part of the sphere’s inside surface is proportional to the lamp’s total light output. A photocell is fitted into a small hole in the wall of the sphere to measure this illuminance so that the luminous flux can be calculated from it. The calculation part of the measurement is usually automated.



1. Source
2. Opaque screen
3. Photocell
4. Light ray (reflected once)
5. Light ray (reflected once)

Luminance

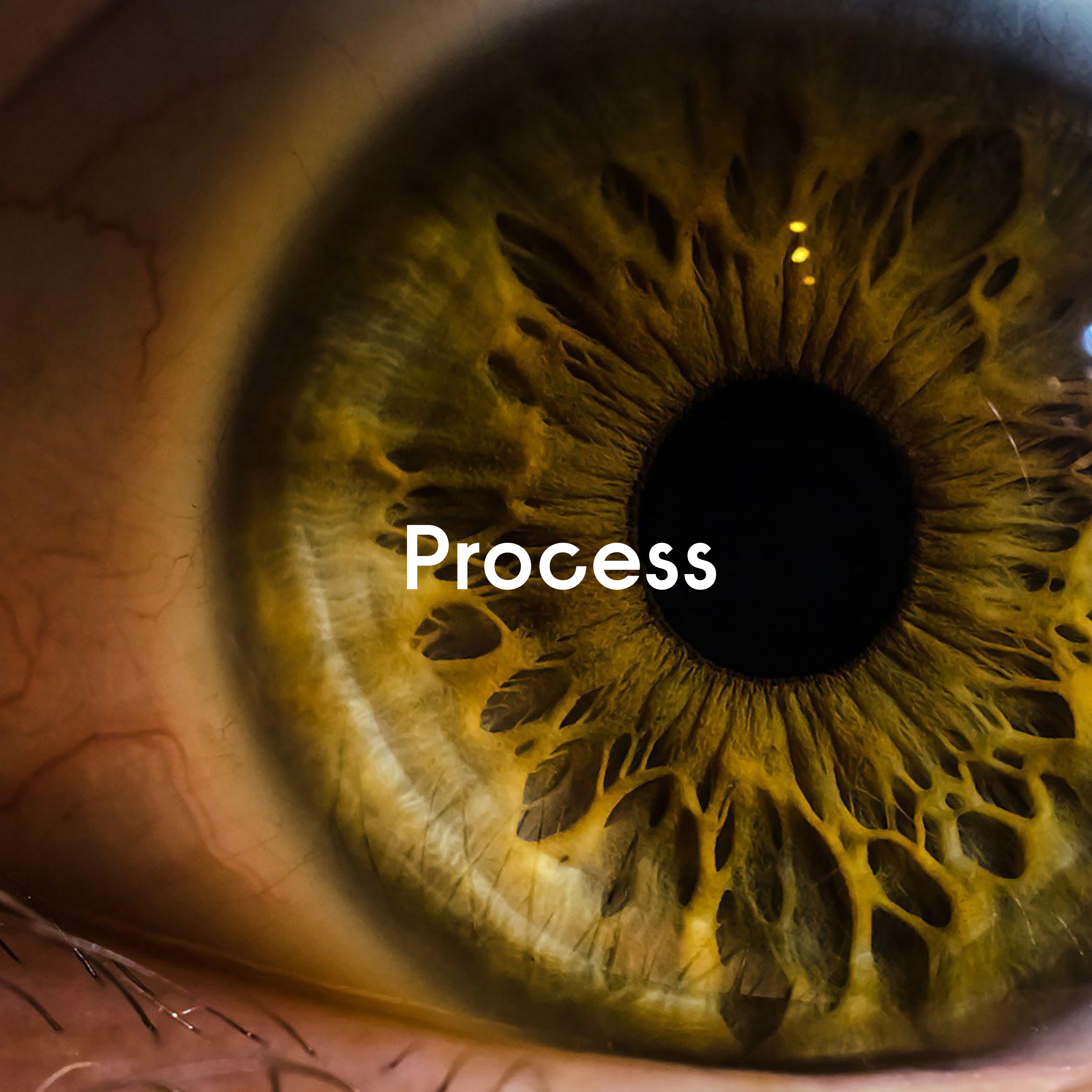
If an image of the surface whose luminance has to be measured is projected onto the surface of a photocell, the illuminance reading of this cell becomes proportional to the luminance of the surface in the direction of measurement.

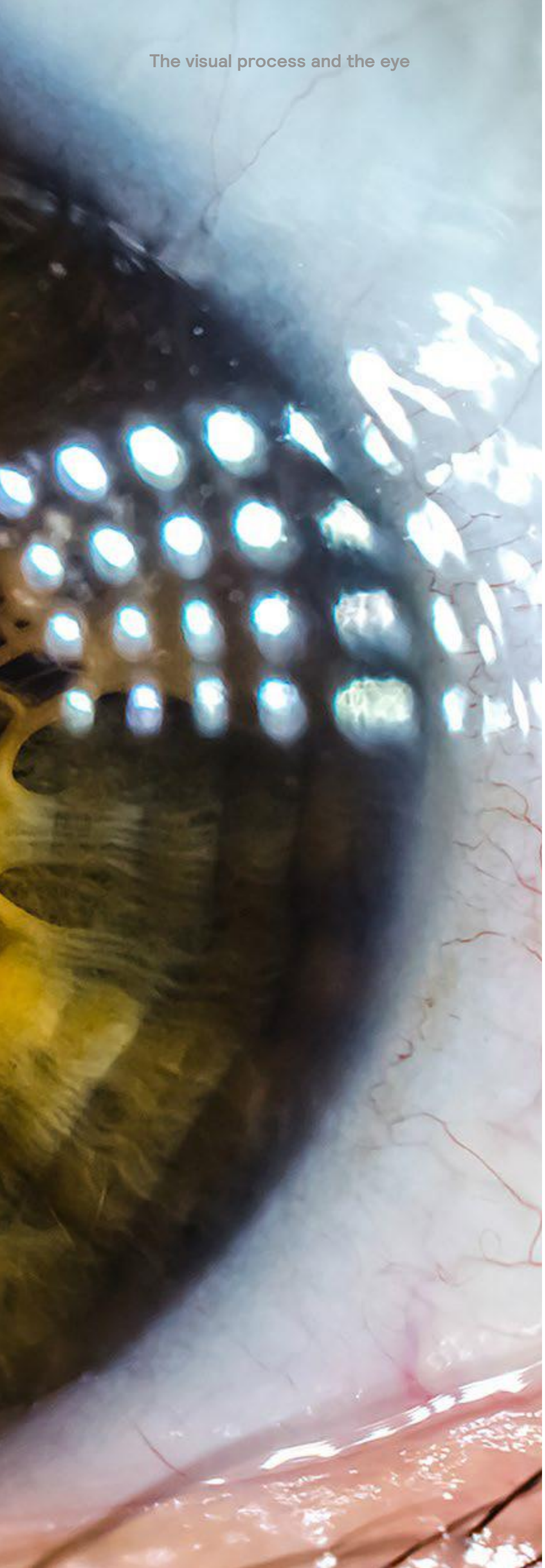
A luminance meter therefore consists of a photocell and an optical system that projects an image of the area to be measured onto the surface of the cell (Image 4.3). The measuring circuit is calibrated to give luminance values in cd/m².

Image 4.3. Example of a handheld luminance meter.

Light and vision

5


Process



The visual process and the eye

Fundamentally, light enables us to perceive the world around us. This is possible thanks to extremely delicate organs such as the human eye and the brain.

The role of light in our contact with the environment can hardly be overestimated. Indeed, more than eighty per cent of the information we receive from the outside world “passes through our eyes”. There is a close relationship between the way the visual scene is presented to us and the ability of the eye to fulfil its task properly. The way the visual scene is composed has much to do with the lighting.
In order to understand the various lighting criteria and their relationship with visual performance and visual comfort, it is necessary to understand something of the working of the human eye.

Learn more about the visual process of the eye
view more >>

25

Diameter in mm

6

Number of positioning muscles

The human eye is roughly spherical with a diameter of 25 millimeters (Fig. 5.1). Six positioning muscles allow it to swivel in any direction. Our eye functions in roughly the same way as a traditional camera with a lens that projects an inverted image of the scene onto a light-sensitive inner film. In the eye, this film is replaced by the retina and consists of light-sensitive nerve endings. Here the light is transformed via a (photo) chemical process into an electric current and transmitted through the nerves into the brain that interprets it as visual information. The iris in front of the lens can open or close, like the diaphragm of a camera, to control the amount of light that enters the eye. The opening in the center of the iris is called the ‘pupil’. When more light is incident on the eye, the pupil size becomes smaller and, again like with a camera, the depth of focus, or the distance over which we see sharp images, becomes greater. This better depth of focus is one of the advantages of having more light.

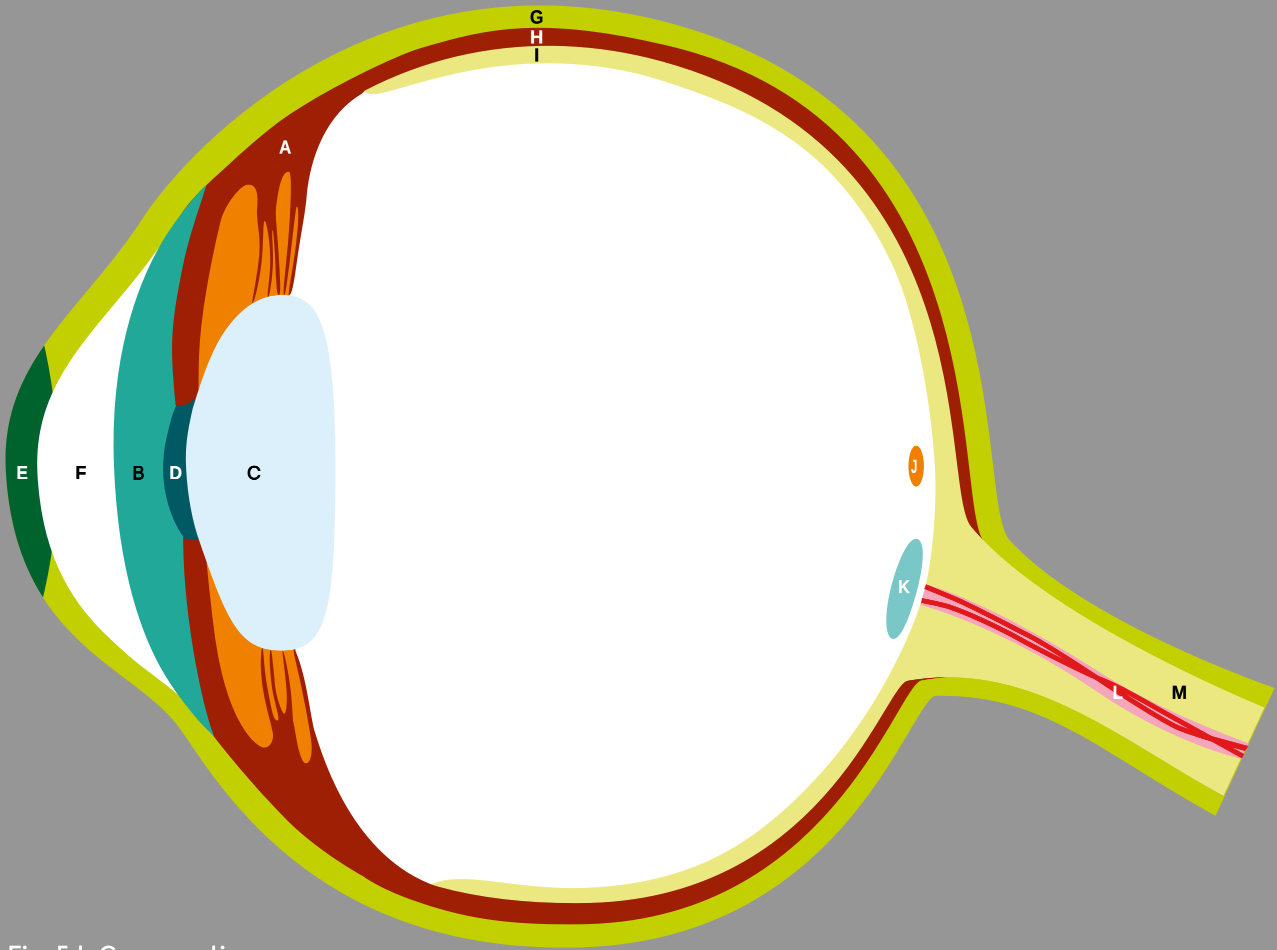


Fig. 5.1. Cross sections through the human eye.

A Ciliary muscle
B Iris
C Lens
D Pupil (diaphragm stop)
E Cornea (lens adjust the focus)
F Anterior chamber
G Sclera (eye ball, camera body)
H Choroid
I Retina (film)
J Fovea centralis (yellow spot)
K Blind spot
L Blood vessels
M Optic nerve

The retina is the start of the nervous system leading into the brain. It consists of more than a hundred million light-sensitive nerve endings of two types, which because of their shape, are called 'rods' and 'cones' (Fig. 5.2). We have ten to fifteen times more rods than cones. The rods are spread fairly evenly over the retina with the exception of the visual axis in the center, a spot called the 'fovea', where they are entirely lacking. The cones, on the other hand, are concentrated in the fovea and occur only sparsely in other parts of the retina. The rods and cones connect to the brain via ganglion cells and nerve fibres.

The unique properties of the eye – a sensitivity over an enormous lighting-level range of more than 1 to 10 million and the ability to distinguish between up to 100,000 shades of color – are obtained through "division of work" between the highly-specialized cones and rods. The rods are highly light-sensitive and are principally responsible for the detection of rough shapes and movement, but cannot distinguish colors. Cones, on the other hand, are less sensitive to light, but can distinguish colors. They also enable us to see fine detail.

At the beginning of this century, it was discovered that about 1 per cent of the ganglion cells are also sensitive to light. They play a role in the non-visual biological effects of light and are therefore important as regards lighting and health (see Chapter 7 "Light and health").

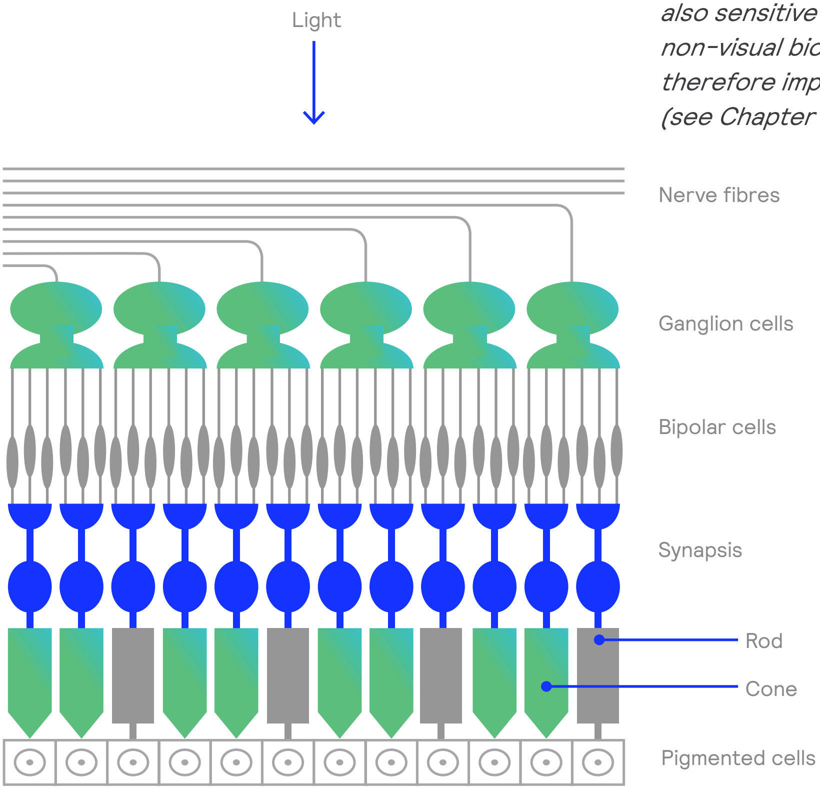


Fig. 5.2. Section of the retina of the eye.

Rods and scotopic vision

At very low lighting levels of less than some 0.01 cd/m² (less than moonlight) the sensitivity of the cones is so low that they do not function. Vision is then by rods only, and is termed scotopic vision. Groups of some hundreds of rods connect to a common nerve fibre that goes into the brain. In this way the stimuli of many rods combine, making these groups highly sensitivity to light. But because of this grouping, the exact position of where the light came from is not known. Under the condition of rod vision only, we therefore experience a rather blurred picture.

As mentioned before, the rods are entirely lacking on the fovea, the spot around the center of the visual axis that coincides with the direction of view. The maximum concentration of rods is at about 15° away from the direction of view. Scotopic vision is therefore off-axis, peripheral vision. Although with rods we cannot distinguish colors, their sensitivity does actually vary for the various spectral colors – the maximum sensitivity is at a wavelength of 507 nm (blue-green) and sharply decreases toward the red end of the spectrum (Fig. 5.3, curve in dark green).

Learn more about
lighting vision
view more >>

Cones and photopic vision

The cones take over completely at lighting levels greater than some 3 cd/m² (somewhat brighter than a lit motorway). We then speak of photopic vision. Each individual cone, unlike with rods, connects to the brain via a single nerve fibre. Visual acuity or resolving power with cone vision is therefore far better than with rod vision – we see sharp images. As mentioned before, the cones are concentrated in the fovea, the spot around the center of the visual axis that coincides with the direction of view, and occur only sparsely in other parts of the retina. Photopic vision is therefore essentially on-axis vision centered around a two-degree field. We see larger scenes as one complete picture through continuous and subconscious scanning by very rapid eye movements.

The sensitivity to light for cones is far less than for rods. Indeed at high lighting levels when the cones are active we can do with low sensitivity and at low lighting levels when rods are active we need high sensitivity. The overall spectral sensitivity curve for the cones is different from that for rods. The point of maximum sensitivity lies at 555 nm (green-yellow), and the fall-off toward the red side of the spectrum is less pronounced (Fig. 5.3, curve in light green).

The cones enable us to distinguish colors. This is possible because there are in fact three types of cones, with pigments sensitive to the red, green and blue parts of the spectrum, respectively (Fig. 5.4). Persons who miss one type of cone are partially color-blind. In very rare cases, only one type of cone functions, and persons having this defect are completely color blind.

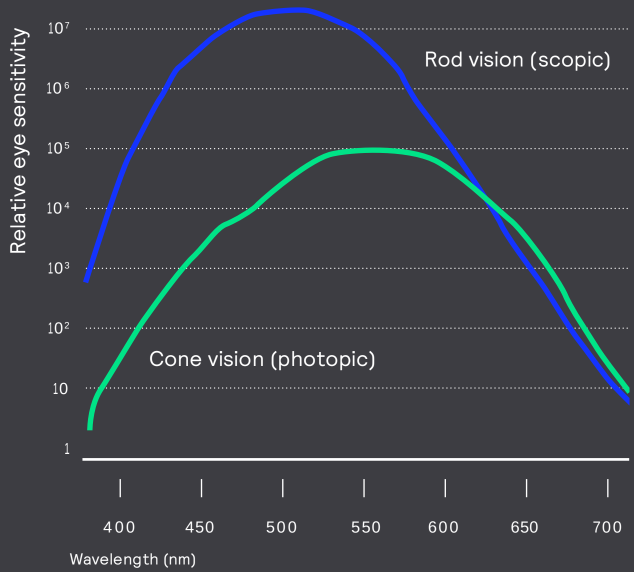


Fig. 5.3. Spectral sensitivity curves of the cones (dark green) and the rods (light green).

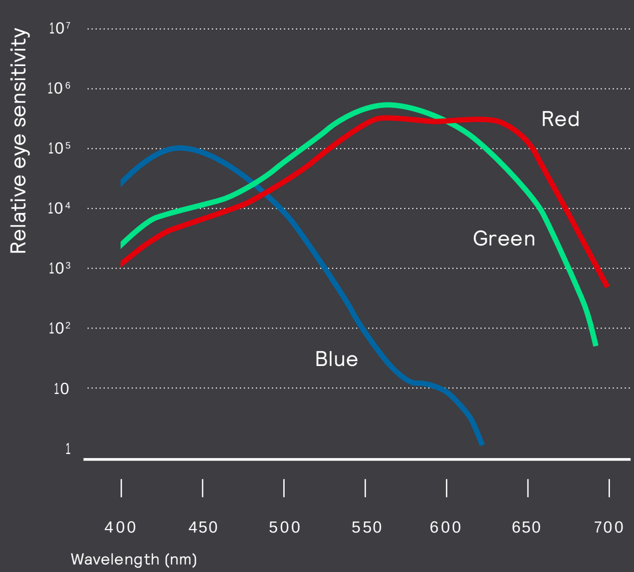


Fig. 5.4. Spectral sensitivity curves of the three color receptors in the cones.

Mesopic

Image 5.1. Mesopic vision: sharp vision moves gradually towards off-axis, less sharp, peripheral vision, and color vision gradually disappears.

Standardized spectral eye-sensitivity curves

The shift in spectral sensitivity between cones and rods is more evident if we draw the curves relative to their maximum sensitivity (see Fig. 5.5).

The photopic V(λ) curve was standardized as early as 1924 by the international lighting commission CIE; the scotopic V'(λ) curve in 1951. The photopic curve is the result of the combined effect of the three types of cones, and is the basis for all photometric units such as lumen, candela and lux.

Mesopic vision

At lighting levels intermediate to the scotopic and photopic levels – between approximately 0.01 cd/m² and 3 cd/m² – both the rods and the cones are active. With transition from high to low lighting levels the activity of the cones becomes less important. The overall spectral sensitivity gradually shifts from V(λ) to V'(λ), that is to say into the direction of short wavelengths (blue). This effect is known as the "Purkinje effect". On-axis, sharp vision moves gradually towards off-axis, less sharp, peripheral vision, and color vision gradually disappears.

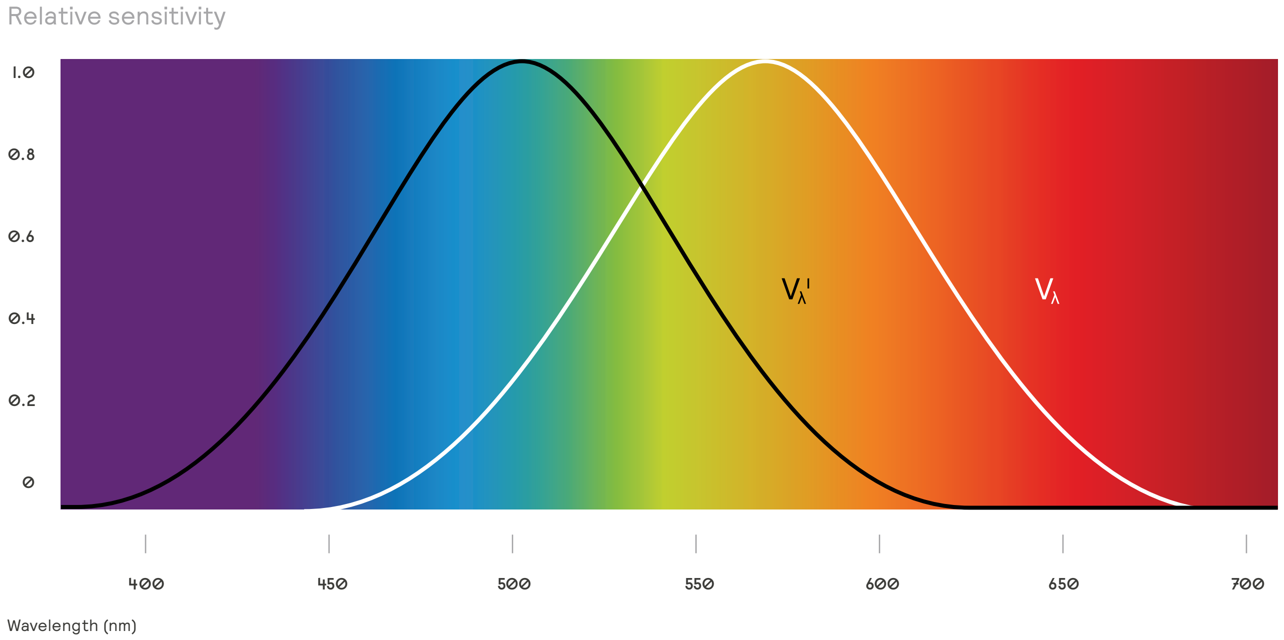


Fig. 5.5. Relative spectral sensitivity curves for photopic V(λ) and scotopic V'(λ) vision as defined by the CIE.

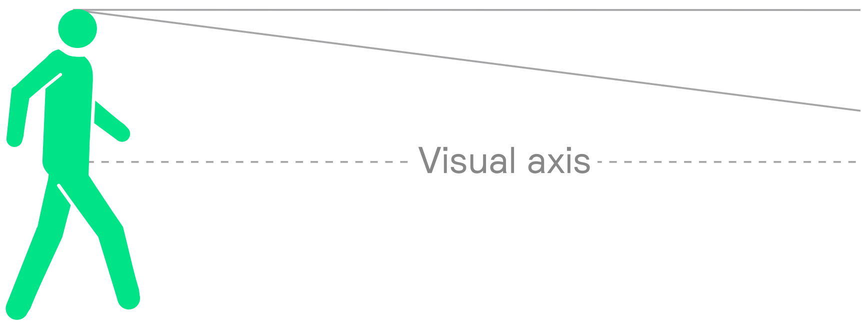
Adjustment mechanisms of the eye

Accommodation

Focusing at different distances is not achieved by altering the distance between the lens and retina – as with a camera – but by changing the refracting power (focal length) of the lens. The lens of the eye can contract under muscular control, making it more convex, thus shortening the focal length. This process is called accommodation (Fig. 5.6).

The accommodation process takes place subconsciously. The speed of accommodation depends on the brightness of the overall scene and ones degree of tiredness. Furthermore, the ability to accommodate varies strongly with age.

Young children, for example, can see sharply down to a distance of less than 10 cm, while most adults above 50 years of age require optical help in the form of reading glasses to see clearly at a distance of less than some 30 cm. As mentioned before, the pupil size will be smaller with higher lighting levels and consequently the depth of focus, or the distance over which we see things sharply, will be greater. This is one of the reasons why more light is “accommodating” for the elderly.



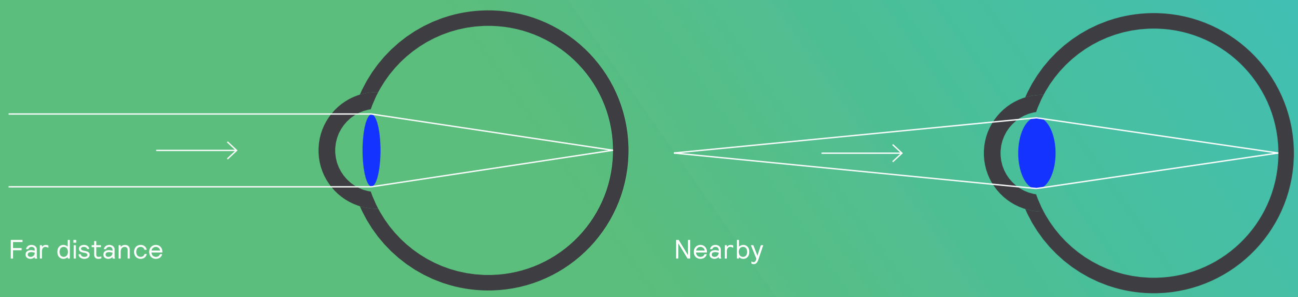
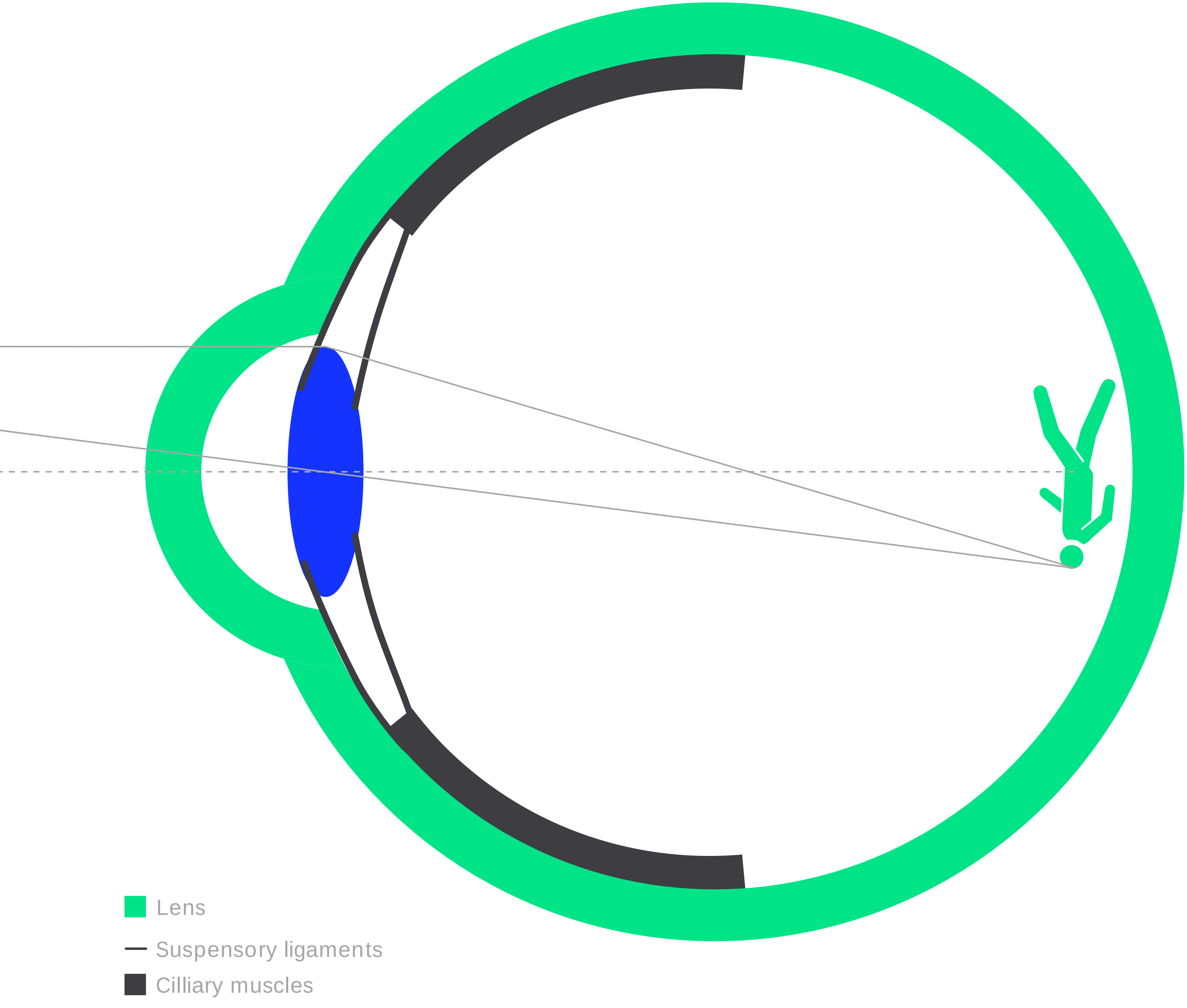


Fig. 5.6. Accommodation through change of refracting power of the eye lens


Lens
Suspensory ligaments
Cilliary muscles

Adaptation

Adaptation is the mechanism by which the eye changes its sensitivity to light. Three processes are involved: change in pupil size (between 2 mm and 8 mm), change in the neural system of the retina and the optic nerve and, most important, a change in the chemical composition of the light-sensitive pigments of the rods and cones.

Adaptation from dark to light usually takes less than a minute, but adaptation from light to dark can take between 5 and 30 minutes depending on the transition difference (Fig. 5.7). This is quite important in tunnel lighting, for example, where during the daytime, adaptation from the bright open road outside the tunnel to the dark tunnel interior requires a lot of artificial light in the tunnel entrance to reduce the adaptation time.

Convergence

We use both eyes to look at one and the same target. To achieve this, we unconsciously rotate our eyes in our eye-sockets. We call this “convergence”. When we look at an object, the lines of sight of the two eyes will intersect at the target point. The closer the object, the greater the inward rotation of the eyes (Fig. 5.8). The required amount of rotation is a measure of the object distance as noted by our brain. Good depth vision therefore requires two eyes.The rotation of the eyes is controlled by the eye muscles.

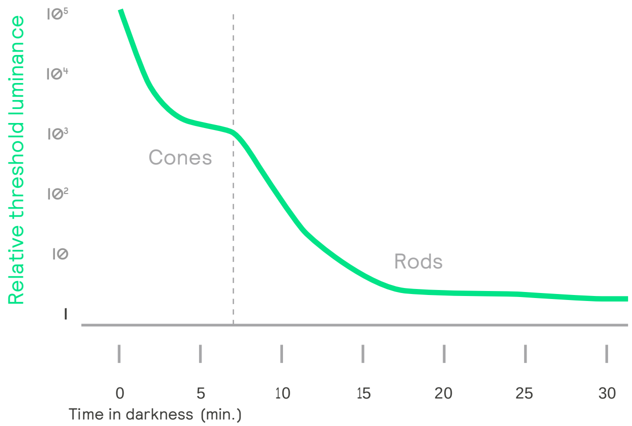


Fig. 5.7. Adaptation time from light to dark.

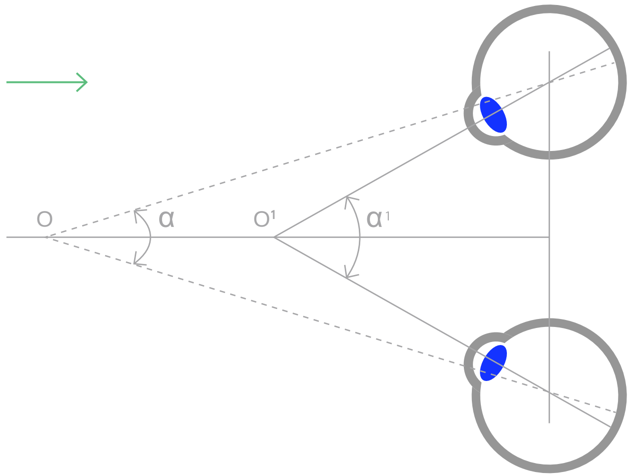
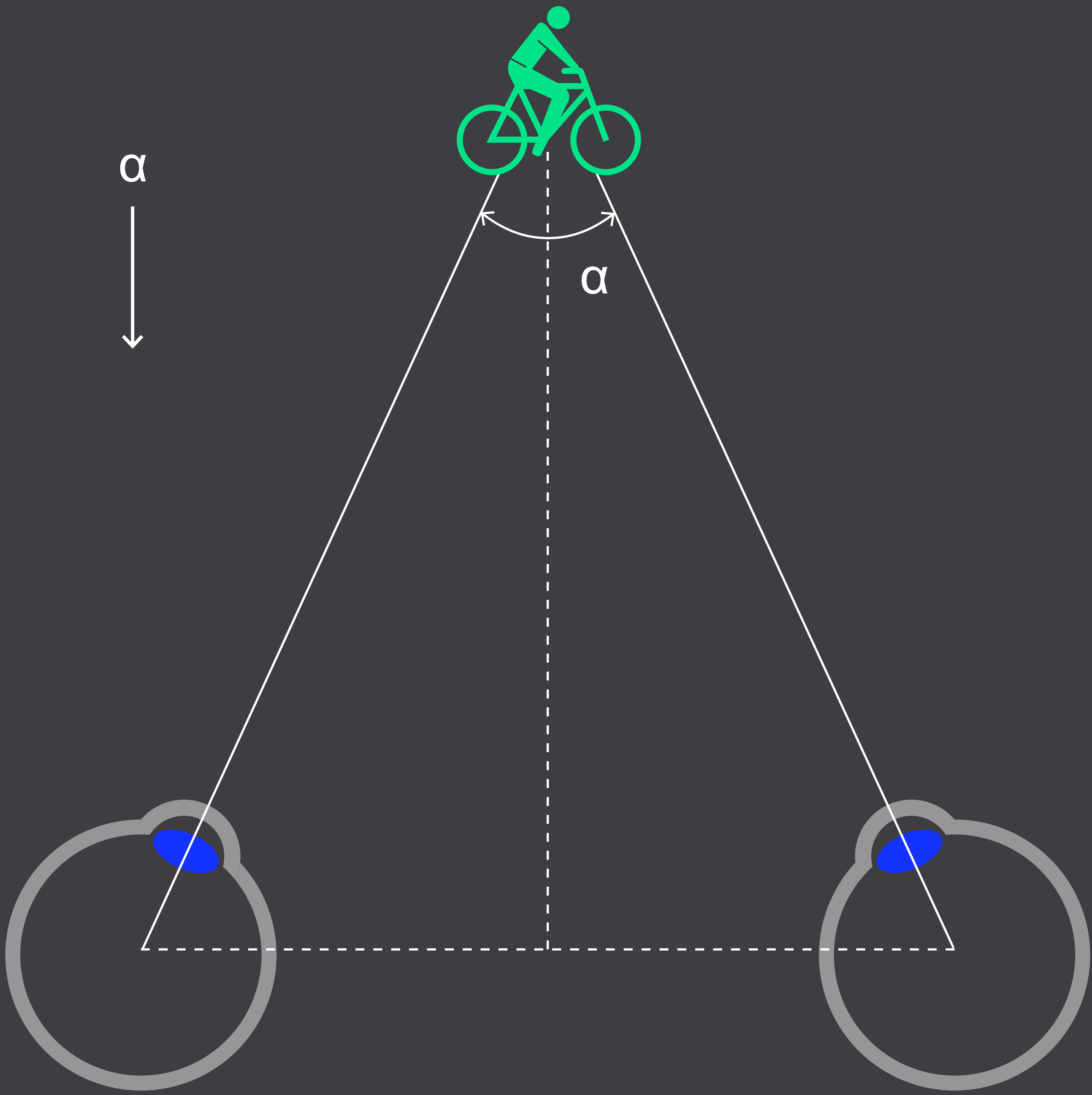


Fig. 5.8. Different angles of convergence for objects at different distances help us to see depth.


α
α

Visual performance and comfort

We continuously select and process, more or less subconsciously, that part of the visual information that is important to us. In this process we are heavily dependent on our ability to see contrasts and details.

Lighting has to enable us to perform well visually. For most situations, mere threshold visibility is not good enough. Ease of performance is what we need, and this calls for supra-threshold visibility. Ease of performance also means that we must feel comfortable with the visual environment. Lighting therefore has to provide both good visual performance and good visual comfort.

Image 5.2. Contrast between dark letters and white paper.

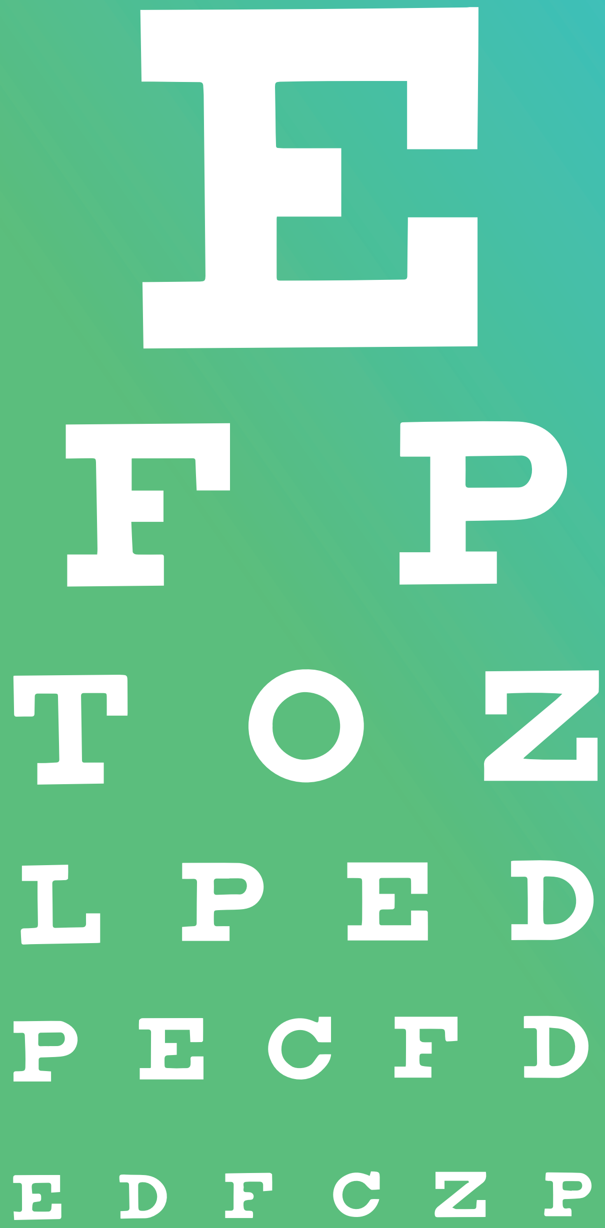


Fig. 5.9. Visual-acuity test chart.

Visual acuity

Visual acuity is expressed as the minimum angle under which two targets can still be seen to be separate. The optician measures visual acuity in the process of determining what sort of spectacles will best correct a given vision problem.

Visual acuity depends in the first place on the quality of the visual organ, viz. the eye, but also varies with the ambient brightness and with the contrast of the targets, and hence with the quality of the lighting. Age has a marked negative effect on visual acuity.

Contrast detection

Most of the visual information we receive is the result of luminous differences in the field of view. Contrast expresses the difference in luminance or color between neighboring areas of a scene.

Luminance contrast

Contrast in luminance can be expressed in several ways. The simplest way is the ratio of luminances resulting from difference in surface reflectance, according to the equation:

$$C = L_{high} / C_{low}$$

Where: C = contrast ratio
L_{high} = higher luminance
L_{low} = lower luminance

Fig. 5.10. Contrast between road surface and walls in a tunnel.

Fig. 5.11.
The contrast of objects at many different locations may be of interest in this complex visual situation.

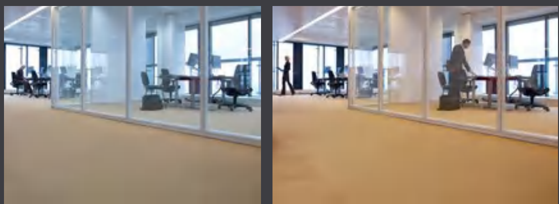


Fig. 5.12. Left: Luminance contrast: cool white correlated color temperature. Right: Luminance contrast: warm white correlated color temperature.

The contrast ratio is, for example, used to judge the quality of black or grey letters printed on the white paper of a book (Image 5.2) or when we judge the brightness relationship between the walls and road surface of a lighted tunnel (Fig. 5.10). If, on the other hand, the total scene is involved, it becomes important to differentiate between the object of interest, with its immediate background, and the overall luminance of the scene (Fig. 5.11)

For this reason, the concept most commonly-used by lighting engineers is the contrast value, according to the equation:

$$C = (L_o - L_b) / L_b$$

Where: C = **contrast value**
L_o = **object luminance**
L_b = **background luminance**

The ability of the eye to detect luminance contrasts depends very much on the state of adaptation of the eye, which is determined by the overall luminance of the scene. The power of the eye to detect contrasts – also called the contrast sensitivity – increases with increasing luminance to which the eye is adapted (Fig. 5.12).

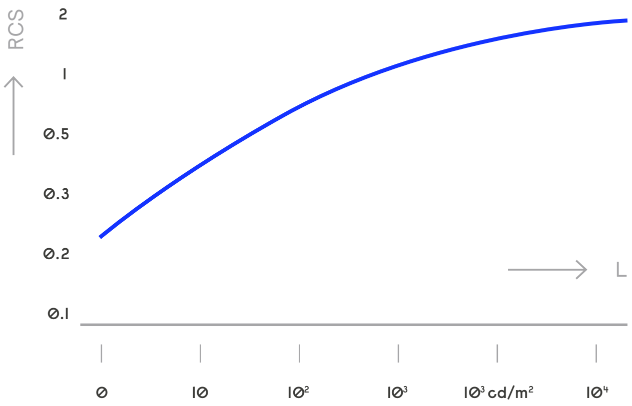


Fig. 5.13. Relative contrast sensitivity, RCS, set arbitrarily at value 1 at 100 cd/m², as a function of adaptation luminance L.

The eye will not appraise luminance values in the same way under all circumstances. If strong luminance contrasts occur in the field of view, the subjective brightness impressions will be exaggerated. A grey surface placed against a black background will make the former appear "lighter" than the same grey placed against a white background (Fig. 5.14). These effects of strong contrasts are sometimes used in the advertising world to attract more attention.

This is an important reason why visual performance usually increases with increase of overall lighting level: it then becomes easier for our eyes to detect contrasts. As we become older, contrast sensitivity decreases sharply, especially at lower adaptation luminances. Which is another reason why the elderly need sufficiently high lighting levels. Other factors influencing contrast detection are, of course, the size of the contrasting object and the observation time. Usually lighting should be so designed as to increase contrasts of visual targets. Excessive contrasts, however, may hamper visual performance and may also lead to a feeling of discomfort. One of the many reasons why extremely non-uniform task illuminances must be avoided.

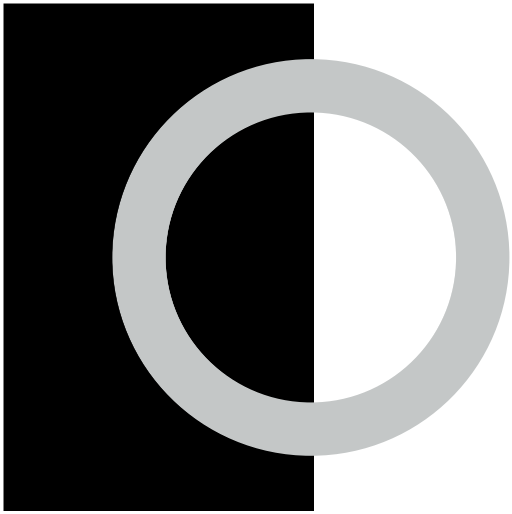


Fig. 5.14. Same grey seen differently against a black and a white background.

Color contrast

Although difficult to assess, it is generally accepted that color contrasts contribute to a lesser degree to visual information than do luminance contrasts. They may, however, be very important for producing pleasing situations. Popularly stated: a black-and-white photograph gives most of the information, but the colored photograph will usually be more inviting to look at. Color contrasts are therefore of particular interest to the interior decorator, but also to the lighting designer. They determine in how far color effects will enhance or just spoil the overall result of a scene.

Contrasting colors have a mutual influence on each other. For example, the red and green circles have a different apparent brightness against the yellow background than they do against the blue background (Fig. 5.15). Butchers take advantage of this effect by displaying their meat on a bed of lettuce leaves to give it a fresh, red appearance.

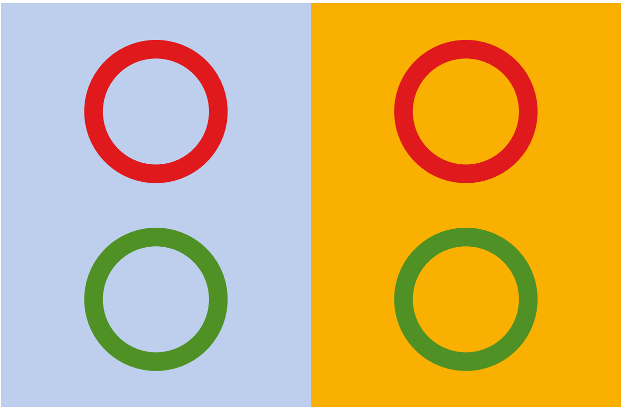


Fig. 5.15. The circles have a different apparent brightness with a different colored background.

Glare

Glare is the negative sensation produced by luminances in the visual field that are so much greater than the luminance to which the eyes are adapted that they cause discomfort, reduced visibility, or both.

Glare can take either of two forms: discomfort glare or disability glare. Sometimes these forms occur separately, but they are often experienced simultaneously. The problem of glare is of particular importance to the lighting engineer, as much can be done to prevent it by judicious design of lighting installations.

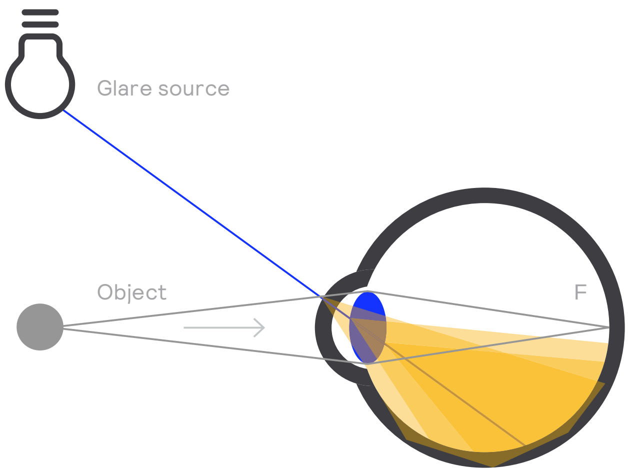
Discomfort glare

Discomfort glare is a sensation of discomfort, or even pain, caused by excessive luminances in the field of view. The physical parameters that determine the degree of discomfort are largely known. We can use them to predict whether discomfort glare in different lighting situations is acceptable or not. The more important parameters are the luminance of the glare source in the direction of the observer, the background luminance, the size of the glare source (the smaller the size, the higher the chance of discomfort), and the position of the source or sources relative to the viewing direction.

Learn more about
the concept and types of glare
view more >>

Disability glare

Disability glare results in reduced visual performance, with excessive luminances leading to a loss of visibility. Probably the most important cause is scattering of light from the glare source in the optical system of the eye (Fig. 5.16) – notably in the cornea, the lens and the eye chamber – to such a degree that a uniform luminous veil is drawn over the retina. It is this veil that reduces the apparent contrasts in the visual scene to impair visibility. Just compare this with the apparent contrast reducing effect of a veil that a bride wears during her wedding. The scattering in the eye, and thus the value of the veiling luminance with accompanying loss of visibility, can be calculated. So, we also can predict whether or not the degree of disability glare in different lighting situations is acceptable.



Glare

Overhead glare

Glare sources that are completely out of our field of vision (for example, those positioned more or less directly overhead) can still cause some glare. Possible reasons for this are light reflected into the eyes via the nose or via spectacle lenses to create a disturbing veil. Of course, this can only be a problem in the case of high-intensity light sources.

The sun is an example of such a source. When the sun is almost straight overhead, the wearing of a hat serves to provide the necessary screening (Image 5.3). Narrow-beam luminaries in interiors aimed downwards can also sometimes lead to excessive overhead glare.

Image 5.3. A hat provides screening against glare from an overhead sun.

Visual performance and the elderly

Eyesight deteriorates with age – first slowly and then more rapidly. This is largely due to a reduction in pupil size, loss of transparency of the vitreous humor (the jelly-like substance between the eye and the retina), and hardening and yellowing of the lens. Hardening of the lens results in reduced accommodation ability, which means that close-up viewing (reading for example) becomes more difficult, necessitating the use of reading glasses. Yellowing of the lens (cataract) reduces overall sensitivity, visual acuity, contrast sensitivity and color sensitivity (blue gradually disappears).

Also, the nerve pathway connecting the eye with the brain becomes less efficient. The sum of all these conditions affects the eye to such an extent that an average 60-year-old person may need up to roughly 15 times more light than a 10-year-old does to perform the same visual task (e.g. reading) with the same degree of comfort and effectiveness (Fig. 5.17).

When providing higher lighting levels for the elderly, special precautions have to be taken to prevent excessive glare. The vitreous humor, especially, scatters more light as it gradually becomes “cloudy”. This makes the older eye more sensitive to glare.

Light requirment as function of age

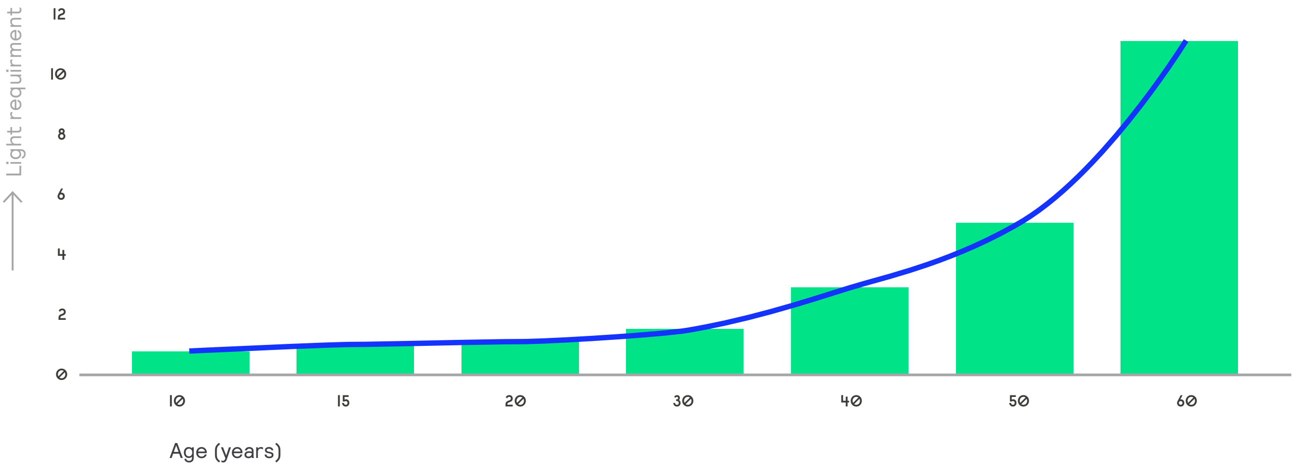


Fig. 5.17. Light requirement for a specific reading task, plotted against age.

Psychological and emotional aspects of vision

The eye sees, the brain perceives

The eye scans the total visual scene in small, two-degree parts and the brain "assembles" it to form a complete picture. The brain can also correct this. For example, in one scene a grey surface in full sunshine may have a higher luminance than a white surface in the shadow, but the brain will have no problems in giving us the impression that the grey surface is the darker of the two. But the visual image can also play tricks with the brain. Well-known examples are the so-called optical illusions.

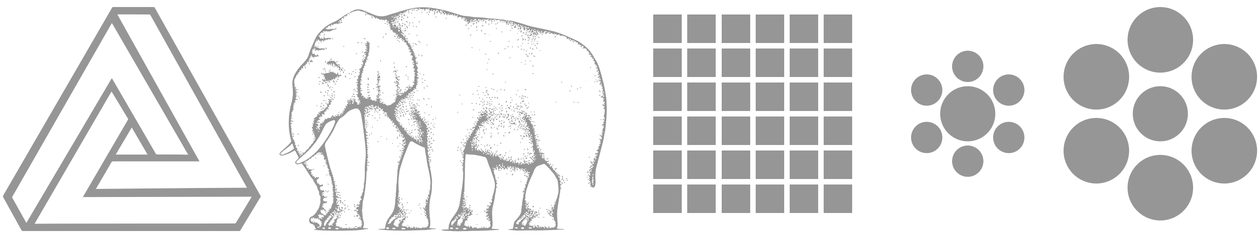


Fig. 5.18. Optical illusions. From left to right: perspective, double image, contrast and size.

Emotional effects of light

We all regularly experience light as having a direct emotional influence, but we still know little about the process behind it. Past experience has sometimes to do with it. We experience a face that is strongly lighted from below as being scary because we are accustomed to the light coming from above.

Particularly manifest is the influence of color on the mood of people. Red and yellow colors create a feeling of warmth and comfort, blue gives a cool impression and stimulates activities, whereas green generally induces a feeling of rest and relaxation. Here again, past experience plays a role. The same colors may have a different emotional impact on people originating from different parts of the world. Colors also have an influence on our impression of space. A room with red-colored walls looks smaller than one with blue or white walls of the same dimensions. Also, white light alone can be used to change the apparent dimensions of a space. For example, by making the ceiling and/or upper parts of the walls of a room brighter, the room seems to become higher.

There is also an emotional relationship between lighting level and the tint of white light. At home, many people will experience a relaxing atmosphere at relatively low light levels with a warm light color (low color temperature). Where a more active and stimulating atmosphere is required, as in offices, factories and schools, many prefer higher light levels with a cooler color (higher color temperature). Research into the relationship between preferred lighting level and color temperature by Aries Anders Kruithof in 1941, done in a Philips laboratory, became famous.

The result of these investigations is shown in the curves of Fig. 5.19 – curves that can be found in almost any lighting handbook. The white area between the two curves represents the comfort zone. Above the upper limit (high lighting level / relatively-low color temperature) or under the lower limit (low lighting level / relatively-high color temperature) we experience the lit space emotionally as being unpleasant and unnatural. Here, too, past experience plays a role: the emotional feeling with light of a certain color temperature may change after a certain habituation time.

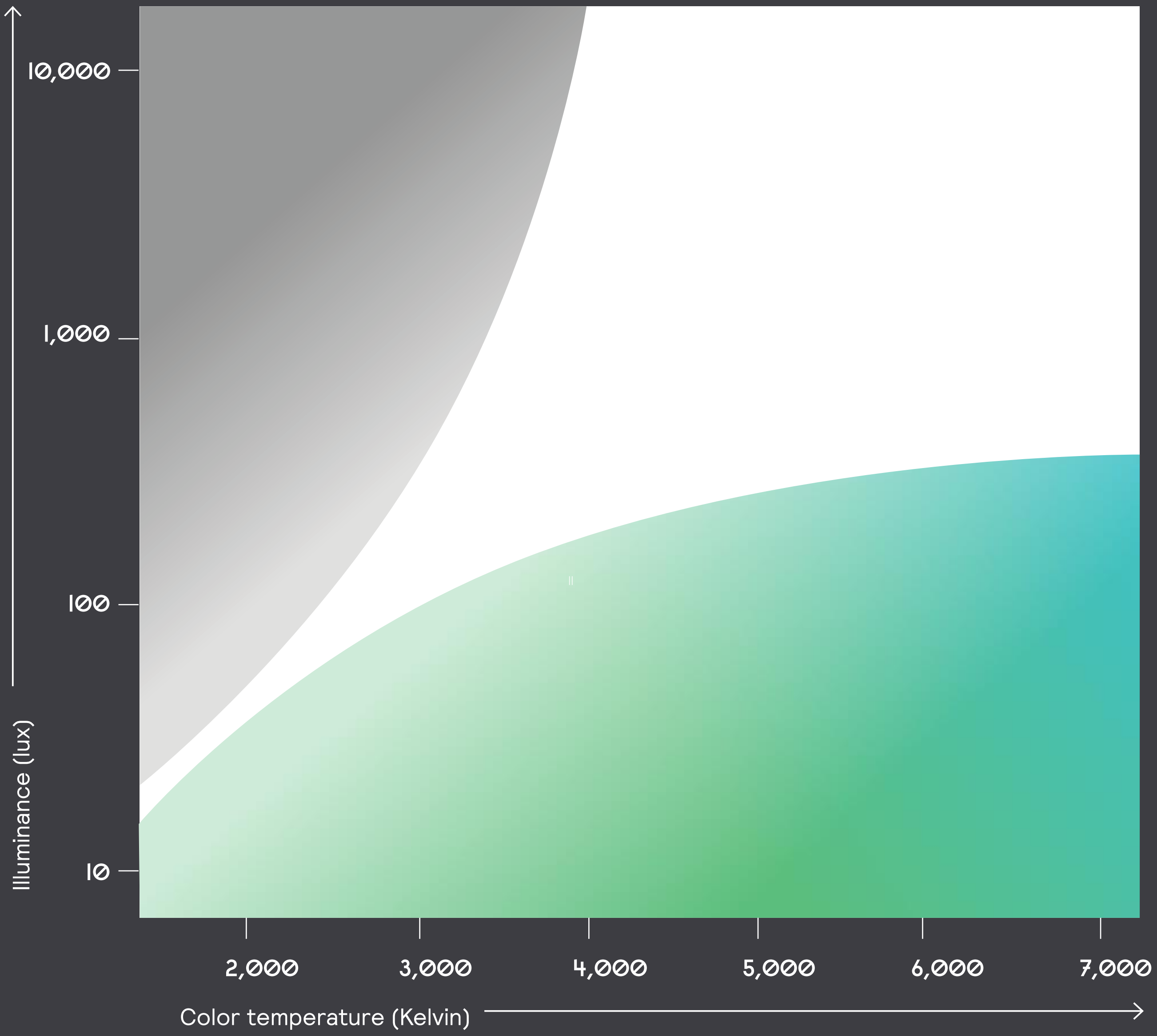
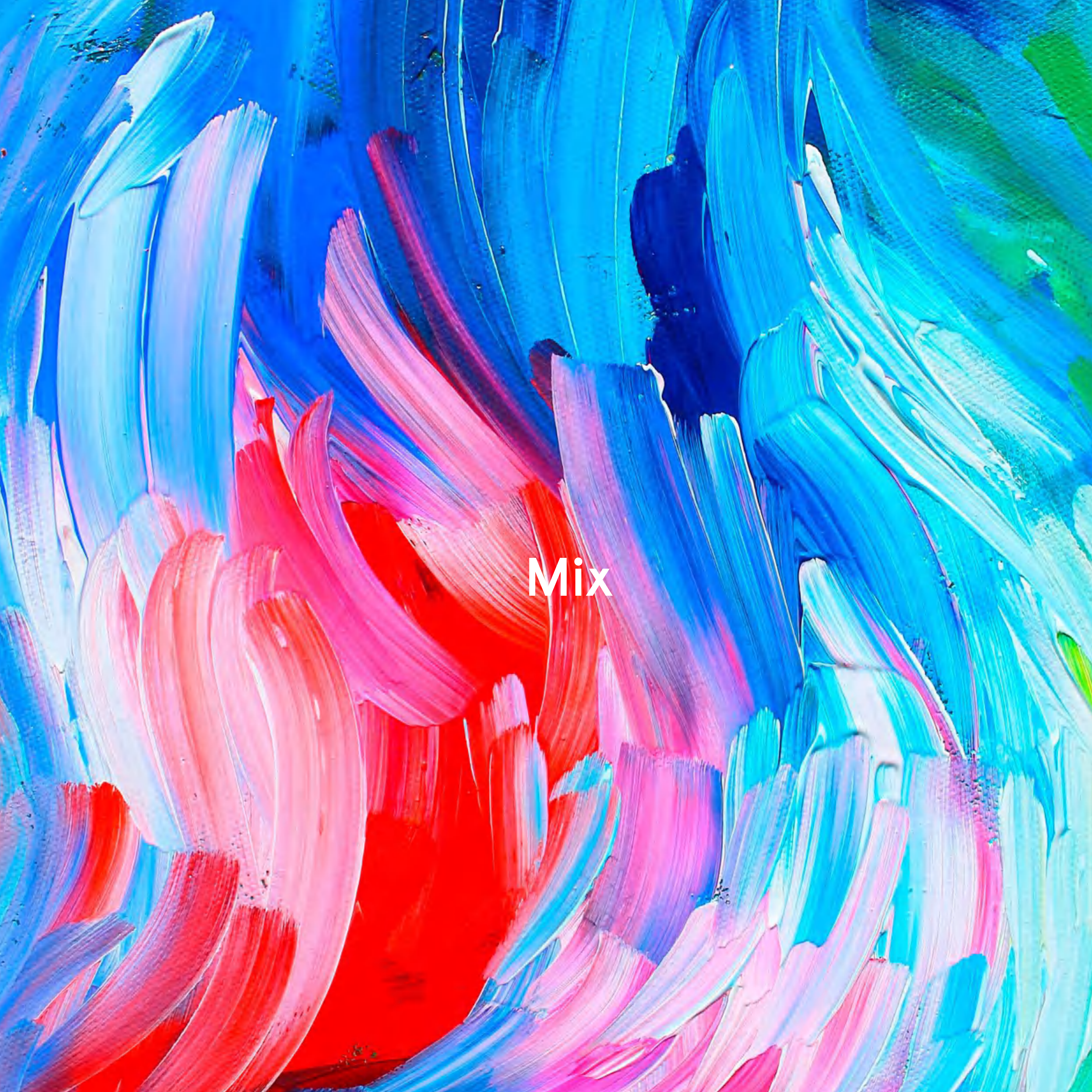


Fig. 5.19. Preference of color temperature of light in relation to the lighting level, according to Kruithof.

Light and color

6


Mix

Color mixing

White light is composed of a mixture of colors. We have already seen that light from a thermal radiator – the sun or an incandescent lamp – can be separated into the full range of spectral colors; red, orange, yellow, green, blue and violet.

But not all spectral colors occur in all light sources, and where they do occur may be in varying proportions. If white light strikes a surface, generally not all its colors will be reflected to the same degree. Those that are reflected most will together determine the color impression of that surface. Thus, a green surface will reflect the light from the green part of the spectrum, but it will absorb red and violet.

Learn more about color mixing
view more >>

Additive color mixing

If colored lights are mixed, the result will always be brighter than the individual component colors. This is called additive color mixing. What happens with additive color mixing can be understood by considering the three basic colors of the visible spectrum: red, green and blue. These three basic colors are known as the primary colors (RGB). If these primary colors are mixed, the result is white light (Fig. 6.1).

Yellow, magenta and cyan are called secondary colors, because they each consist of a mix of two primary colors (Fig. 6.2). They are also called complementary colors because when mixed with the primary color that is not contained in it, the result is again white light.

The complementary color yellow mixed with the primary color blue gives white light; the complementary color magenta with primary green or the complementary color cyan with red also give white light (Fig. 6.3).

Fig. 6.1. Additive color mixing of light.

Fig. 6.2. Additive mixing of a complementary color with the appopriate primary color gives white.

Fig. 6.3. From top to bottom: secondary colors cyan, yellow and magenta.

Subtractive color mixing

If colored paints are mixed, the result will always be darker than the original paints (Fig. 6.4). This form of color mixing is called subtractive mixing. The mixing of two or three primary paint colors will produce black.

The subtractive mixing of the complementary colors will again produce the primary colors. Thus, yellow and magenta make red; yellow and cyan make green; and magenta and cyan make blue. Cyan, magenta and yellow together make black (Fig. 6.5). This is the reason why cyan, magenta and yellow (and “key black”) are the ink colors used in multi-color printing (CMYK printing).

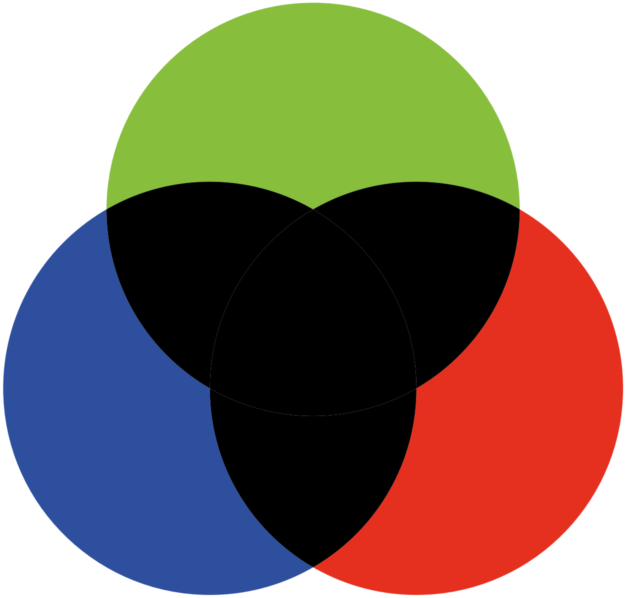


Fig. 6.4a. Subtractive color mixing with paints.

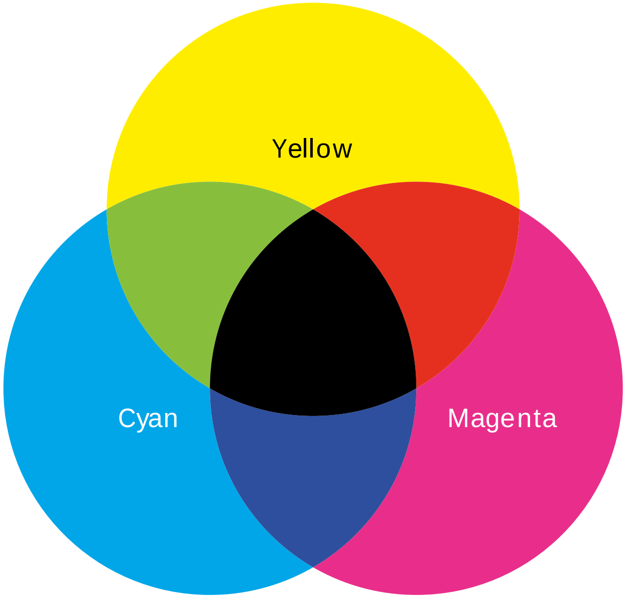


Fig. 6.4b. Subtractive mixing aof the complementary colors cyan, magenta and yellow gives black.

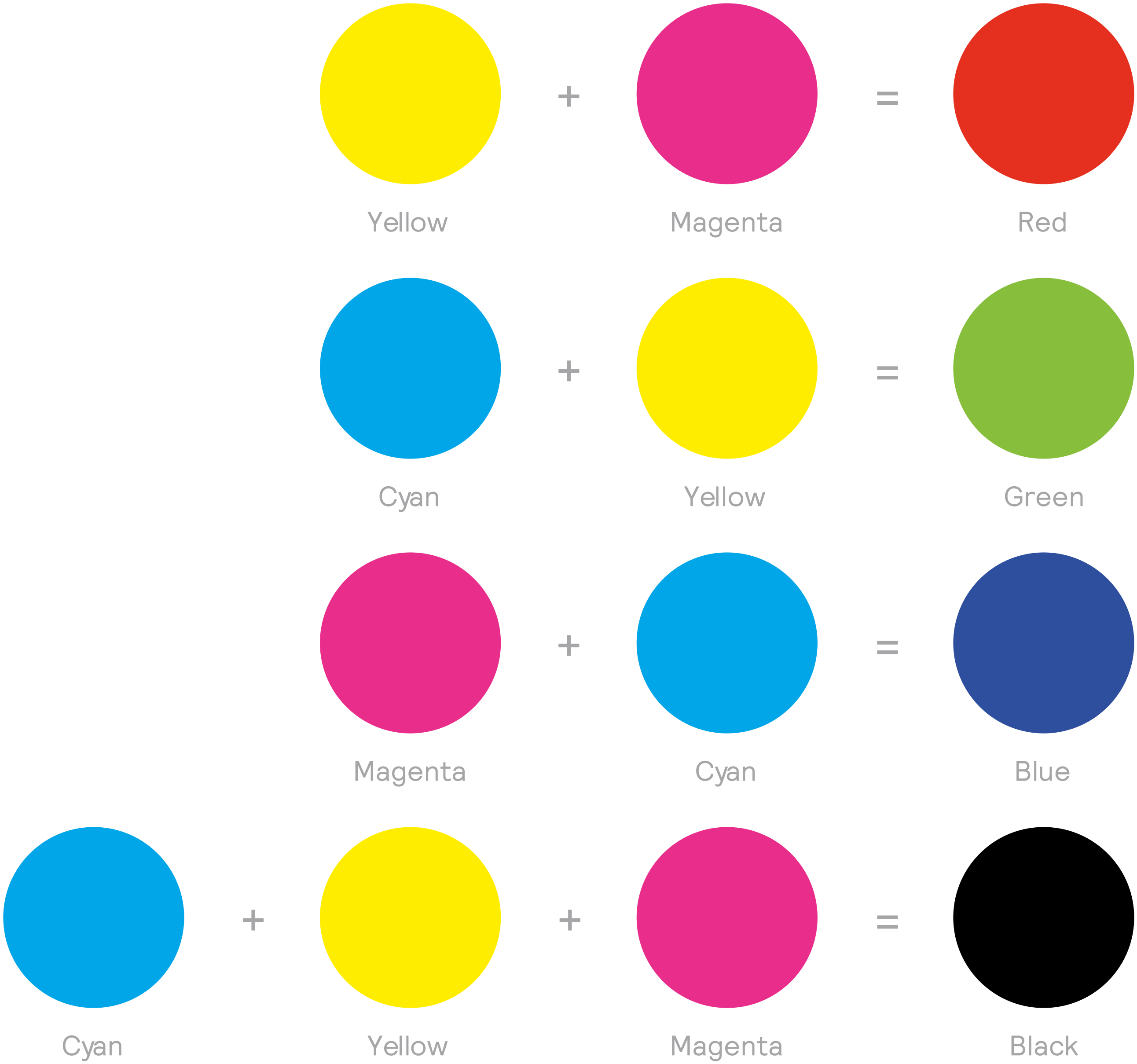
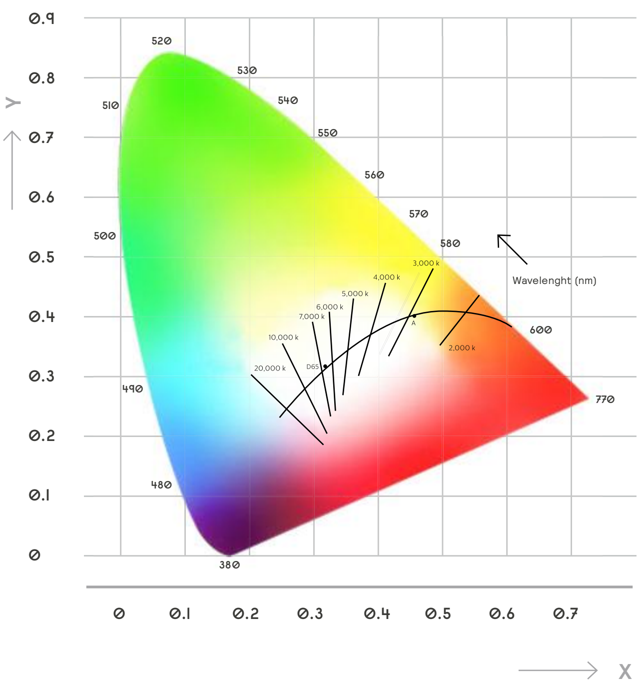


Fig. 6.5. Subtractive mixing of the complementary colors cyan, magenta and yellow gives black.

Color triangle

In order to exactly characterize the color of light, the international lighting commission CIE (Commission Internationale De L'Eclairage) developed the chromaticity diagram, also known as the "CIE color triangle" as early as 1931.



It is based on the theory of additive color mixing. Along the sides of the triangle the spectral colors are plotted, with the primary colors - red, green and violet-blue - placed at the corners (Fig. 6.6). The most saturated colors are at the circumference of the color triangle. Going inwards, they become lighter and at the same time less saturated, and the center of the triangle - we can see white. Numerical color values are plotted along the x and y-axes so that each color can be defined by its x and y values, which are called the chromaticity coordinates. From a lamp's spectral energy distribution, the x and y coordinates can be calculated so that the position of its light color in the color triangle can be determined. This position (x-y coordinates) of a light source is called the color point of the source.

Fig. 6.6. The CIE chromaticity diagram (CIE color triangle). The curved line is the black-body locus.

Color temperature and the color triangle

In Chapter 2 “How is light produced?”, on page 19 it was explained that a solid body, when heated to a certain temperature, emits visible radiation of a color specific to the temperature of the body. This temperature is called the color temperature (in Kelvin). To have an unambiguous definition of such a radiator, the idealized black-body has been defined. By plotting the x-y coordinates of a black-body radiator of different temperatures in the CIE triangle a curved line is obtained that is called the black-body locus. Moving from right to left on this black-body locus we move from radiators with a low color temperature (red-white light) to radiators with a high color temperature (blue-white light). Any thermal radiator has its place on, or very close to, the black-body locus. For example, point A in Fig. 6.6 is the color point of an incandescent lamp (2750 K).

Correlated color temperature and the color triangle

In contrast to thermal radiators, the ‘white’ light from light sources such as gas discharge and solidstate lamps may correspond to any random color point a distance away from the black-body locus. For these lamps the concept of correlated color temperature has been explained in Chapter 2 “How is light produced?”. The correlated color temperature is the color temperature of a blackbody radiator that resembles, as far as color is concerned, most closely that of the gas discharge or solid-state light source in question.

In the CIE color triangle, lines of constant correlated color temperature (called iso-color-temperature lines) have been drawn. By first assessing the color point of the source in question, and then following the corresponding iso-color-temperature line to the point where it intersects the black-body locus, the correlated color temperature of the source can be determined (Fig. 6.7). This method is only valid if the color point of the light source is not too far away from the black-body locus.

Some examples of lamps with their correlated color temperature:

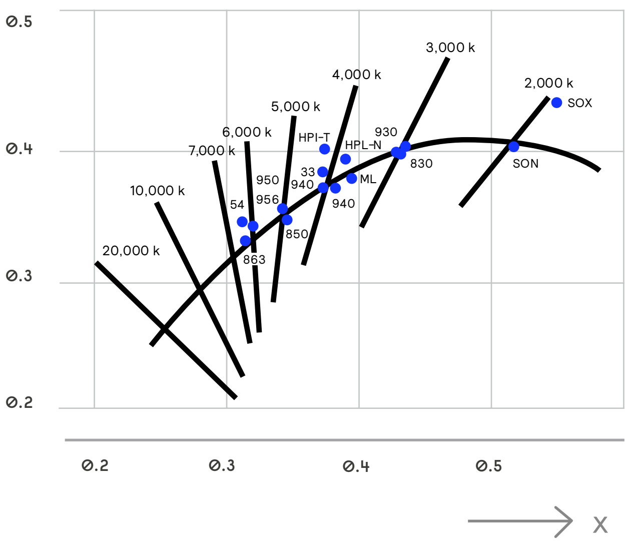
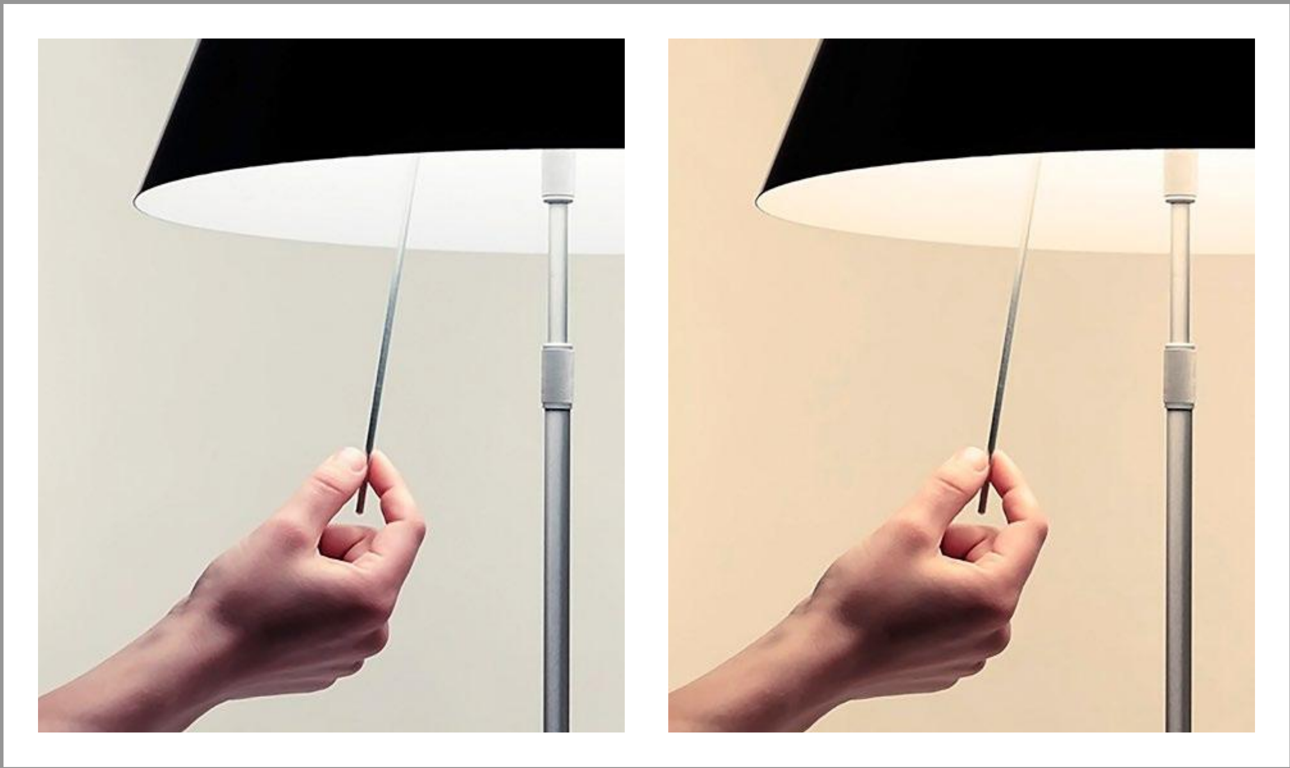


Fig. 6.7. Color points of various tubular fluorescent and high-intensity discharge lamps in the CIE color triangle.

TL lamp color 827	2700 K
TL lamp color 830	3000 K
TL lamp color 840	4000 K
TL lamp color 865	6500 K
High-pressure sodium SON	2000 K
High-pressure mercury HPL	3800 K
Metal halide HPI	4200 K

Image 6.1. Example of a lamp with cool white light (left; around 4000 K) and warm white light (right image; around 2700 K).



Color appearance and color temperature

The color appearance of a light source radiating some kind of white light is highly influenced by the spectral composition of its light and can be characterized by its (correlated) color temperature.

A white light source with a high proportion of red and thus a low color temperature, such as is the case with an incandescent lamp (Fig. 6.8), will appear warmer and a white light source with a higher proportion of blue, and thus a higher color temperature, as with natural daylight (Fig. 6.9), will appear cooler.

As we have seen, white light can also be obtained by mixing certain selected wavelengths, while other wavelengths are totally absent; for example by mixing red, green and blue, or merely blue and yellow. Such light sources, like gas discharge and solid-state lamps, have so-called discontinuous spectra (Fig. 6.10) contrary to the continuous spectrum of an incandescent lamp and of daylight (Fig. 6.8 and 6.9).

In order to characterize the different types of white light of lamps with a discontinuous spectrum, the correlated color temperature is used in the same way as color temperature is used for thermal radiators. So, a gas discharge lamp or a solid-state lamp with a high proportion of red, and thus a low correlated color temperature, will appear warmer, while a white light source with a higher proportion of blue, and thus a higher correlated color temperature, will appear cooler.

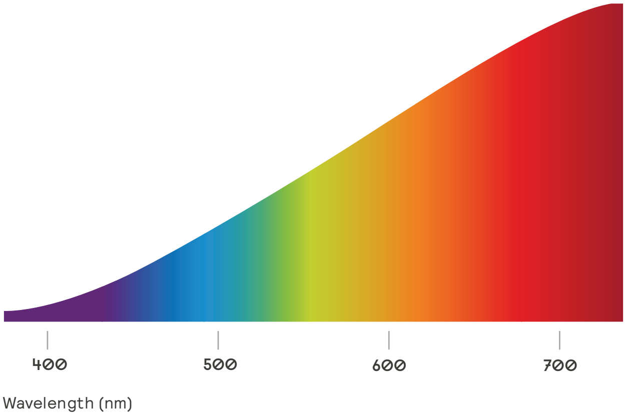


Fig. 6.8. Spectral energy distribution of an incandescent lamp (2800 K).

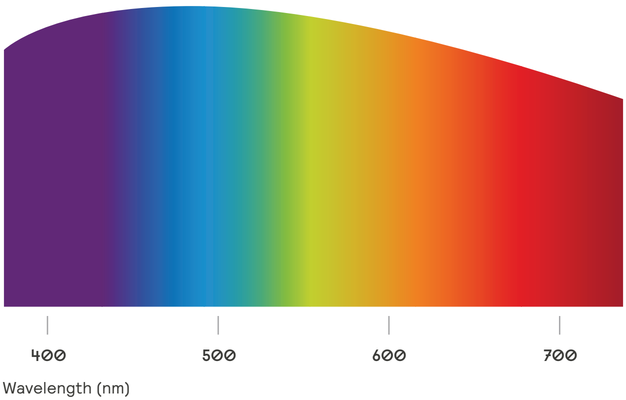


Fig. 6.9. Spectral energy distribution of daylight (5000 K).

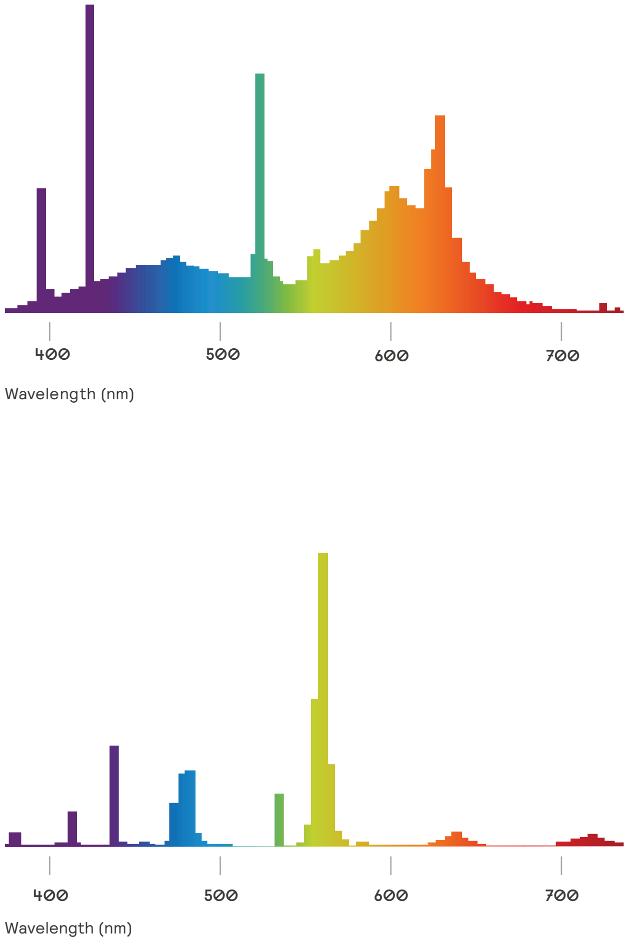
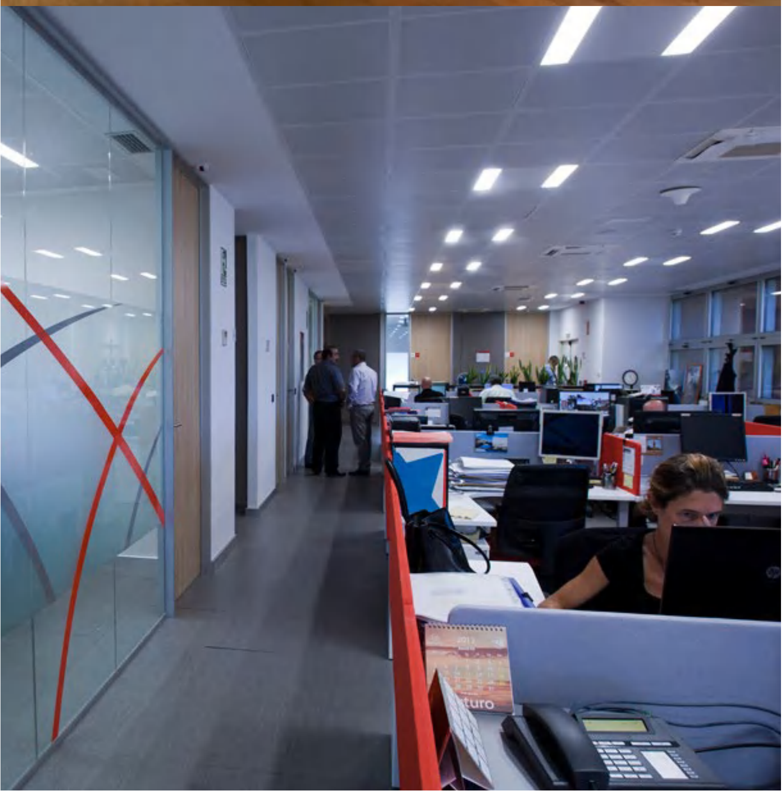


Fig. 6.10. Discontinuous spectra of two different gas discharge lamps.



(Correlated) color temperature is also used to classify groups of color temperature / color appearances (Table 6.1).

Color temperature	Color appearance
Less than 3300 K	Warm (yellowish) white
3300K - 5000 K	Neutral / intermediate white
More than 5000 K	Cool (bluish) white

Table 6.1. Classification of color temperature / color appearance groups.

In Chapter 5 “Light and vision”, we saw that the preferred color temperature of the lighting in a space is often dependent on the lighting level installed. Usually, with a lower lighting level, a lower color temperature is preferred, while with a higher lighting level a higher color temperature is more desirable (Fig. 6.11).

Fig. 6.11. Lit with high color temperature lamps (top) and lighted with lower color temperature lamps (bottom), resulting in a different appearance and atmosphere.

Chromatic adaptation

The eye and brain actually adapt to a given color and, in the absence of clues to the contrary, we tend to perceive that color as ‘white’.

A striking example of this is the case of the ordinary incandescent lamp: looked at in the full light of day it appears rather yellow (Fig. 6.12), but the same lamp seen in the evening, when daylight is no longer available as a reference, is decidedly white.

Similarly, if various different ‘colors’ of fluorescent lamps are installed in one and the same ceiling, each will clearly show a distinct color tint (Fig. 6.13), whereas all will be judged as being ‘white’ when no direct comparison can be made.

Fig. 6.12. An incandescent lamp in full daylight looks yellowish instead of white.

Fig. 6.13. Different TL fluorescent tubes seen together show distinct colors, different from white.

Color rendering and the color rendering index

Object colors play an important role in the perception of most scenes, and lighting influences the appearance of object colors.

The red, blue and green objects of Fig. 6.14 will only be seen in their true colors if the incident light has at least red, blue and green in its spectrum. Color rendering is the ability of the light to reproduce (render) faithfully the colors of objects. Light sources with a continuous spectrum do this better than light sources with a discontinuous spectrum.

When discussing color rendering it is important to realize that “true colors” do not exist. People tend to judge colors under what they consider to be natural, or true, lighting conditions, often mistakenly using daylight for this purpose. But colors seen under daylight on a sunny day can differ widely from those seen under daylight with an overcast sky. This is due to the fact that the spectral distribution of daylight is not constant, but changes from hour to hour and from season to season. The correct thing to do is to assess the colors under the same type of lighting as that existing in the area where they will be finally seen. For example, an evening dress should be chosen under warm lighting, for this is the sort of lighting employed in the evening function where it is worn.

Learn more about
color rendering
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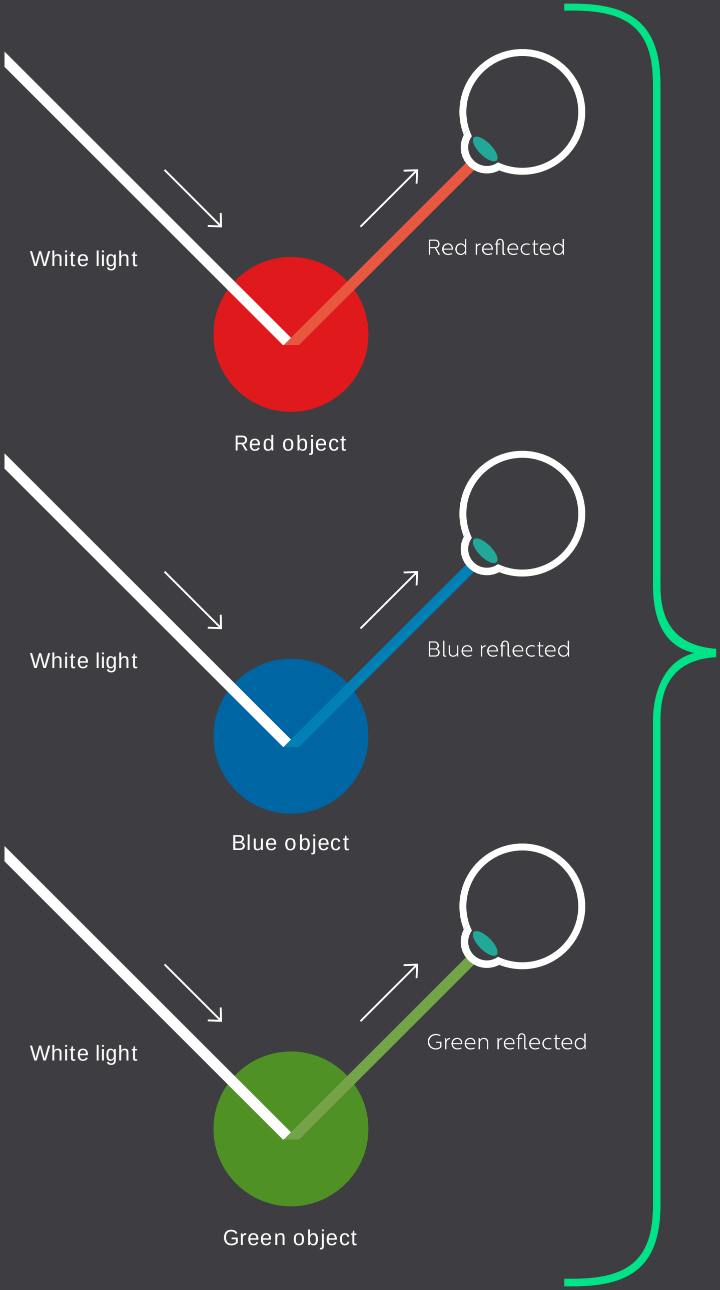


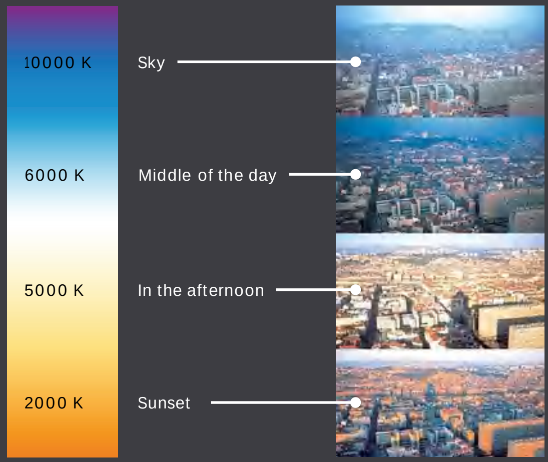


Fig. 6.14. Incident white light reflected from different colored surfaces.

Light sources having the same color temperature and thus the same color appearance, will not necessarily render colored surfaces the same. Two lights that appear the same white may be the result of different compositions of wavelengths. A piece of red cloth will only appear ‘true’ red when illuminated by white light with a continuous spectrum – in an equally- white-looking mixture of yellow and blue light it will look greyish brown. Because of the absence of red wavelengths, there is no red for the cloth to reflect into the eye. This principle is also illustrated in Figs 6.15 and 6.16. The full-spectrum lamp in Fig. 6.15, emitting light of all colors, illuminates an umbrella. The light reflected from the umbrella enters the eye of the observer resulting in an image as depicted in the top-right corner. In Fig. 6.16, the light falling on the horse has no red in its spectrum. This means that no light is reflected from the red parts of the umbrella and these parts will therefore appear dark to an observer.

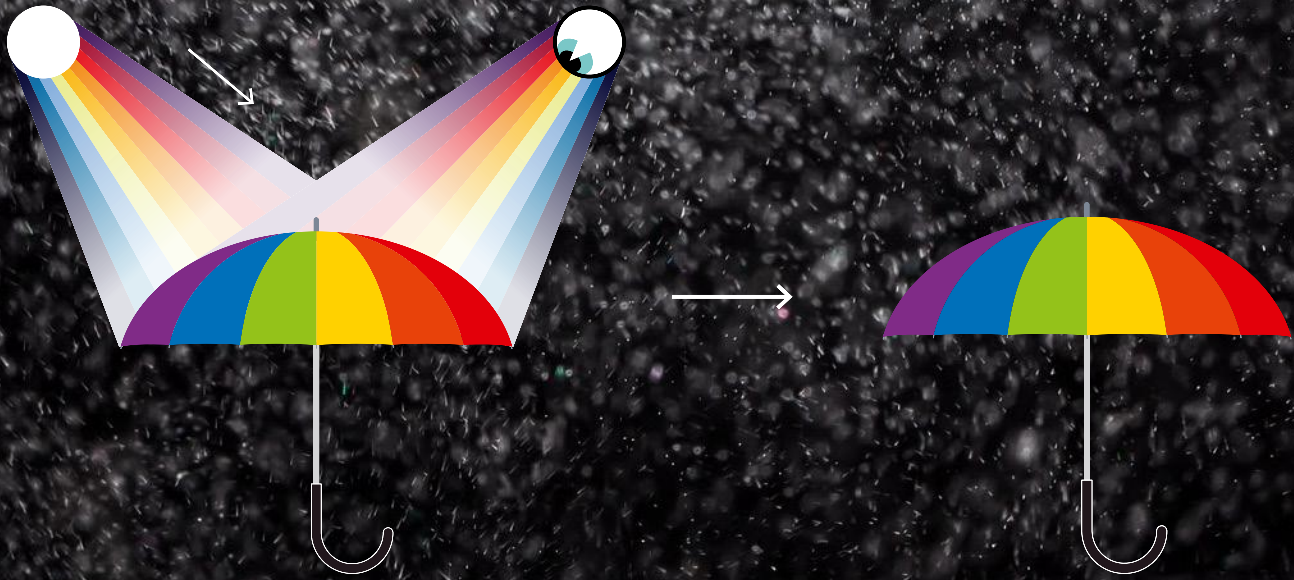
In order to be able to rank light sources according to their color rendering capabilities, CIE introduced the “general color rendering index” R_a. This index is based on the appearance of eight standardized colors under the light source in question compared to their appearance under a reference light source. This index thus represents the average color shift of these eight standardized colors. If there is no shift at all, as is the case with light sources having a continuous spectrum (viz. all thermal radiators), the value of R_a equals 100.

If all colors disappear completely, as in the case with low-pressure sodium light, R_a is negative. Since the general color rendering index R_a represents the average shift of eight colors, light sources with the same R_a value can nevertheless differ in the rendering of individual colors.

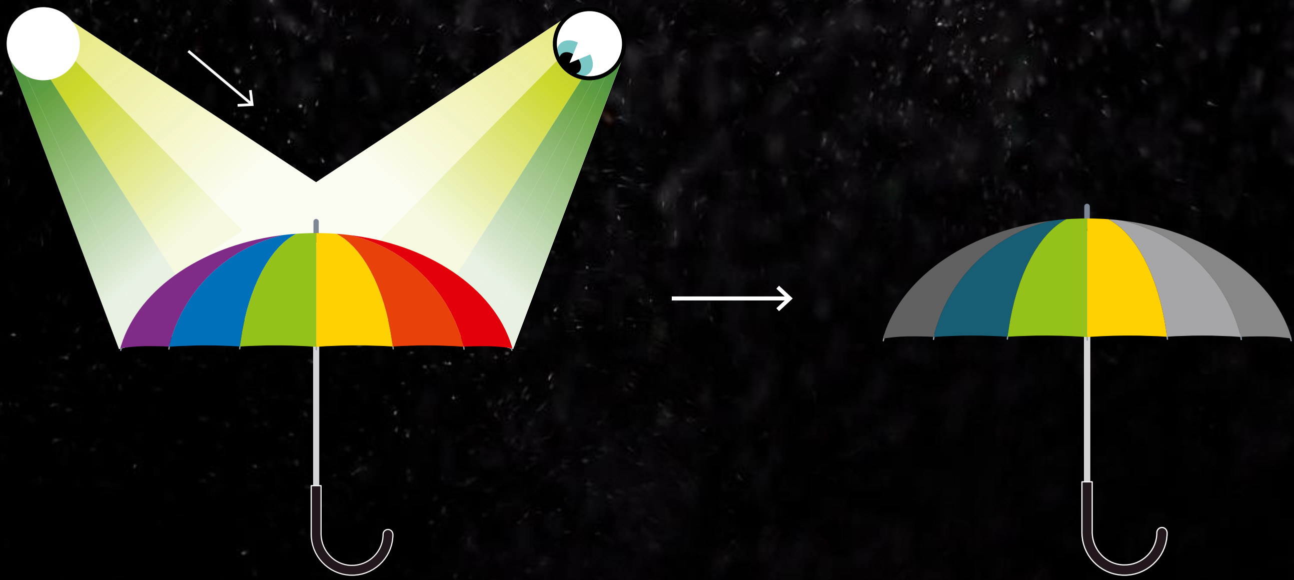
For indoor lighting applications, R_a is also used to classify light sources according to their color rendering quality (Table 6.2). Table 6.3 gives actual R_a values of some lamp types.

R_a range	Color rendering
90 – 100	Excellent
80 – 90	Good
60 – 80	Moderate
70 – 80	Moderate in N.A.
< 60	Poor
< 70	Poor in N.A.

Table 6.2. Color rendering classification.



Figures 6.15. and 6.16. An umbrella lighted by light with a continuous and a discontinuous spectrum, respectively. The colored images as seen by an observer are widely different (right in the pictures).



Color rendering index and LEDs

Modern fluorescent lamps and white LEDs have one or more narrow peaks in their spectrum. The general color rendering index R^a does not always give a good enough representation of the color rendering by these light sources. CIE is therefore investigating new methods for assessing the color rendering properties of white light sources with the goal of recommending a new color rendering metric.

Light sources with a lower color rendering index are often more efficient than those with a higher one. It is therefore an important task of the lighting designer to balance the relative importance of efficiency and color rendering quality for each different application.

Lamp type	R_a
Incandescent and halogen	100
TL 940	90
TL 840	80
TL 640	60
White LED	60 – 95
Metal halide	70 – 90
High-pressure sodium	25
Low-pressure sodium	0

Table 6.3. Color rendering index of differen t lamp types.

Light and health

7

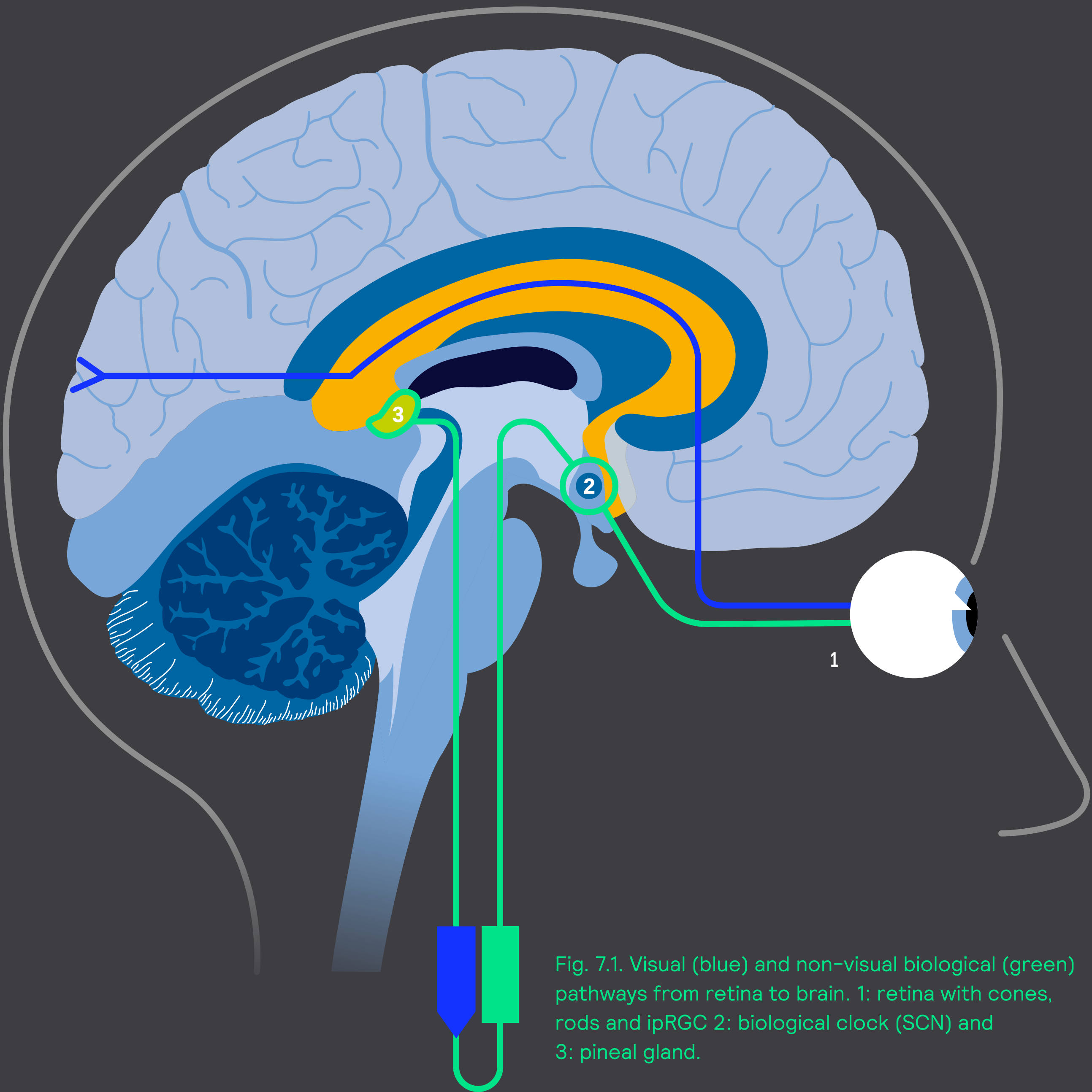


Fig. 7.1. Visual (blue) and non-visual biological (green) pathways from retina to brain. 1: retina with cones, rods and ipRGC 2: biological clock (SCN) and 3: pineal gland.

Photoreceptor

For about 200 years, rods and cones were considered to be the only photoreceptor cells in the eye. Around the year 2000, medical scientists discovered that about one per cent of our ganglion cells in the retina of the eye are also sensitive to light.

This third type of photoreceptor cell is called the intrinsic photo sensitive Retinal Ganglion Cell, or ipRGC. These cells have a nerve connection to the biological clock located in the brain (also called the suprachiasmatic nuclei, SCN). The SCN in turn has a nerve connection with the pineal gland, which is responsible for the regulation of some hormones in our body (Fig. 7.1).

So there is a direct connection between light, bodily timing and hormones. Lighting has not only a visual effect but also a non-visual biological effect. In short, lighting is important for our health.

Circadian rhythms

The rotation of the earth about its own axis in exactly 24 hours results in a 24-hour rhythm of light and dark. This light-dark rhythm regulates quite a few bodily processes.

These include, for example, the sleep-wake rhythm, the rhythm in body temperature and heart rate, and the rhythm according to which certain hormones are produced. These 24-hour rhythms are called circadian rhythms.

Fig. 7.2 shows the circadian rhythm of our body temperature. If we are healthy, our body temperature varies in the course of the day and night by about 0.4 degrees centigrade under the influence of the natural light-dark rhythm.

The same light-dark mechanism controls the hormones cortisol and melatonin over the course of the day and night (Fig. 7.3). These hormones (cortisol: the “energy hormone”, and melatonin: the “sleep hormone”) play an important role in regulating our degree of alertness and sleep. Cortisol, amongst other things, increases blood sugar to give the body energy. Cortisol levels increase in the morning, then decrease gradually but remain at a sufficiently high level to give sufficient blood sugar (and thus energy and alertness) over the course of the day, falling finally to a minimum at midnight. The level of melatonin, the sleep hormone, drops in the morning, reducing sleepiness.

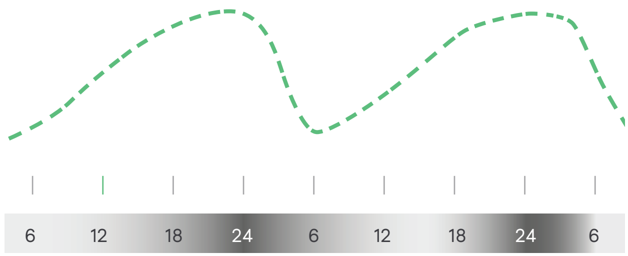


Fig. 7.2. Double plot (2 x 24 hours) of typical daily rhythms of body temperature (relative scale).

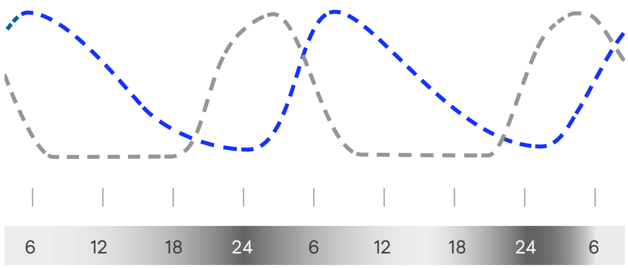


Fig. 7.3. Double plot (2 x 24 hours) of typical daily rhythms of cortisol (blue) and melatonin (grey) (relative scale).

In healthy persons it then rises again when it becomes dark to facilitate sleep (this sleep effect is strengthened because cortisol is then at its minimum level).

Apart from regulating all this, the natural 24-hour rhythm of light and dark also ensures that our biological clock keeps to the 24-hour rhythm.

It is the light of morning that again synchronizes our internal body clock to the earth's 24-hour light-dark cycle. In the absence of this "synchronization process", our body would gradually adopt the wrong rhythm of alertness and sleepiness, ultimately leading to a period with alertness during the dark hours and sleepiness during the daylight hours.

Non-visual biological spectral sensitivity

The sensitivity of the recently-discovered photo receptor cell varies with different wavelengths of light, as does the sensitivity of cones and rods.

Fig. 7.4. shows the non-visual biological spectral sensitivity curve and the visual eye-sensitivity curve for photopic vision V(λ), both as a function of wavelength. By comparing the two curves it is immediately evident that the biological sensitivity to light is quite different from the visual sensitivity.

Where the maximum visual sensitivity lies in the yellow-green wavelength region, the maximum biological sensitivity lies in the blue region of the spectrum. High-color-temperature light is thus “biologically” more effective than low-color-temperature light. This phenomenon is important for the specification and design of healthy lighting installations.

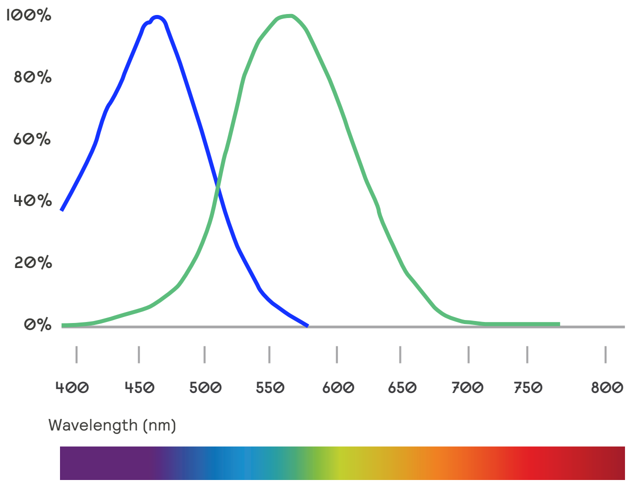


Fig. 7.4. Spectral non-visual biological sensitivity curve (based on melatonin suppression), in blue, and the visual eye-sensitivity curve V(λ), in green.

Lighting and therapy

In previous chapters the importance of lighting for healthy people has been described. But lighting can also sometimes be used as a therapy for people with disturbances in their biological clocks.

Examples are therapies for certain forms of sleep disorder, especially in elderly, for seasonal affective disorders, or SAD (a form of severe winter depression), for certain forms of eating disorders, for burnouts, and for sleep-wake rhythm problems as often occurring in Alzheimer patients.

Disturbances in the biological clock can also be caused by our way of living. Here, too, appropriate lighting can help minimize such problems. Examples are jet lag (due to long flights through many time zones) and shift work.

Learn more about the basic conceptsof light and health
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Lighting
quality

8


Lighting is an art
as well as a science.

There can therefore be no hard and fast rules governing the lighting design process. Nor will there be one ideal solution to a particular lighting problem.

What is important, however, is that the solution chosen should provide the lighting quality needed to ensure that visual performance and visual comfort are adequate. Investigations carried out throughout the world over a very long period into how the eye works, how we see, and what role light plays in this, have yielded the principal lighting quality criteria. These criteria can be described as:

- **Lighting level**
- **Spatial distribution of the light in the field of view**
- **Directionality of the light**
- **Color of the light**

Lighting level

Lighting level is used to specify the amount of light present.

In order to give a rough idea of the sort of lighting levels encountered, it should be noted that the natural illuminances provided by daylight can range from a few tenths of a lux (e.g. moonlight), in which human perception is just possible, to as high as 100,000 lux in the middle of summer out in the open (Fig. 8.1). Compared to this range of daylight levels, the levels accepted as being satisfactory under electric lighting are really very low indeed: 3 to 25 lux for road lighting, 10 to 50 lux on average for mood lighting indoors, and 300 to 1,000 lux for reading and working.

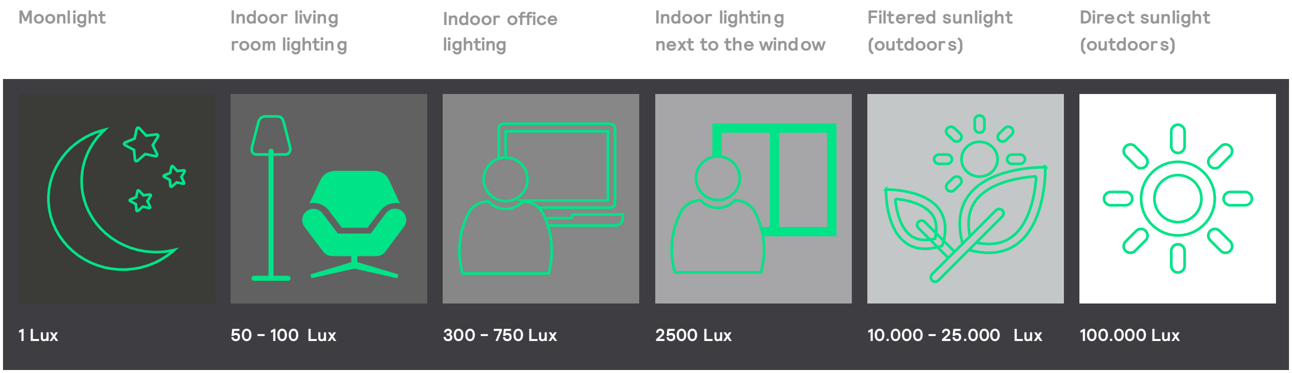

Fig. 8.1. Range of lighting levels.

Learn more about lighting level requirements.
view more >>

Luminance versus illuminance

Before dealing with the subject of lighting level in more detail, we should first look at how it is measured. In Fig. 8.1 we used the so-called horizontal illuminance to specify what daylight is “giving us quantitatively”. But what we “see” as a result of all that daylight is in fact a luminance pattern in which the reflectances of the objects, in combination with the amount of daylight falling on them, play a major role. However, in applications where a variety of reflectances occur, it is impractical, if not impossible, to directly specify lighting levels in terms of luminance – in fact it is only in road lighting, where the reflection properties of the road surface are usually well defined, that the average luminance of the road surface is used as the measure for lighting level. In most other applications it is the average illuminance on the most relevant plane, often the horizontal plane, that is used as the measure for lighting level.

Effect of lighting level

It is the lighting level that determines the adaptation state of the eye. As explained earlier, the higher the adaptation state of the eye, the better the contrast sensitivity and the visual acuity and the lower the risk of disturbing or discomfort glare. Therefore, the more difficult the visual task (in terms of size, contrast and, where relevant, speed of execution), the higher the lighting level needed. In addition, the risk of errors and the time required to perform the task play an important role in determining the proper lighting level.

There are various national and international recommendations and standards covering a wide range of indoor and outdoor lighting applications, with detailed specifications for lighting level values.

Fig. 8.2. The horizontal working plane in a typical office.

Planes for specifying lighting level

Often the plane on which the lighting level is specified is the horizontal plane (Fig. 8.2). Indoors, it is usually measured on the working areas (e.g. the desks). But where the precise working area is not known, the lighting level on an imaginary horizontal surface about 75 cm above the floor is specified. In road lighting, it is the road surface, and in sports lighting the horizontal playing area.

But in many situations the lighting of vertical objects is important as well. For example, in sports lighting for television broadcasting, the illuminance on specified vertical planes is used as an extra criterion to guarantee a proper view of the “vertical” players. And in residential areas where crime could be a problem, the so-called semi-cylindrical illuminance, as defined in the European norms EN 12464, is often used as a lighting criterion to facilitate facial recognition. This is because the human face more resembles a half cylinder than a vertical plane.

As was explained earlier in this book, light incident on the eye controls our circadian rhythms. Therefore, as far as lighting and health is concerned, specification of lighting level should be in terms of illuminance on a plane perpendicular to the line of sight.

Spatial distribution of light

Our visual environment consists of a variety of patterns of brightness and color. It is therefore not enough to ensure a proper functioning of the eye by having an appropriate average lighting level.

It is also the spatial distribution of light in the space that is important, and this should be such that it results in a balanced luminance distribution. Uniformity and luminance-ratio requirements, together with glare-restriction limits, will help in achieving such a balanced situation.

Uniformity and luminance ratios

If the average lighting level is adequate, but is obtained in such a way that there are large differences in individual levels on the plane or planes specified, both visual performance and visual comfort may suffer. In other words, some areas on the specified planes will be too dark relative to the overall lighting level. Therefore, in addition to the average lighting level, a uniformity requirement is specified. This is usually done in terms of a requirement for the minimum (il)luminance on a specified plane relative to the average (il)luminance: E_{min}/E_{av} or L_{min}/L_{av}. As is the case with lighting level, various national and international recommendations and standards specify uniformity values for many different applications.

In addition to avoiding dark areas relative to the overall lighting, it is also important to avoid creating light and dark spots too close to each other. An example here is the “zebra effect” of a poorly- designed road-lighting installation due to the lighting columns being spaced too far apart. Driving on such a road is very uncomfortable because of the continuously-repeated sequence of light and dark areas. Here an appropriate specification of a minimum value for the minimum-to-maximum luminance ratio on a line parallel to the road axis will eliminate the problem: (Lmin/Lmax) lengthwise. A similar problem may occur in indoor spaces where the luminances of the walls are widely different.

This is because when looking around in the room the eye has to continuously readapt. This is annoying in itself, but can also lead to fatigue. Too small luminance differences, on the other hand, will result in a dull and monotonous visual scene with no point(s) of interest. Some recommendations and standards therefore specify minimum and maximum values for the luminance ratios for the larger surfaces in an interior space. Careful matching of surface reflectances in the field of view is one of the main requirements to ensure good and comfortable luminance ratios (Fig. 8.3).

Ranges of useful reflectances for the major interior surfaces are:

- **Ceiling: 0.6 to 0.9**
- **Walls: 0.3 to 0.8**
- **Working planes: 0.2 to 0.6**
- **Floor: 0.1 to 0.5**

As a general rule, the luminance ratio in the direct neighborhood of the visual task should not be greater than 3 : 1 (Fig. 8.4).

Fig. 8.3. Careful matching of surface reflectances to achieve good and comfortable luminance ratios.

Glare restriction

Glare by artificial light

We have seen that glare is the unpleasant sensation created by luminances in the visual field that are much greater than the luminance to which the eyes are adapted. Glare, which can be caused by bright luminaires, can in fact have a disabling effect, a discomforting effect, or both. There are therefore various national and international recommendations and standards that specify restrictions for both disability and discomfort glare.

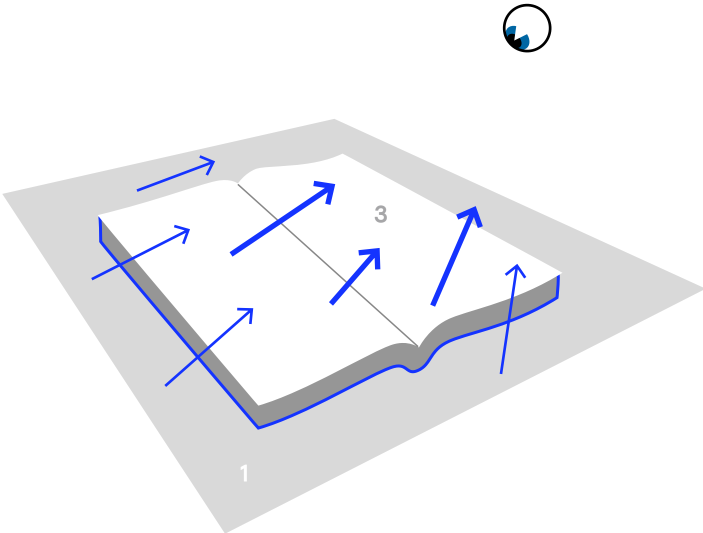

Fig. 8.4. The luminance ratio in the direct neighborhood of the visual task should not be greater than 3 : 1.

Glare by daylight

Windows can have disturbingly high luminances compared with other luminances in the room. The luminance of the bright sky can be as high as 8,000 cd/m². With an overcast sky the value can still be as high as 200 cd/m². Depending on the orientation and design of the window, it may therefore be necessary to install sunshades or curtains to eliminate such disturbances.

Indirect glare by reection

Light from a bright source reflected by a glossy surface into the eyes of an observer can produce feelings ranging from mild distraction to considerable discomfort and disability. In the past, poor computer monitor screens (visual display units, or VDUs) produced these feelings to such a degree (Fig 8.5) that special “low brightness VDU luminaires” were developed to minimize these problems.

Today, with modern reflection-free VDUs, special lighting measures are usually no longer required. Nevertheless, reflections of bright windows in even good-quality VDUs can seriously impair viewing. This is another reason for having proper sunshades.

Fig. 8.5. Old VDU screen that, especially with a dark background, leads to disturbing reflections.

Learn more about the basic calculations that are required for a lighting design.

view more >>

Learn more about Lumen method and calculate the right light level for every space.

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Directionality of light

The direction of the light flow and the shadows produced influence the way in which we perceive the three-dimensional world around us. We can distinguish between directional light, diffuse light and indirect light.

Directional light

Directional light usually comes in the form of a narrow beam and reaches an object directly. It produces high contrasts and a marked modelling effect. In display lighting (Fig. 8.6 and Fig. 8.7), it does this by casting deep shadows and creating bright highlights to clearly and dramatically reveal the contours of the object illuminated. However, very deep shadows are unpleasant and can obscure object details. Good three-dimensional viewing generally calls for directional lighting from at least two directions. An intensity balance of 1 : 2 is often used, where the main beam (or key light) is backed up by a secondary bean (fill light) see Fig. 8.8.

Light from other directions can be added. Back-lighting, for example, can be used to reveal the contours of the article on display (Fig. 8.9). Backlighting is also employed to achieve silhouette effects against a bright background. Very dramatic effects can be achieved using lighting from below, or ‘uplighting’ (Fig. 8.10).

Diffuse light

Light that reaches an object from many different directions produces scarcely any shadow. The modelling effects with such diffuse light are far less pronounced, and with completely diffuse lighting are totally absent (Fig. 8.11). The impression of a space with completely diffuse lighting is dull and monotonous, and it is difficult to identify objects and judge distances. It can be compared with an outdoor situation with a completely overcast sky.

Indirect light

Indirect lighting is obtained when light is reflected by a light-colored wall or ceiling before it reaches its final goal. When the walls or ceiling, or both, are not glossy (which is usually the case) the reflected light is mostly of a diffuse nature.

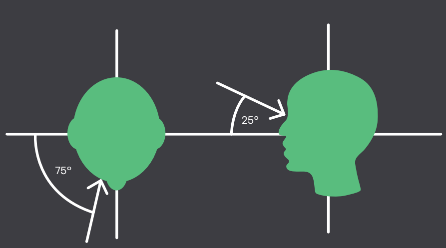


Fig. 8.6.Directional light from the right of the figure.

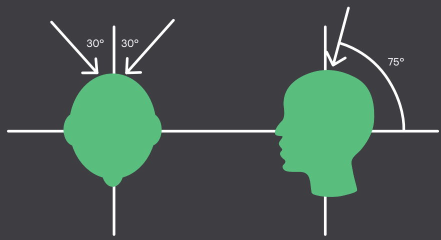


Fig. 8.9. Backlighting.

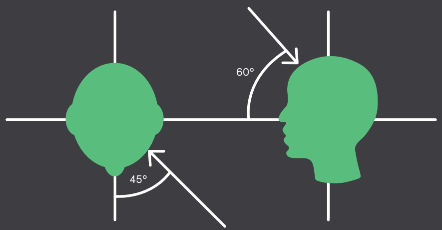


Fig. 8.7. Directional light from top left of the figure.

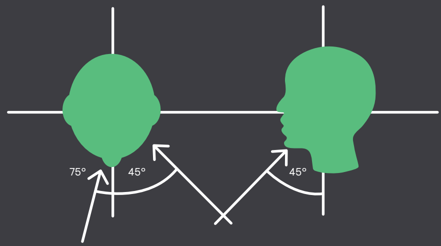


Fig. 8.10. Uplighting.

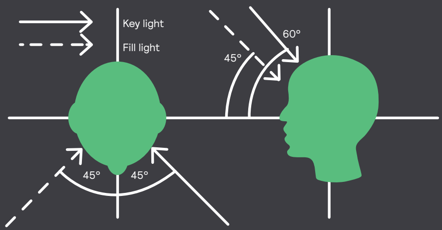


Fig. 8.8. Combination of key and fill light.

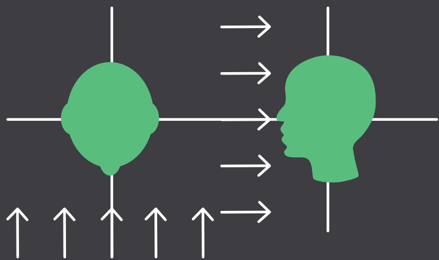


Fig. 8.11.Diffuse lighting.

Light distribution of luminaires

When lighting an interior, it is important to choose a luminaire having the most appropriate light distribution, for it is the light distribution of the luminaires and their location that determine the direction given to the light, which in turn determines where the shadows will be cast.

The light distribution of a luminaire can be given in a so-called luminous intensity polar diagram (Fig. 8.12), often simply called “light distribution curve”. From such a diagram one can see whether the light reaches the working plane directly, or whether it will only do so after reflection from walls and ceiling. The light distribution of a luminaire also determines to a large extent the amount of light that directly reaches the eye, and thus in turn the likely degree of glare. The same holds true for the light incident on poorly-designed VDU screens to create indirect glare.

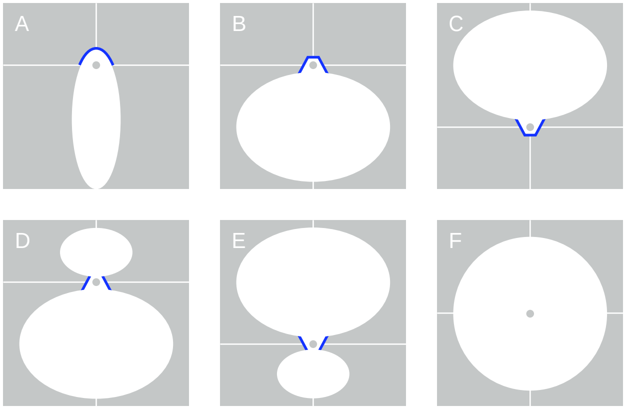
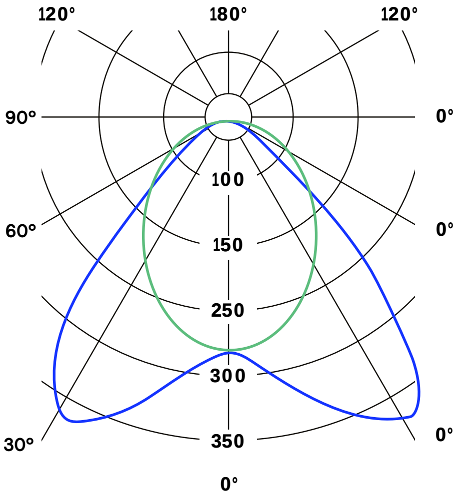


Fig. 8.12. Luminous intensity polar diagrams for A: narrow beam B: wide beam C: indirect beam D: predominantly direct beam E: predominantly indirect beam F: omnidirectional beam.



Photometrics

Types of symmetry for luminaires:
Polar intensity diagram

Light distribution of luminaire in 2 planes:

- Plane C0-C180 Vertical plane through cross axis of luminaire
- Plane C90-C270 Vertical plane perpendicular to length axis of luminaire

Luminous intensity in candela / 1000 lumen

Color of light

As was explained in Chapter 6 “Light and color”, it is the spectral distribution of the visible radiation emitted by a light source that determines both the color rendering capability of the source and the color impression, or color appearance, received when looking at the source.

These two characteristics are of great importance with regard to lighting quality, as together they largely determine the color impression that is received from the lighted scene.

Color rendering

Proper color rendering is of importance when objects must be seen in their ‘true’ colors. All national and international recommendations and standards specify minimum values for the general color rendering index R_a for a wide range of indoor and outdoor lighting applications.

Color temperature

Since the tint of white light (i.e. the color appearance) is often considered to be a question of taste, only a few application recommendations and standards specify specific color temperatures. Where the influence of lighting on health is a consideration, the color temperature of the lighting installation can be instrumental (see Chapter 7 “Lighting and health”). For this reason it can sometimes be beneficial to have dynamic lighting where both the lighting level and the color temperature change in the course of time.

Colored light

Colored light is entering our daily life more and more. In the past, the domain of colored light was mainly limited to the theatre. With LED lighting we now see colored light all around us (Fig. 8.13): in shops, reception areas, for city beautification, and sometimes even in office environments. For the international lighting designer it is important to realize that the acceptance of the use of colors – and especially of strong, saturated colors – varies with the cultural and geographical background of people. Needless to mention that next to saturated colors, it is also good to use some white light with a good color rendering to generate a nice natural effect.

Fig. 8.13. Colored scenes created with LED lighting.

Economics of light

A lighting installation that fulfils all relevant lighting quality requirements but is needlessly expensive, difficult to maintain, and inefficient in its energy usage can only be described as a bad installation.

Lighting installation

Right from the first discussions about a lighting project, economics should be an integral part of all considerations.

Total cost of ownership is an assessment of all the costs involved with a lighting solution over its lifetime. Typically, it is calculated for each design alternative to determine the most cost-effective choice. At this point, many cost factors are estimates. It is part of the quality process of designing an installation to determine these estimates reliably.

Cost factors to be included are:

Investment costs
The investment costs for a particular lighting installation can be split up as follows:

- Initial purchase costs of lamps, luminaires, ballasts and lighting controls
- Additional costs of mounting components and electrical components (ceiling supports, masts, cabling, etc.).
- Installation costs

Running costs
The most important running costs are those involving:

- Energy costs
- Lamp replacement costs
- Maintenance costs

Learn more about the process of lighting installations and the cost factors
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The major running cost is the cost of energy. This means, of course, that the lighting, apart from meeting all the other requirements, must also be as efficient as possible so as to keep the electricity consumption to a minimum. Except where access to the luminaires is difficult, or would hinder normal work flow, maintenance costs represent a relatively small part of the total annual costs. Ease of maintenance, however, is essential in order to guarantee a proper functioning of the installation throughout its lifetime.

Lighting control

Lighting installation efficiency should be combined with usage efficiency. Only that amount of light that is needed for the performance of the actual tasks carried out at a specific moment should be made available at that moment. We call this demand-dependent lighting. Modern lighting control systems should offer far more possibilities than a simple switch-on switch-off function.

Remote or automatically controlled dimming of lighting groups can result in important energy and cost savings without sacrificing task performance of the installation (task-dependent control).

Task-dependent lighting control is relevant for all lighting application fields, ranging from indoor lighting (task and age dependent) to road lighting (traffic density, weather type, time-of-night dependent) and sports lighting (type of competition, or training only). In indoor lighting installations an efficient control system should also take advantage of daylight by dimming and switching off the electrical lighting at those moments and places where enough daylight enters the indoor space (daylight linking). Simple passive infrared detection systems can be combined with such intelligent control systems to ensure that the lighting is off if nobody is present (presence control).

Modern lighting control systems will be discussed in more detail elsewhere in this series.

Light and the environment

Already as early as 1972 the Club of Rome, a small international group of professionals from the fields of diplomacy, industry, academia and civil society, produced its report “The limits to growth”.

This report showed for the first time the contradiction of unlimited growth in material consumption in a world of finite resources. It brought, in particular, the issue of limited energy resources to the top of the global agenda. The lighting world reacted by developing more energy-efficient lighting products and by reconsidering lighting recommendations and standards with regard to more-clearly defined minimum required values. Since the nineties of the last century, the negative consequences of CO_2 (carbon dioxide) emissions on climate change also became apparent.

Learn more about lighting and the environment.

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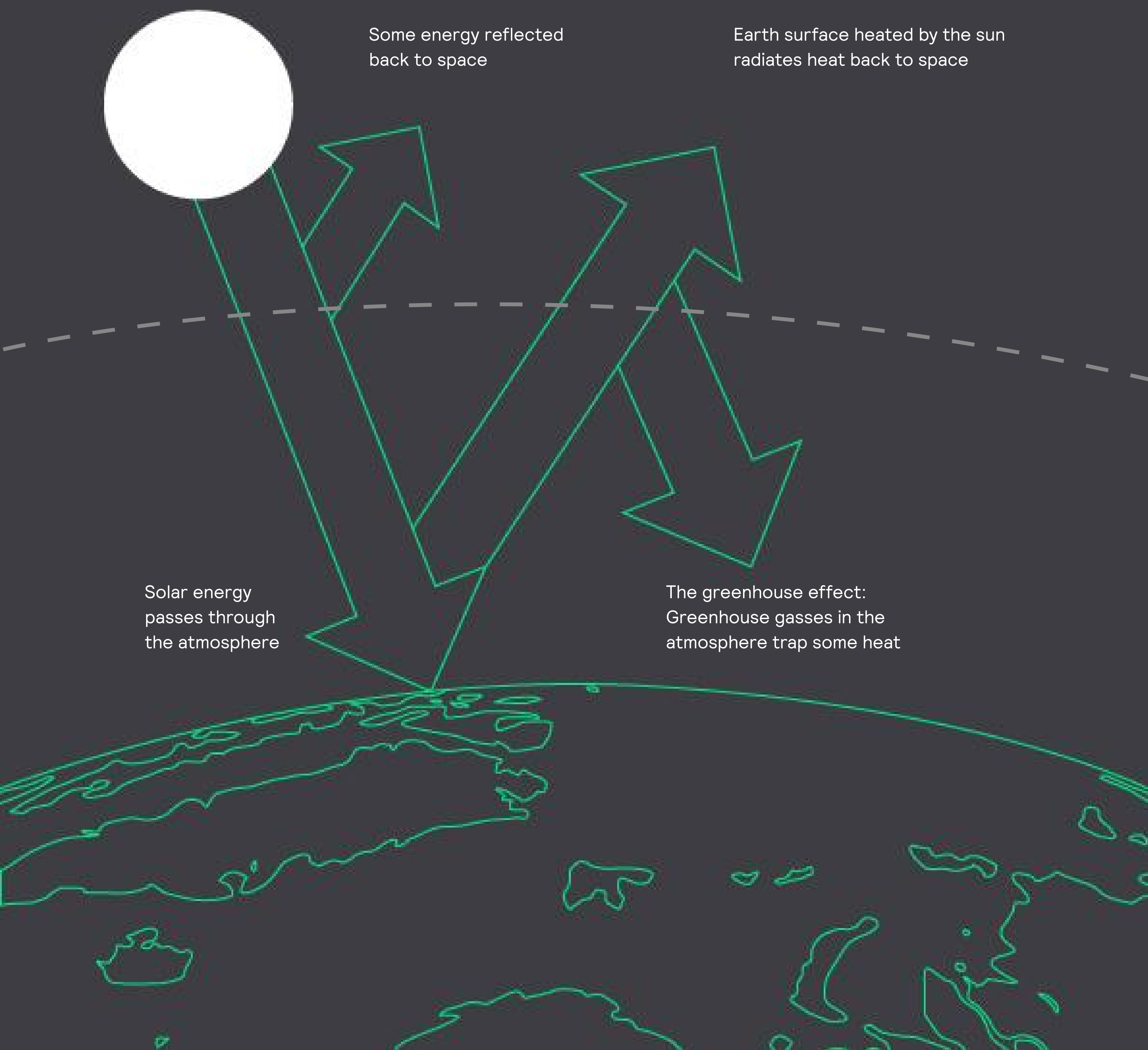

Some energy reflected back to space
Earth surface heated by the sun radiates heat back to space
Solar energy passes through the atmosphere
The greenhouse effect: Greenhouse gasses in the atmosphere trap some heat

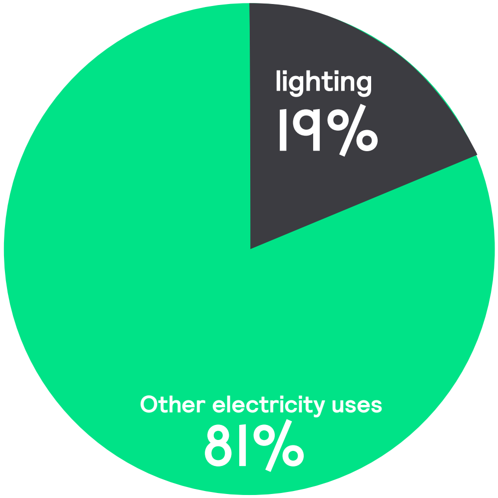
Climate change

The earth is heated by solar radiation, which passes easily through the atmosphere. This solar radiation heats the surface of the earth. As a result, the earth emits infrared radiation. Some of this infrared radiation is absorbed by the atmosphere, which prevents it from completely escaping into space. This causes a gradual warming of the earth's environment. The main components of the atmosphere – oxygen and nitrogen – are transparent to the emitted radiation. But carbon dioxide has a much stronger absorbing effect. Increasing carbon dioxide emissions strengthen the absorption of infra-red radiation in the atmosphere.

This is what causes the 'greenhouse effect'. Power stations that generate electricity from fossil fuels are major emitters of CO_2, the most important greenhouse gas.

Lighting accounts today for 19 per cent of all electricity used worldwide and is therefore responsible for a substantial part of CO_2 emissions.

Some lighting products use hazardous substances as for example mercury. What we must do constantly is maximize energy efficiency and product reliability, minimize the use of hazardous substances, reduce waste (also through recycling) and avoid light pollution to create greater sustainability. This can be defined as: "balancing the positive effects of lighting with the negative impacts of that lighting on the environment". The right balance can only be obtained if all the disciplines involved in the lighting chain are taken into account in a professionally responsible way. We then improve people's quality of life, as well as the quality of the world we live in.



Glossary

Glossary of terms and abbreviations

Candela (CD): The SI unit of luminous intensity. The Candela is most often used on polar curves, to measure the intensity of light in any given direction. You should take care while reading candelas because they can easily be misinterpreted.

CIE:An abbreviation for Commission Internationale de l'eclairage. Also known as the International Commission on Lighting. This is a global, independent, non-profit organization that deals with all aspects of lighting knowledge and research. The CIE makes recommendations that are often then used as national Codes of Practice.

Color Rendering: The effect of a light source on the color appearance of objects compared with their color appearance under a reference light source, such as a tungsten filament lamp or daylight.

Color Temperature: A term to describe the color appearance of a light source, measured in degrees Kelvin (K). Warm light sources are around 2,000 K 3,000 K. Cool light sources are typically 4,500 K 6,500 K, or more. Strictly speaking, the appearance of all other lamps and LEDs (apart from incandescent sources) should be referred to as Co-related Color Temperature, CCT.

Driver: This is similar to a transformer except that it produces a constant current as output instead of a constant voltage. As more LEDs are added to the circuit, the output voltage from the driver increases to maintain a constant current through the LEDs. Note that in Europe the output voltage is limited to a maximum of 50 V. This makes LED installations inherently safe. See main text for a full description.

Efficacy: A way of describing the efficiency of a light source, such as a lamp or LED. Efficacy is measured in lm/W.

Glare: A light that causes discomfort or reduces the ability to see because it comes from a source that is too bright compared with its background. Glare can be reduced by dimming the source, blocking the direct view, or increasing the background level of luminance. Although there are methods for calculating glare in lighting designs, what is 'glare' remains very subjective and is affected by many factors, for example the age group of the people.

Lumen (lm): A measure of the total amount of visible light emitted by a source. The term is derived from the SI term luminous flux and is denoted by the symbol lm. It tells you nothing about the color, intensity or quality of light. It only is a description of how much light the source emits. See also Lux.

Luminaire: The correct term for what is generally called a light fitting or light fixture. Strictly speaking, a luminaire is the apparatus containing the light source.

Lux: An abbreviation for lux, the unit of illumination level (the SI term is illuminance). One lux is one lumen per square meter. An office might be lit to 300 lux, a domestic lounge to 50 lux. Note that this is an average; it does not tell you how uniform the light is spread over the area. Neither does it tell you anything about the quality of light or its color.

Mesopic vision: The viewing condition in low but not quite dark lighting situations. Mesopic vision is typical of the viewing conditions at dusk or where there is streetlighting. It is the intermediate stage between photopic and scotopic vision.

Photopic vision: This is our normal viewing condition throughout the day where there is plenty of illumination and colors can be seen clearly. In photopic vision, the cone receptors in our eye are fully operational. Compare this with mesopic and scotopic vision.

RGB: An abbreviation for the colors red, green, blue. These three colors can be combined to produce a huge range of colors and shades. Note that it may not be possible to achieve the exact hue. This is important if you are trying to match a particular paint color.

Scotopic vision: This viewing condition occurs when it is so dark that we cannot see colors; objects are only different shades of grey. This only occurs at very low levels of illumination, typically less than that of moonlight. See also mesopic and photopic vision.

Solid-state: General term that refers to all electronic light sources. It not only refers to LEDs but also to OLEDs, PLEDs, flat panels, etc.

UV: Ultraviolet. This is a shortwave radiation which is damaging to materials such as fabric, paints, and plastics. LEDs do not emit any UV.

Volt: The unit of electromotive force or potential difference. High voltage can kill and it is the insulation covering (normally PVC) electrical cables that protects us.

Watt (W): The unit of power. For simple resistive circuits, volts x amps = watts. Note that other forms of power, such as mechanical and thermal, can also be expressed in watts.

Chapter 1

Electromagnetic waves
Learn more about the different types of light waves.
view more >>

The electromagnetic spectrum
Learn more about the spectrum of electromagnetic radiation.
view more >>

What is prism?
Learn more about the function of prism.
view more >>

Chapter 2

Color temperature
Learn more about color temperature.
view more >>

Incandescent and halogen lamps
Learn more about color temperature.
view more >>

Gas discharge
Learn more about the basic concepts of gas discharge lamps.
view more >>

What is HID?
Learn more about high intensity discharge and its benefits
view more >>

What is fluorescent?
Learn more about fluorescent light and delivery system.
view more >>

Connected LEDs
Learn more in our Connecting LEDs ebook.
view more >>

LED
Learn more about how LED works.
view more >>

Chapter 3

Light reflection and light absorption
Learn more about how Light absoprtion works.
view more >>

Refraction
Learn more about the refraction of light
view more >>

Chapter 4

What is the value of 1 watt?
Learn more about the value Watt
view more >>

Photometrics
Learn more about photometrics
view more >>

Luminous flux
Learn more about luminous flux
view more >>

Luminous intensity
Learn more about luminous intensity
view more >>

Luminance and illuminance
Learn more about the refraction of light
view more >>

Chapter 5

The visual process of the eye
Learn more about the visual process of the eye
view more >>

Lighting vision
Learn more about lighting vision
view more >>

What is glare?
Learn more about the concept and types of glare
view more >>

Chapter 6

Color mixing
Learn more about color mixing
view more >>

Color rendering
Learn more about color rendering
view more >>

Chapter 7

Light and health
Learn more about the basic conceptsof light and health
view more >>

Chapter 8

Lighting level requirements
Learn more about lighting level requirements.
view more >>

Lighting calculations
Learn more aboutthe basic calculations that are required for a lighting design.
view more >>

What is Lumen method?
Learn more about Lumen method and calculate the right light level for every space.
view more >>

Economics of lighting
Learn more aboutthe process of lighting installations and the cost factors
view more >>

Lighting and the environment
Learn more about lighting and the environment.
view more >>

Index

Index

Index

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Prof. Wout van Bommel is Dutch and has spent 37 years with Philips Lighting in different lighting application functions. He was responsible for the company's international lighting application knowhow center (LiDAC). Some concepts now used in international standards for lighting are based on his research work. For the period 2003 - 2007 he was President of the International Lighting Commission, CIE. He is a board member of the Dutch "Light & Health Research Foundation", SOLG. In 2004, Wout van Bommel was appointed Consulting Professor at the Fudan University of Shanghai. He has published more than 150 papers in national and international lighting journals. He is the author of the book "Road Lighting". He has presented papers, taught at universities and schools and has lectured at conferences all around the world.

Upon his retirement from Philips Lighting, Prof. Bommel now independently advises lighting designers, researchers, companies, municipalities and government bodies.

Abdo Rouhana MSc

Abdo Rouhana, a citizen of both Canada and Lebanon, graduated as an electrical engineer from the University of Montreal, Canada. After receiving his master degree from the same university in 1983, he joined Philips Lighting in the Middle East, where he became a lighting application specialist. He has been responsible for the design of many impressive lighting projects in the area. He combined this function with key positions in sales and marketing.

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