Chapter 1

What is light?

Have you ever tried to define light? If so, your definition is probably related to vision, the ability to see things. The Merriam-Webster English dictionary defines light as "something that makes vision possible". However, the definition of the "nature of light" is a complex term already discussed by philosophers of Ancient Greece. In the 17th century, the debate on the matter focused on whether light was a particle or a wave, based on the different properties of light that had been gradually discovered over time. Isaac Newton (1642–1727) was a defender of the corpuscular theory of light, which considered light to be formed by particles, i.e., small pieces of matter, like dust or grains of sand. He was the author of *Opticks* (1706), the front cover of which appears in Fig. 1.1. Christian Huygens (1629–1695), on the other hand, supported the theory that light is a wave. These are two completely different definitions of the same physical concept.

A range of experiments were developed to attempt to clarify this dilemma, but it was only until 1900 when Max Planck (1858-1947) introduced the basis of a theory that would go on to revolutionize scientific thinking, marking the beginning of modern physics: quantum theory.

Developed during the 20th century thanks to advances made by scientists such as Niels Bohr, Born, Heisenberg, Schrödinger, Pauli, Dirac, Einstein or de Broglie, quantum theory clarified that light is neither a particle nor a wave, but that it has a dual nature: it behaves like a wave as it spreads but like a particle in its interactions with matter. In this book, we will specify where necessary whether light behaves as a particle or as a wave, although in most cases we refer to rays of light, which always represent the direction of propagation of light.

What is a wave?

A wave is a disturbance that transmits energy from one point of a medium to another, without the medium itself moving noticeably. We have all seen how throwing a stone into a pond causes ripples on the flat surface of the water, which spreads in all directions in the form of waves. The wave moves via small oscillations or vibrations of the particles making up the medium, which always return to the same position they were in when the wave reached them: just as water in a pond rises and falls as a wave moves across it but does not move along with it.

Light is a specific kind of wave known as an *electromagnetic wave* because of the type of energy it carries. Figure 1.2 shows a wave in relation to distance. In other words, it shows the wave as if taking a photograph as it spreads along the horizontal axis, observing minimum values ("*valleys*") and maximum values ("*peaks*") on the vertical axis. The vertical distance from the horizontal axis to the top of the crest is known as the *amplitude* of the

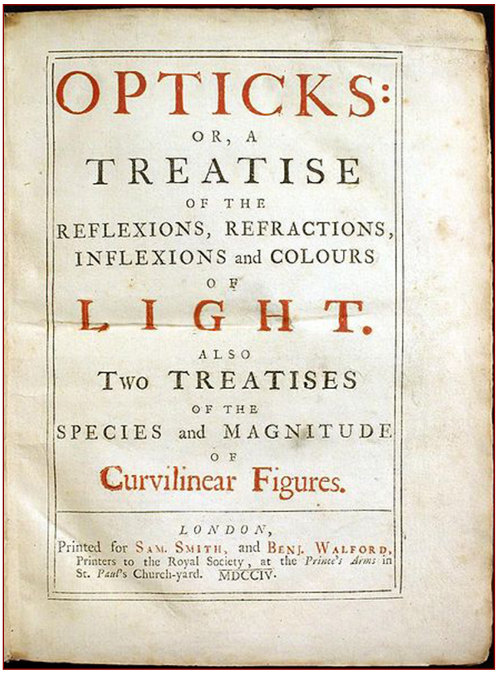

FIGURE 1.1 Cover of *Opticks, or a Treatise of the reflections, refractions, inflections and colors of light*, published by Newton (1706).

Source: Newton, Wikimedia Commons.

Did you know...?

Newton, famous for his theory of gravity, also made great contributions to optics. The title of his 1706 publication contains terms that are significant in this chapter: *Opticks: or, a Treatise of the Reflections, Refractions, Inflections, and Colors of Light (Fig. 1.1).*

wave. The greater a wave's amplitude is, the stronger its vibration, meaning that it produces greater intensity of light.

Figure 1.2 shows several of the characteristics of an electromagnetic wave: we can see that the shape of the wave is continuously repeated; this is what we call a periodic wave, which is mathematically described using the sine or cosine functions. Furthermore, we can see how the wave travels horizontally, while its vibration propagates vertically (oscillating up and down, like a spring), perpendicular to the direction of the wave. For this reason, we say that electromagnetic waves are *transverse waves*.

If we look again at the periodic shape of the wave, we can see how there are always points of vibration that "do the same"; they are at the same point of oscillation: some are at the crest; others at the valley; others on the horizontal axis (the balance point); and others at positions in between. When two particles are at the same point of oscillation, we say that they are in *phase*. Phase is normally expressed as an angle (degrees or radians). If we look at the sine or cosine functions, the values of the function are repeated every 360°, or the equivalent, 2π radians.

The distance between two consecutive particles in the same phase is always the same, regardless of the phase in question, and is known as *wavelength*. It is represented using the Greek letter λ (*lambda*). As it is a concept related to distance, its units are expressed in meters (or divisions).

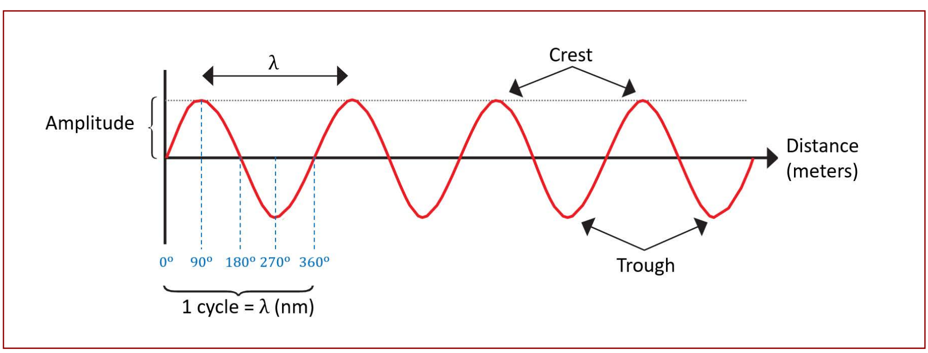

FIGURE 1.2 Representation of a wave at a specific point of travel, i.e., as if it is "frozen".

Source: Adapted from J. Donnelly and N. Massa (2007): *Light: Introduction to Optics and Photonics*.

For example, the light from green laser pointers has a wavelength of around $\lambda = 530$ nm (nm = nanometers, 1 nm = 1×10^{-9} m). A complete cycle is therefore completed when a wave is equivalent to λ meters, and the phase has evolved 2π radians (360°).

Again, we can find points on the graph that represent, in this case, the same particle in the same phase of vertical movement (e.g., on a crest). The time the vibration takes to reach that same phase on the wave again, i.e., to complete a cycle, is known as the *period*. It is represented using the Greek letter T (*tau*) and is measured in seconds (and its multiples/divisions).

Another key concept is *frequency*, defined as the number of cycles (or oscillations) per unit of time (generally one second) and, therefore, is the inverse of the period (*frequency* = $1/T$): the more oscillations per second, the greater the frequency. It is represented using the Greek letter ν (*nu*). The unit used is *hertz* (Hz), which is the inverse of the second (Hz = s^{-1}).

If we know the *wavelength* and the period of a wave, we can calculate the speed of the disturbance, or velocity. As speed is space/time, the velocity of a wave can be calculated as λ/T. The velocity of an electromagnetic wave in vacuum has a constant value of 299,792,458 m/s, or approximately 300,000 km/s. The speed of light in vacuum was officially included as a constant on the International System of Units on October 21, 1983. It is represented by the letter c, taken from the Latin word *celeritas* (*celerity* or *speed*). As a result, in vacuum:

$$c = \lambda/T = \lambda \cdot \nu.$$

One of the reasons why doubt was cast over the wave nature of light was precisely because of the way it behaves in a vacuum: if a wave requires the oscillation of material particles in order to propagate, like water in a pond when you throw in a stone, or molecules of air in the case of sound waves, how then could light waves propagate in vacuum? The answer is that electromagnetic waves propagate via the oscillation of their *electrical and magnetic fields*, hence their name, rather than via a *mechanical oscillation*, which requires the movement of matter. A static electrical charge (an electron) creates an electrical field around itself that "repels" charges of the same sign and "attracts" charges of a different sign. The electrical field created by that electrical charge does not require matter in order to propagate. When the charge oscillates, the electrical field also oscillates. That variation (disturbance) of the electrical field also affects the charges around it, i.e., that disturbance will propagate through space. This is the reason why we can perceive the light emanating from the stars, as it can travel through the vacuum of outer space, but their sounds cannot reach us, as sound waves require material particles in order to propagate.

Finally, since the early 19th century, thanks to the discoveries of Ørsted, Ampère, Biot and Savart, we know that the variation in the electrical field causes a change in the magnetic field, and vice versa. The propagation of electromagnetic waves, with their corresponding electrical and magnetic fields, was described by James Clerk Maxwell (1831-1879) through his four famous equations.

Are there different types of light? The electromagnetic spectrum

As we have seen, light is an electromagnetic wave. However, it is not difficult to imagine that there are different types of EM waves, given that, for example, we can perceive different "colors" of light, as will be seen in Chapter 4. Although color is not a physical property of light but rather an attribute created by our visual perception, the way in which our visual system perceives color is related to a physical property of EM waves: frequency (and, therefore, wavelength, if we remember that $c = \lambda \cdot \upsilon \rightarrow \lambda = c/\upsilon$). In fact, the range of electromagnetic waves that we can "see" is small; it comprises a very specific region of the EM spectrum that we call the visible region of the spectrum or the *visible spectrum*. In reality, by "light" we are referring only to the small part of the spectrum visible to the human eye, and by "radiation" we mean all types of EM waves in general.

The *EM spectrum* is the organizational "map" of electromagnetic radiation depending on its frequency or wavelength, as shown in Figure 1.3. This is because these properties define key characteristics of the different types of radiation, such as the energy with which it interacts with matter, as we will see at the end of this chapter. The greater the frequency (or the shorter the wavelength) is, the more energetic the radiation and therefore potentially more dangerous to our health.

The range of EM waves on the spectrum includes, at one end, a wavelength of kilometers (and therefore very low frequencies of hundreds or thousands of kilohertz), such as radio waves, which as a result can travel through obstacles such as buildings and mountains. As we move along the scale towards shorter wavelengths, we find microwaves, with just a few centimeters or even microns of wavelength (frequency of hundreds or thousands of megahertz), used by our mobile telephones and, more intensely, in the microwave ovens in our kitchens. Next, as we will see, we have infrared waves, with a shorter wavelength than that of microwaves.

At the other end of the electromagnetic spectrum, we find gamma rays, with the shortest wavelength (0.03–0.003 nm) and the greatest energy on the EM spectrum. These waves, which are generated in nuclear explosions, can kill live cells and are used in medicine to remove cancer cells. Then we have *X-rays*, whose wavelengths can be shorter than the distance between atoms. (0.1–0.01 nm). They therefore have quite high frequency and associated energy, meaning that in high doses they can be harmful to our health. This radiation does not naturally reach the Earth's surface, as it cannot pass through our atmosphere from outer space.

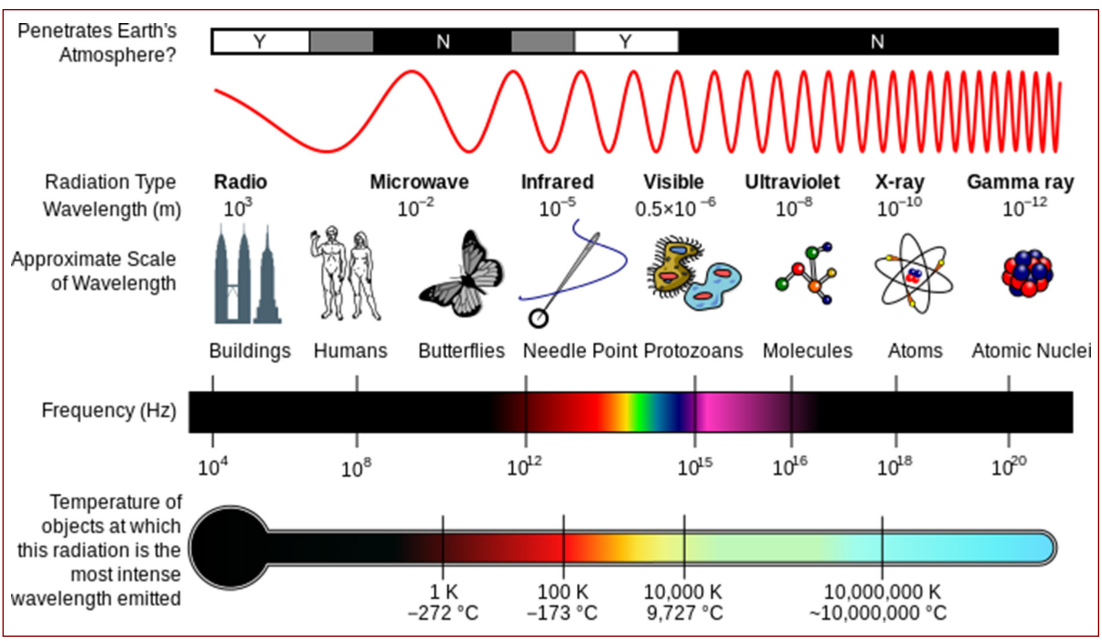

FIGURE 1.3 EM light spectrum. On the left, waves with shorter frequency (longer wavelengths), and on the right, waves with greater frequencies (shorter wavelengths).

Source: Adapted from Wikimedia Commons.

Between the *infrared radiation* (IR) that we perceive as heat and *ultraviolet radiation* (UV), which is responsible for both tanning and sunburn, we have the *visible spectrum* (VIS), the kind of electromagnetic radiation that can be detected by the human eye and whose wavelengths approximately cover the interval from 380 nm (violet) through to 440 nm (indigo), 480 nm (cyan), 530 nm (green), 580 nm (yellow), 650 nm (orange), 700 nm (red) and 780 nm (dark red).

Optics arose from the study of vision and was therefore also related to the visible spectrum, but nowadays the range of the spectrum that is studied using the laws of optics is larger, ranging from UV to near IR; the latter is extremely important in fiber optic communications. This range is sometimes called the *optical spectrum*.

How does light travel?

One of the properties of light that we can verify at first sight is that it travels in a straight line. We can confirm this, for example, in the propagation of a ray of sunlight through dusty atmospheres (Figure 1.4) or when using a laser pointer. This straight-line propagation is only observable when the medium through which the light is travelling is isotropic, i.e., it presents the same properties in all directions. When light travels through a non-homogeneous medium (e.g., air on a sunny day), it no longer does so in a straight line, and depends on the properties of the material at each point, resulting in phenomena such as mirages, as we will see in Chapter 5.

FIGURE 1.4 Rays of sunlight travelling in straight lines through the leaves of trees.
Photograph: in house.

This straight-line propagation of light has a common consequence: the appearance of shadows where there are opaque obstacles positioned between the source and the target, preventing the light from reaching its destination. The shadow created is the projection of the obstacle on the plane of the target source. If there is more than one image point, an area of penumbra is generated, as at certain points the presence of an obstacle prevents all light from getting through, while at others, only part of the light is blocked as the light from specific sources is not impeded. An interesting example of the formation of shadows and penumbra are solar and lunar eclipses, as we will see in Chapter 5.

In cases where light travels from one medium to another, some of the light is reflected, some is absorbed, and some is refracted, continuing to travel in a straight line provided that the second medium is homogeneous and isotropic. In the case of reflected and refracted light, we talk about *angles of incidence, refraction and reflection*. By common consensus, these angles are always measured in relation to the *normal* that separates the two media, i.e., a straight line running perpendicular to the surface at the point where the light meets the surface.

What is reflection?

When a ray of light meets the boundary between two different media, part of that light changes direction, returning to the first medium, at the same angle (*angle of reflection*) as the incident light (*angle of incidence*), as shown in Figure 1.5. This phenomenon is known as *reflection*. Not all materials behave in the same way: for example, metals reflect practically all the incident light (which is why they are used to make mirrors), while transparent materials reflect a lot less light (e.g., the glass in a shop window).

FIGURE. 1.5 Example of reflection in nature. The River Tormes flowing through Salamanca.
Photograph: Warein Holgado.

There are two types of reflection: *specular*, typical of polished surfaces such as mirrors (Figure 1.5), and *diffuse*, typical of rough surfaces where rays of lights are reflected in different directions, such as on wood or our skin. If we use the simile of a ball, specular reflection is like bouncing a tennis ball on a court, and diffuse reflection is like bouncing it on a stony surface.

What is refraction?

Refraction is the change in the speed of light that occurs when it travels through a medium other than a vacuum. A consequence of this change in speed is seen when light meets a surface at an angle other than zero (i.e., in a direction other than the normal). In these conditions, the light changes direction when it meets the second medium. An effect of this diversion of refracted rays is that the image of an object submerged in two different media will have different characteristics depending on the medium in which each part of the object is submerged. One example of this phenomenon is a pencil in a glass of water; it looks like the pencil is broken because the rays complete the image in a different position, depending on the refractive index of the medium they are passing through—air or water—as shown in Figure 1.6. Refraction also occurs when light passes through layers of air at different temperatures, which affects the refractive index (the cause of mirages, for example).

FIGURE 1.6 Example of how a difference in the refraction index causes a diversion of light.
Photograph: in house.

The phenomenon of refraction, illustrated in Figure 1.7, is described mathematically using a trigonometric equation known as Snell's law, which relates the refractive index of the material through which the ray of light is travelling (n_1) and the angle of incidence (θ_1) to the index (n_2) and angle (θ_2) of the material where the ray is refracted:

$$n_1 \sin(\theta_1) = n_2 \sin(\theta_2) \leftrightarrow = \frac{\sin(\theta_1)}{\sin(\theta_2)} = \frac{n_2}{n_1}$$

Snell's law tells us that refracted light bends in proportion to the difference between the indices of refraction that it encounters along the way (see **Experiment 1.1**):

- When light passes from a material with a lower refractive index to one with a higher refractive index, such as, for example, from air to water, the ray of light is refracted at a smaller angle than the angle of incidence (Figure 1.7, left), i.e., the refracted light bends away from the *normal.*
- However, when light passes from a larger index to a smaller one, e.g., from water to air, the ray of light bends at a greater angle than the angle of incidence (Figure 1.7, center), i.e., the refracted light bends towards the normal.
- In this case, as the angle of incidence increases, a point is reached in which the light is not refracted, but travels parallel to the surface (*angle of refraction* = 90°). This angle of

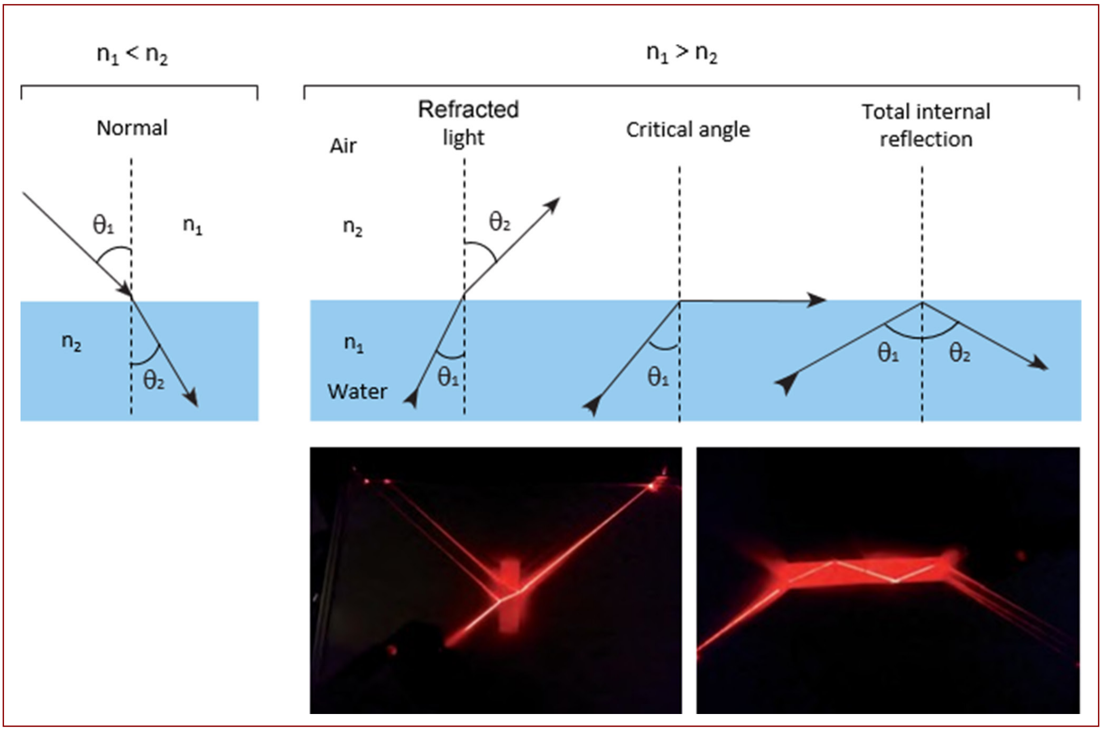

FIGURE 1.7 A ray of light passing from one material to another with a different refractive index changes direction of travel. When $n_1 > n_2$ and the angle of incidence reach a critical angle, the rays are not refracted, but fully reflected. These photographs illustrate these two situations, refraction and full reflection.

incidence, the point at which for the first time there is no refracted beam, is called the critical angle, θ_1 and it depends on the index of refraction of the media: $\sin(\theta_{crit}) = n_2/n_1$. For example, the value of the critical angle for water and air is

$$\theta_{crit} = \arcsin\left(\frac{1}{1.33}\right) = 37^{\circ}$$

For incident light with an angle greater than the critical angle, there is *total reflection* on the surface of the material: there is no refracted light; it is all reflected. For smaller angles of incidence, only part of the light is reflected (and part is refracted).

- As we have already mentioned, where light is travelling perpendicular (normal) to the surface (zero angle of incidence), it will not bend.

What is the refractive index?

Have you ever tried to run underwater? We find it harder to move in water than when we are out in the air, as usual. This is because of the *resistance* of the medium we are moving through. In the case of light, the way it travels is also affected by a change in medium. So, the speed at which light travels through a medium other than vacuum depends on the *refractive index* of the specific material it is travelling through. The refractive index is a number that indicates how the speed of light is reduced when travelling through a certain medium other than vacuum. It is represented using the letter n, and it depends on the properties of the material that affect the movement of light through it, such as electrical and magnetic properties, or the density of the material in question. The speed at which light travels through a medium is equal to

$$c_{material} = \frac{c}{n_{material}}$$

Therefore, the refractive index of vacuum is 1.

What is dispersion?

We have seen how the refractive index depends on the properties of the material. However, we have not yet mentioned that it also depends on the wavelength of the incident light: the shorter the wavelength is, the greater the refraction. So, the index of refraction increases as wavelength decreases, which, if we apply Snell's law, means that shorter wavelengths (such as those corresponding to blue light) are refracted at a greater angle than longer wavelengths (the color red at the opposite end of the visible spectrum). This phenomenon is known as *chromatic dispersion*, and it is responsible for the rainbow effect we see when white light (the combination of all wavelengths on the visible spectrum) diagonally passes through drops of water or when a beam of white light passes through a *prism*, as shown in Figure 1.8 (see **Experiment 1.2**).

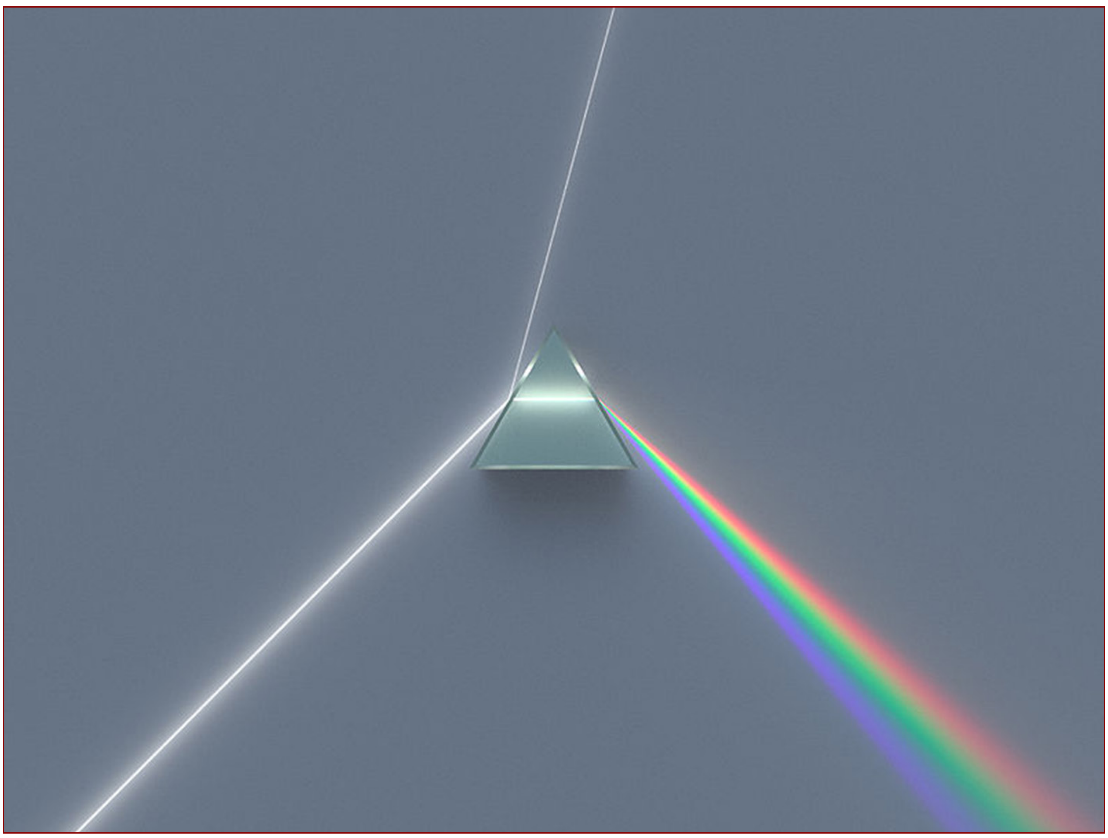

FIGURE 1.8 Chromatic dispersion of a beam of white light passing through a prism.

Photograph: Spigget, Wikimedia Commons.

FIGURE 1.9 View of an object through sunglasses.
Photograph: in house.

Did you know...?

Sunglasses are made from materials that absorb visible light and reduce its transmission. They also have a special filter to protect our eyes from ultraviolet radiation. These filters are usually covered with fine layers made from minerals to reflect the radiation. Other types of sunglasses use organic filters that are also very effective, although their mechanism of action is different.

What is absorption?

Absorption is the process via which the energy in any EM wave is captured by matter. All materials absorb some kind of radiation in part of the spectral range, and that energy can be emitted in the form of new radiation or transformed into another type of energy, such as heat or electrical energy. Materials that can absorb across the entire range of visible light are opaque, while materials that do allow that range of wavelengths to pass are considered transparent.

The colors of everything we see depend on this process of absorption and re-emission, as we only see the light that reaches our retina. So, a white object is one that reflects all types of visible radiation, while a black object is one that absorbs all visible light. This is one of the reasons why in summer we avoid wearing black. Interestingly, a green object absorbs all wavelengths except that of green, which is why we see that color. In **Experiment 1.3**, we will see the importance of sunscreen for our skin to avoid damage from harmful ultraviolet rays.

What are the wavelike properties of light?

We will now describe some phenomena associated with the wavelike behaviors of light, in particular the following three properties: interference, diffraction and polarization.

Interference

Although you may not have realized, you are bound to have seen at one time or another an interference pattern: typically, this is a series of stripes, sometimes colored (illuminated with white light) or in a single color (illuminated with a laser), alternating bright and dark stripes.

Does that sound familiar? You have surely seen something similar on the surface of soap bubbles or patches of oil on a wet road. These stripes are caused by light wave interference.

Interference takes place when two or more electromagnetic waves overlap (are at the same place at the same time), giving rise to a new wave, which is the algebraic sum (considering the sign) of the overlapping wave. However, we do not see stripes every time light hits the surface, because specific conditions also need to be met, e.g., the overlapping waves must have the same wavelength and vibrate in the same direction.

The brightest stripes seen in the pattern, regardless of color, are called interference maxima and appear when the two overlapping waves coincide at their highest (crests) and lowest points (troughs), forming a new wave with an amplitude equal to the sum of the amplitudes of the initial waves. In this case, the two waves are said to be in phase, and they give rise to a *constructive interference* (Figure 1.10, left).

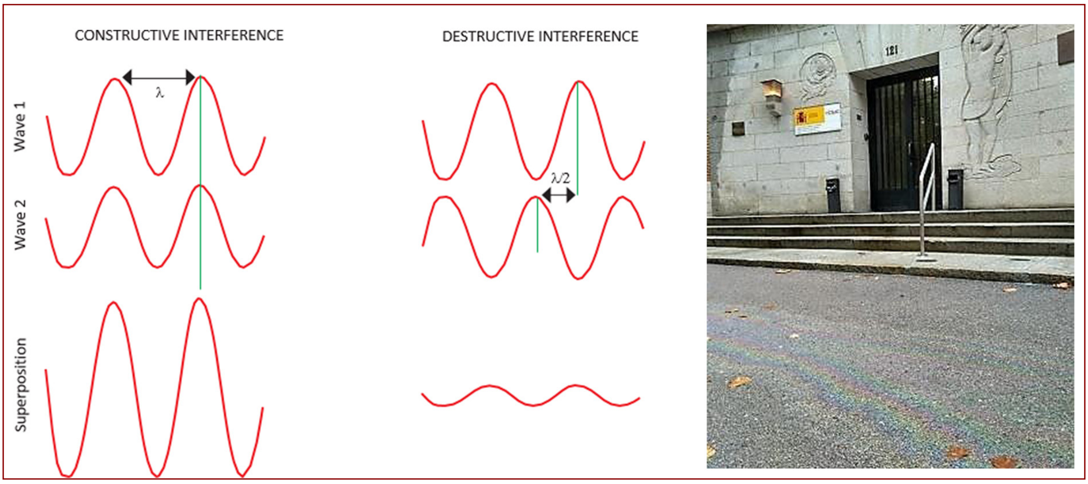

FIGURE 1.10 Pattern of constructive and destructive interference of two waves (left). Patch of petrol on a wet road (right).
Source: Internally created. Photograph: in house.

FIGURE 1.11 Aerial view of the Virgo interferometer near Pisa, Italy, showing the Mode Cleaner, the main building, the 3-km western arm and the beginning of the northern arm.
Source: The Virgo Collaboration, Wikimedia Commons.

Did you know...?

An interferometer is an optical instrument that uses the interference of light waves to precisely measure tiny variations in the space covered by two waves. In 2016, the Laser Interferometer Gravitational-Wave Observatory (LIGO) allowed us to discover gravitational waves, which had been predicted by Einstein based on his theory of relativity in 1915.

The darker stripes in the pattern are called *interference minima*, and they appear when the maxima of one of the overlapping waves coincides with the minima of the other (i.e., the opposite of in phase). In this case, *destructive interference* is created. The resulting wave has an amplitude equal to the difference between the amplitudes (Figure 1.12, right), i.e., a faded wave (see **Experiment 1.4).**

Diffraction

So far, we have talked about how light travels in straight lines. However, in certain circumstances, light can "go around" the edge of objects, travelling beyond obstacles in its path. This property is called *diffraction*, and it is an exclusive property of waves that allow us, for example, in the case of sound waves, to hear people in another room despite not being right outside the door; it is also the reason why in photographs taken at night, spots of light (street lamps, stars) appear with spikes of light, generated by diffraction through the slits in the camera shutter.

Huygens explained this phenomenon in the 17th century, considering that each of the points making up a wavefront (points in phase) acts as a small emitter of secondary waves with the same wavelength as the initial wave, forming part of the same wavefront. As the wave advances, the new wavefronts are formed by the wave envelope.

When a wavefront meets an obstacle, part of the light is blocked (absorbed or reflected), and part has its propagation altered as it passes along the edges of that object. It is like a crowd of people that can only pass through a single door. Once everyone has passed through that door one by one, they can then freely move forward in all directions. This is known as diffraction, and it occurs in any type of wave (light, sound, etc.) As this wavefront passes close to the edge of the object, new wavefronts are formed. In the early 18th century, Fresnel adapted Huygens' principle to explain that if the waves are coherent, they overlap after passing the obstacle, creating a pattern of interference that is characteristic of diffraction. This is what is known as a *diffraction pattern*, and it is made up of a set of light and dark stripes, as shown in Figure 1.12 in the case of a small gap. You can see this effect for yourself by forming a small slit with your fingers and looking at a light background through them (see **Experiment 1.5**).

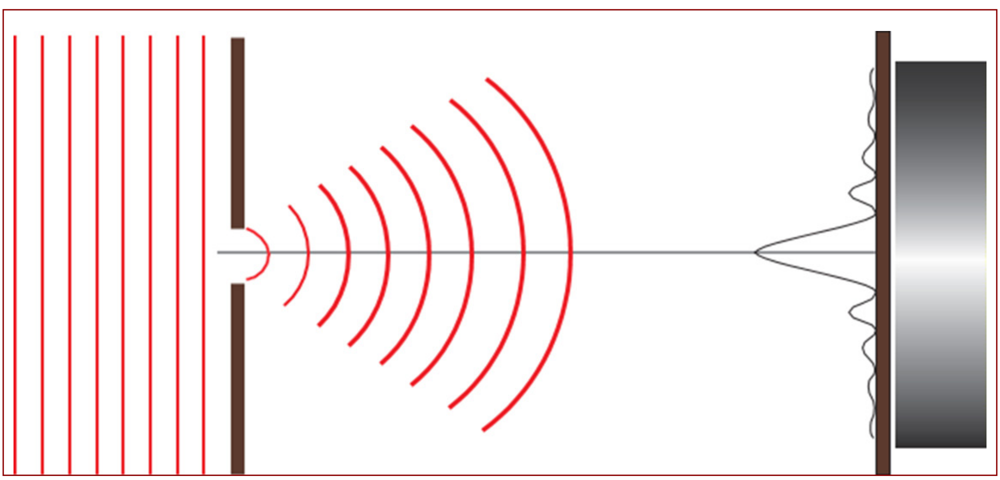

FIGURE 1.12 Diffraction of a wavefront through a small aperture. On the right, the diffraction pattern (distribution of light intensity) is formed after passing through the aperture.

Source: Internally created.

In the particular case of a metal sheet with two small holes or slits, known as Young's double slit experiment, performed in 1801 and explained in the early 20th century using quantum mechanics, the original wavefront gives rise to two new fronts, one "emerging" from each of the slits (see **Experiment 1.6**). This is like a crowd of people having two doors to go through rather than one. As they travel, these two fronts interfere with each other, forming a pattern of interference. So, we can see how the phenomena of diffraction and interference are closely related.

Polarization

As we have already mentioned, EM waves are transversal, i.e., the magnetic and electrical fields created by the wave oscillate perpendicular to the direction in which they are travelling. For simplicity, we will only represent the oscillations of the electric field (E). Depending on the direction in which the electrical field oscillate, we can define:

- *Polarized light:* we say that an EM wave is polarized when its electrical vector oscillates in an "orderly" fashion, i.e., not at random. Depending on the shape formed by the oscillations of the electrical field as the wave moves, we can define different types of polarized light: in the case of linear polarized light, the electrical field oscillates along a line, hence the name. To get the idea, it is as if we—representing the oscillations of the electrical field—were to jump up and down while moving somewhere; then we could say that "our wave" is vertically polarized. If, however, the person next to us jumps left to right as they move forward, "their wave" is horizontally polarized. The oscillation (up-down or right-left in this example) is known as the *plane of polarization*. The wave that we normally represent, like in Figures 1.2 or 1.3, is a linear polarized wave that oscillates vertically (at 90°), although in reality there are linear polarized waves at all possible angles (at 180° (horizontal), at 30°, etc.). In addition to the linear polarized light, we find other types of polarized light, circular and elliptic, where the electrical field oscillations change direction as the wave progresses, creating a circle and an ellipse, respectively. In this book, we are only going to look at linear polarized light, so where we refer to *polarized* light, this refers to *linear* polarized light.
- *Non-polarized light or natural light:* the majority of the light around us, coming from the sun or artificial sources, such as lightbulbs, is non-polarized. This means that the oscillations of the electrical field are in random directions (although they always remain perpendicular to the direction of travel) and change as the wave progresses. In the above example, it is as if we were jumping up, to the right, to the left to the right, diagonally, downwards, etc., in random order.

Although most of the light around us is non-polarized, there are different physical phenomena that can polarize it:

- *Polarization by absorption:* just as we can use color filters to select a single wavelength by absorbing the other wavelengths in white light, we can also use linear polarized filters (Figure 1.13) that only allow through waves vibrating in a certain direction, what is known as the *transmission axis of the polarizer*, absorbing the waves that vibrate in any other direction. In **Experiment 1.7**, we will block or let through light using linear polarizers.
- *Polarization by reflection:* light reflected on a non-metallic surface, such as water or glass, is at least partially polarized in the parallel direction to the reflective surface.

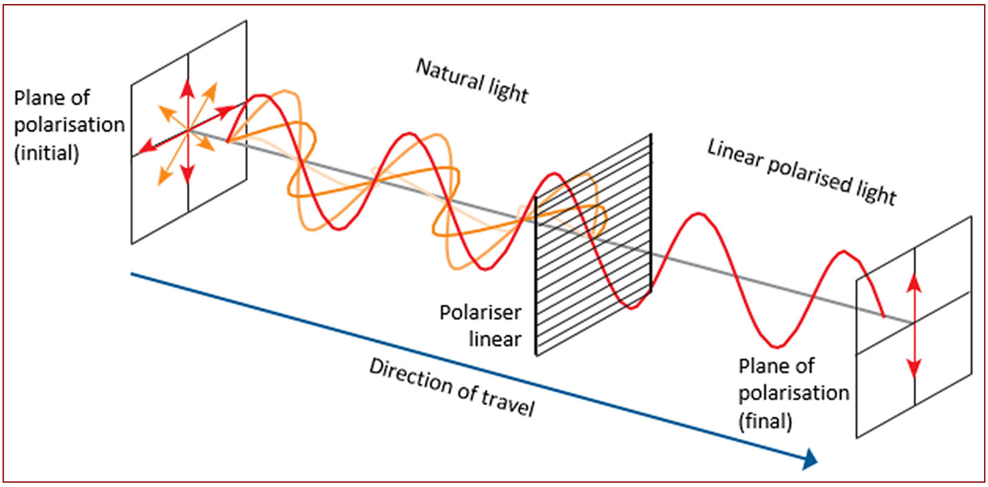

FIGURE 1.13 Diagram showing the effect of a linear polarizer on a source of natural light (non-polarized).
Source: Internally created.

FIGURE 1.14 Polarized sunglasses against a screen. Depending on the angle of the lenses, the polarized light from the screen can pass through or it is blocked.
Photograph: in house.

Did you know…?

If you put on a pair of polarized sunglasses and look at your phone from a diagonal (45°), you can't see anything. Try it for yourself. This is because of the light and the polarizing filters that many mobile telephone screens are filtered with. Note that this does not work with Apple devices such as iPhones, as they do not emit linearly polarized light.

Only when light meets the reflective surface at a certain angle, known as Brewster's angle (θ_B) and which depends solely on the refractive indices of the media on either side of that surface, is polarization total. Because the reflected light is polarized, we can block it using a polarizer on the axis perpendicular to the reflective surface, so that we can only see the light that is transmitted (rather than reflected). This is the optical principle that allows us to see the bottom of a shallow pool using polarized glasses.

FIGURE 1.15 Diffraction in nature as waves of water pass through a small gap in a natural dam. Three Fathoms Cove, near Yong Shue O, Tai Po, Hong Kong.

Photograph: Lorenzarius, Wikimedia Commons.

Did you know…?

We find diffraction in electrons as well as in nature. A beam of electrons diffracts when it interacts with the atoms in a material, providing us with information on the atomic structure of that material. So, as predicted by the winner of the Nobel Prize for Physics Louis de Broglie in 1929, particles—such as electrons—can also behave like waves.

- *Polarization by birefringence* (or double refraction): birefringence is a property of certain materials with different refractive indices depending on the direction in question (they are anisotropic). This means that when a ray of light passes through the material, depending on the direction of incidence it may be affected by two different refractive indices, which we call *ordinary* (n_o), if it affects two of the three directions inside the crystal and *extraordinary* (n_e) if it affects only one direction. This results in a "double refraction": the incident light divides into two, each with different polarization and travelling at a different speed. If we recall Snell's law, the *angle of refraction* depends on the refractive index, which means that each of the rays of light will follow a different path, depending on the refractive index it encounters along the way. Some materials that are isotropic under normal conditions (and therefore not birefringent) can become birefringent under tension or force. This phenomenon is known as *photoelasticity* or the *photoelastic effect*. If the tension or force is not applied evenly, then the birefringence caused by the photoelastic effect will also be uneven. If we place the material between two crossed polarizers, we will see stripes showing the areas of the material under different mechanical tension in different colors. These colors observed in the tension pattern are due to the fact that birefringence depends on wavelength (as it is related to refractive indices); see **Experiment 1.7**.

The photon: light as a particle

At the end of the 19th century, just a few phenomena remained to be explained in the field of what we now call "classical" physics, relating to optics: although the wave theory of light was broadly accepted as it satisfactorily explained most of the phenomena observed (such as the double slit experiment by Young), this theory could not explain the photoelectric effect and *blackbody radiation*.

The photoelectric effect, discovered in an experiment by Heinrich Hertz (1857-1894) in 1887, consists of the emission of electrons when light hits a metal. The explanation for this phenomenon is that light provides electromagnetic energy to the electrons in the metal, and when this energy reaches a certain level, they can "leave" the metal; this is why we say that the metal emits those electrons. However, the emission of electrons, instead of depending simply on the intensity of the light hitting the metal, depends on the wavelength of that light. For example, certain metals would emit electrons under UV light but not under red light (greater λ), despite the intensity of the red light being several times greater than that of UV light.

Albert Einstein (1879-1955) put forward a theory to explain this effect in 1905, for which he was awarded the Nobel Prize for Physics in 1921: the light that hits the metal is not a wave with a continuous supply of energy but rather a flow of particles that were named *photons*. The energy in each photon is directly proportional to its associated frequency of radiation and is therefore greater in photons of UV than in red light, as the frequency of UV light is much greater (and its wavelength much shorter); see **Experiment 1.8**.

The main applications of the photoelectric effect include the photovoltaic effect, well known for its use in the manufacturing of photosensitive cells for the generation of renewable energy from sunlight. These devices transform solar energy into electricity by "exciting" electrons as they absorb the energy from photons. The first solar cell was made by Charles Fritts (1850-1903) in 1884.

So, what is a photon?

A photon is an elementary particle; the minimal part into which a ray of light can be divided while still maintaining its properties: energy, frequency and wavelength. It makes up the quantum unit of light energy. Photons are massless, and their (indivisible) energy is proportional to the associated electromagnetic wave frequency. The energy of a photon is equal to $h\nu$, where h is the so-called Planck constant—named after the German physicist who discovered the relationship in the year 1900—and ν is the oscillation frequency.

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1.1 Experiment

Does Light Travel in a Straight Line?

30 min (+)

Refractive index, invisibility, refraction

OBJECTIVES:

Objective 1: Understand the concept of refractive index.
Objective 2: Observe the direction of light as it passes from one material to another.

MATERIAL

- Transparent bowl
- Water
- Ethyl alcohol (ethanol)
- Olive oil
- Empty glass container (jar)
- Colourless hydrogel beads
- Low-power laser pointer (<1 mW)
- Spoon

On partially cloudy days we can see how sunlight passes more easily through the spaces where there are no clouds or where the clouds are less dense. In these cases we can see beautiful scenes where the light streams through different areas in straight lines that we call *rays* of light.

In this experiment, we will learn the importance of the optical properties of materials in the propagation of light.

FIGURE 1.1.1 Sunlight streaming through clouds.
Photograph: MarcoRoosink, Pixabay.

Procedure

Before the experiment: hydrate the hydrogel beads

Fill a bowl with water. Place 20–40 dry hydrogel beads in the bowl. The beads take at least 2 hours to be completely hydrated.

Experiment with hydrogel beads

1. Once the beads are fully hydrated, note that they are invisible in the bowl. Put your hand in the bowl to check that they are still in there (Figure 1.1.2).
2. Shine a laser beam from one end of the bowl and observe the direction of travel of the light.
3. Remove the water from the bowl, leaving just the hydrated beads. Repeat the previous step, shining the laser at the bowl from some distance (at least 2 meters). Make sure that everyone watching the experiment is positioned behind the laser beam.

FIGURE 1.1.2 Hydrated hydrogel beads. Laser beam shining through the bowl with hydrogel beads.
Photograph: Eliezer Sánchez González/Cultura Científica (CSIC)/IOSA.

Column with different liquids

1. Pour approximately two fingers' depth of water into the glass jar.
2. Now pour more or less the same amount of olive oil as water, then hold the spoon over the surface of the oil and pour the alcohol over it until you have a similar depth layer to the other two. You have created a tower of different liquids (Figure 1.1.3).
3. Point the laser through the column of liquids at an angle of about 45° and observe what happens (Figure 1.1.3).

FIGURE 1.1.3 Pouring liquids into the clear glass jar. Column of three liquids and refracted red laser.

Photograph: Eliezer Sánchez González/Cultura Científica (CSIC)/IOSA.

Explanation

In this experiment, we have seen the importance of a fundamental property of materials: their refractive index. Their different refractive indices cause the light to refract, making the rays of light change direction.

The hydrogel beads become invisible when submerged in water and visible when surrounded by air. This is because, once hydrated, their refractive index is practically the same as that of water (n = 1.33), and therefore there is no difference in index and no change in the propagation of the light. We do see reflection and refraction when we remove the water from the bowl, as the beads are now surrounded by air (n = 1). The change in direction of travel is also seen in our column of liquids, as they have different refractive indices.

According to Snell's law, we can theoretically calculate the refraction phenomena that we have observed. Specifically for the column of liquids we used: the refractive index for water n_{water} = 1.33; for olive oil n_{oil} = 1.47; and for ethyl alcohol $n_{alcohol}$ = 1.36; and an angle of incidence of θ_1 = 45°:

$$\textit{Air-alcohol: } n_{air} \cdot \text{sen } \theta_1 = n_{alcohol} \cdot \text{sen } \theta_2 \rightarrow \theta_2 = 31.3$$
$$\textit{Alcohol-oil: } n_{alcohol} \cdot \text{sen } \theta_2 = n_{oil} \cdot \text{sen } \theta_3 \rightarrow \theta_3 = 28.8$$
$$\textit{Oil-water: } n_{oil} \cdot \text{sen } \theta_2 = n_{water} \cdot \text{sen } \theta_4 \rightarrow \theta_4 = 32.1$$

You can repeat the experiment with a different initial angle θ_1 and use these same equations to obtain the corresponding θ_2, θ_3, θ_4

Tips

- You can do a similar invisibility experiment by filling the bowl with sunflower oil and then adding something made from Pyrex glass. The refractive indices are very similar, so we can make the Pyrex "disappear" by placing it in the oil.
- To see the path of the laser beam more clearly through the alcohol and the water, add a drop of milk to the water and a drop of ink to the alcohol before pouring them into the jar.

Review of what we have learned

- Why do the hydrogel beads become invisible in water?
- How can we see if the refractive index of ethyl alcohol is lower than that of sunflower oil?

Related experiments

Experiment 3.4 Micro-lenses: beyond a magnifying glass
Experiment 5.1 Is everything we see real?

Breaking Light: Newton's Prism

50 min (+) Refraction, electromagnetic spectrum, frequency, speed of propagation

OBJECTIVES:

Objective 1: Build a prism with glass microscope slides and "decompose" white light into colors using the water-glass prism.

Objective 2: Use a converging lens to "join" the spectrum of colors obtained with the prism.

MATERIAL

- Glass microscope slides (x4)
- Hot glue gun or Superglue.
- Water
- Source of white light
- Black and white card
- Cylindrical converging lens

In an era of great, revolutionary scientific discoveries, Isaac Newton was one of the first to understand why white light broke down into colours.

In his experiment, Newton used triangular glass prisms and passed a beam of white light through one of them. The result was the formation of a continuous spectrum containing all the colors from red to violet. Once the spectrum of colors had formed, Newton proved that a second prism could "join" them back together to form white light again. This simple experiment proved that prisms do not add color to light, as many people believed, but rather broke white light down. In this experiment, we will reproduce Newton's experiment with our own prism, and using a cylindrical converging lens, we will blend all the colors back into white, so let's get to it!

FIGURE 1.2.1 Isaac Newton completes his prism experiment (*experimentum crucis*) in his room at Woolsthorpe Manor.

Illustration : Sascha Grushe.

Procedure

1. Using the adhesive (hot glue or superglue), join the longest edges of three glass slides. This should form a triangular shape from the short end (Figure 1.2.2).
2. To make the base of our prism, use a fourth slide and stick the triangular structure to it. It is important that the base is firmly glued along all its edges. Apply enough glue and allow to dry for 10 to 20 minutes.
3. Next, fill the prism structure with water. IMPORTANT: Keep an eye out for leaks! If any water is leaking, the best thing to do is empty the prism, let it air dry and go over all the edges again with glue. If the water doesn't leak out from anywhere, your home-made prism is ready! Now try it out.

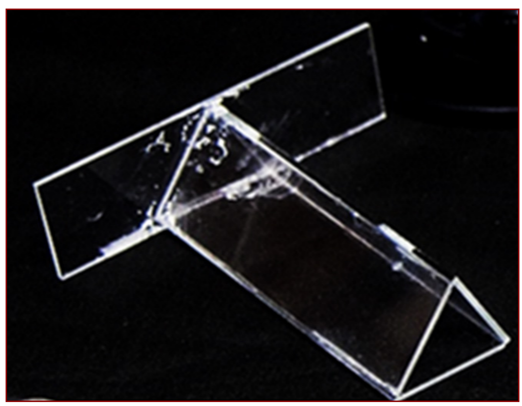

FIGURE 1.2.2 Image of the four glass slides forming a prism.

Photograph: Eliezer Sánchez González/Cultura Científica (CSIC)/IOSA.

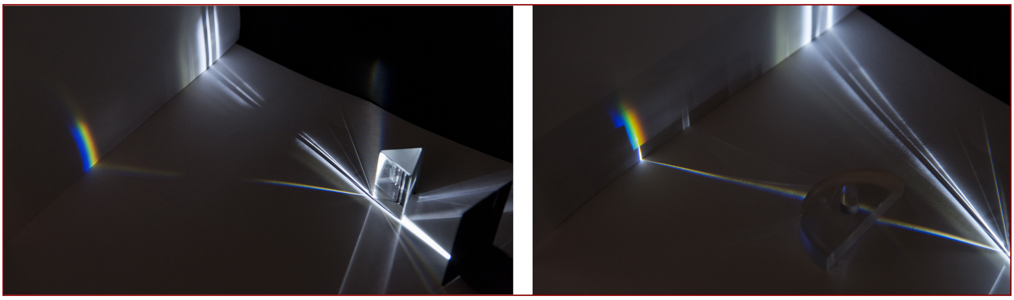

FIGURE 1.2.3 Obtaining the color spectrum with a prism and a source of white light (left), and the colors joined back together to form white light using a converging lens (right).

Photograph: Eliezer Sánchez González/CulturaCientífica (CSIC)/IOSA.

4. Use a source of white light, preferably in the form of a beam. This can be done by making a screen from a black card with a small slit in the center to let the light through. If you move the screen away from the source of the light, the beam will pass more evenly through the slit, although it will be less intense. At this point, it is best to do this experiment in a darkened room.
5. Next, place the prism in the path of the beam and turn it until the light is refracted into the colors of the rainbow (Figure 1.2.3, left).
6. Use another screen from a white card to see the rainbow. Try different distances until you achieve a wide, uniform rainbow.

Once you have it, can we turn it back into white light? Let's try using a converging lens by placing it between the prism and the screen (Figure 1.2.3, right). Is it possible or not?

Explanation

The amount of light refracted is generally expressed in terms of its angle of deviation. This angle is the difference between the angle of incidence of the light on the prism and the emerging beam. In our case, when the light passes from air to glass and then into the water, its speed drops and, as it leaves the prism, returns to its original speed. This is mainly due to the difference in refractive index of the material making up the prism and the medium around it (in this case, air).

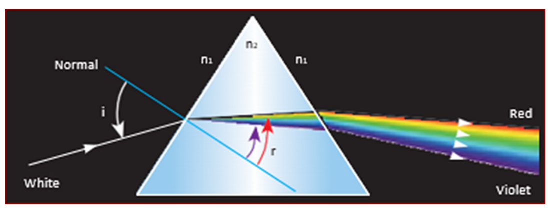

FIGURE 1.2.4 Diagram of the breakdown of light in a prism.

Source: Internally created.

Depending on the wavelength travelling through the material, there will be a characteristic refractive index associated to that wavelength, meaning that colors with shorter wavelengths (blue) have a greater refractive index and, therefore, "bend" the angle of incidence more than colors with a longer wavelength (such as yellow, orange and red). A converging lens is one where parallel rays hitting one of its sides will converge towards a single point. When we focus the rays of color emerging from a prism to a single point, the opposite effect to that of the prism is achieved: the colors are joined together again in one, producing a ray of white light.

Tips

If you build your prism using superglue, the edges will have a more precise finish, allowing you to see the spectrum obtained from white light more clearly.

Review of what we have learned

- Why don't we see the breakdown of colors when we look through a window, which is made of glass?
- What about the wavelengths that our eyes cannot detect? Does the same thing happen to ultraviolet and infrared radiation?

Related experiments

Experiment 2.1 Build your own spectroscope
Experiment 2.5 Beyond the visible: IR radiation
Experiment 5.6 Artificial sunset: the scattering of light in our atmosphere

1.3 Experiment

How Does Sunscreen Work?

20 min (+)

Absorption, reflection ultraviolet, sunscreen

OBJECTIVES:

Objective 1: Check the effect of ultraviolet light using beads sensitive to this kind of light.
Objective 2: Assess the efficacy of our sunscreen.

MATERIAL

- **Sunscreen with different factors [8, 30, 50 and 100 SPF-(Solar Protection Factor)]**
- **Oil with different sun protection factors**
- **Ultraviolet-sensitive beads**
- **Clear plastic bags**
- **Ultraviolet lamp or sunlight.**

The solar spectrum does not have a specific color and is called "white light"; however, it is made up of a combination of different colors: seven visible colors (red, orange, yellow, green blue, indigo and violet) and two ranges of colors invisible to the human eye, infrared and ultraviolet. Exposure to ultraviolet light (UV) can have a harmful effect on our skin. One of form of protection is sunscreen, which, depending on its composition, can absorb or reflect the harmful radiation.

In this experiment, we use UV-sensitive beads to check the efficacy of different sunscreens and understand how they work.

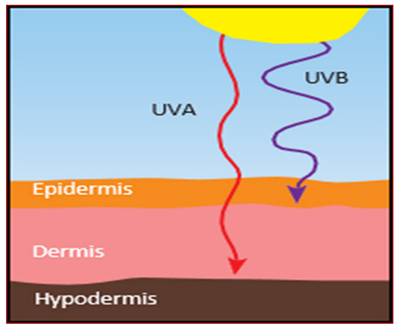

FIGURE 1.3.1 Types of ultraviolet radiation and their penetration into the skin.

Source: Internally created.

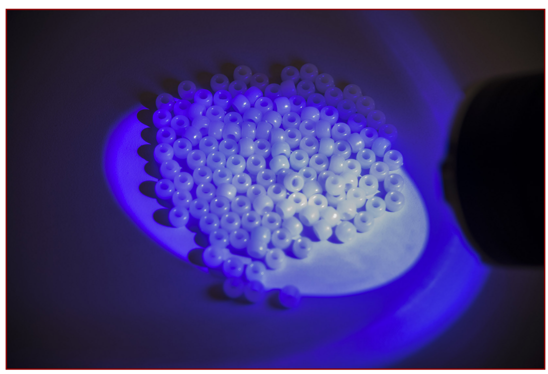

FIGURE 1.3.2 Lighting the beads with an ultraviolet lamp, without sunscreen (not placed inside a bag).

Photograph: Eliezer Sánchez González/CulturaCientífica (CSIC)/IOSA.

Procedure

1. Start this experiment in a room where there is no direct exposure to sunlight and divide the UV-sensitive beads into different bags.
2. Separate some of the beads to use as an example and then compare them with the ones under the use of different sunscreens.
3. Label the other bags with the different SPFs you are using, e.g., Bag 1 = SPF 30, Bag 2 = SPF 50, Bag 3 = 90 SPF.
4. Now apply a layer of sunscreen to each of the labelled bags. Make sure that the edges of the bag are also covered, as radiation could get in through any exposed areas, and the desired effect would not be achieved.
5. Wait a few minutes for the solvents in the sunscreen to evaporate.
6. Use the camera on your phone to take a picture of the labelled bags and the blank beads (as they have not yet been exposed to sunlight or the UV lamp).

7. It's time to run the test! You need to expose all the bags to sunlight (or to the ultraviolet light from the lamp), then wait a few seconds to see which beads change color and how, as shown in Figure 1.3.2.
8. At this point, compare the color of the exposed beads with the ones inside the bags covered with sunscreen.
9. That's it! The beads that have changed less in color are the ones with the most effective sunscreen (SPF 90), as shown in Figure 1.3.3.

FIGURE 1.3.3 On the left, beads in plastic bags with different sunscreens as labelled. On the right, the control beads with an intense color.

Photograph: Eliezer Sánchez González/Cultura Científica (CSIC)/IOSA.

Explanation

The maximum solar protection is obtained with an SPF of 50+ and gradually lowers right down to bronzing lotions of under SPF 10. In the case of our experiment, the "control" beads without sunscreen protection will change color by almost 100%, while the others will change less the higher the protection factor is of the sunscreen applied to the plastic bag.

There are two ways in which sunscreen protects our skin from the UV radiation that reaches it: reflection or absorption. Mineral protectors reflect ultraviolet radiation, due to the titanium and zinc particles that remain on the surface or the skin; these are therefore suitable for sensitive skins affected by dermatitis, rashes or allergies. These sunscreens do not have a minimum time before they become effective, as the skin does not need to absorb them. Organic sunscreens, meanwhile, made from oils and carbon-based molecules act by absorbing ultraviolet solar radiation. They capture the incident energy and re-emit as thermal radiation, which is harmless for the skin. In this case, organic sunscreens need around 30 minutes to become effective, so they need to be applied some time before sun exposure. Depending on the radiation absorbed, there are filters for UV-B, UV-A and broad-spectrum filters; the latter are the best.

Tips

- If you have two types of sunscreen (mineral and organic) with the same SPF, you can do a further experiment to see if one works better than the other (Figure 1.3.4).
- To increase the effect of the experiment, you can remove the violet, blue and pink beads, as they will change color with the visible part of the solar spectrum.
- Dilute a cream with a certain SPF (50, for example) by half. Check to see if it has the same protective effect as a cream with SPF 25.

FIGURE 1.3.4 Two different types of sunscreen, oil-based and mineral.

Photograph: Eliezer Sánchez González/Cultura Científica (CSIC)/IOSA.

Review of what we have learned

- Could we look straight at the sun if we were wearing UV-filter sunglasses?
- Is it true that wearing sunscreen stops the skin from synthesising vitamin D, which is essential for our bodies?

1.4 Experiment

Is Light Really a Wave?

20 min (+)

Interference, thin film, iridescence

OBJECTIVES:

Objective 1: See the wave-like nature of light by creating and observing the phenomenon of interference.

Objective 2: Relate the phenomenon of interference to the thickness of the thin film and the wavelength of the light.

MATERIAL

- Glass microscope slides (x2)
- Flashlight
- Colored transparent paper (red cellophane, for example)
- Transparent circular lid (e.g., from a tub of candy or chips)
- Double-sided adhesive tape
- Liquid soap
- Plastic straw

Light is a fundamental element in our daily life; however, it is difficult to explain the wave–particle duality that defines it and even more difficult to see it. So, how can we really see how light behaves like a wave?

In this experiment, we will discover the wave-like nature of light by observing the phenomenon of interference and the different patterns it creates.

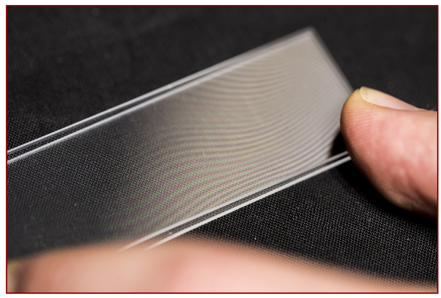

FIGURE 1.4.1 Procedure for observing interferences with two glass slides and white light.

Photograph: Eliezer Sánchez González/Cultura Científica (CSIC)/IOSA.

Procedure

Interferences with two pieces of glass

1. Place the two slides on a dark surface, one on top of the other, taking care not to leave fingerprints on the surface of the glass (Figure 1.4.1).
2. Place the colored cellophane over the flashlight. Switch on the flashlight and position it half a meter over the glass slides. Switch off all other lights.
3. Press down on one end of the top slide.
4. Repeat the experiment without the cellophane, i.e., using white light (Figure 1.4.1).

Interferences with soap bubbles

1. Stand the flashlight upright and use a small piece of double-sided adhesive tape to stick the transparent circular lid over it (Figure 1.4.2).
2. Make up a mixture of soapy water and put some onto the circular lid using a spoon.
3. Use a straw to blow bubbles. Blow gently over the soapy mixture.
4. Next, switch on the flashlight and switch off all other lights. You will see colors forming and moving.

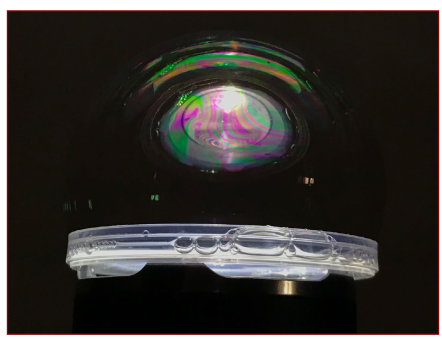

FIGURE 1.4.2 Procedure for observing interferences in soap bubbles.

Photograph: in house.

Explanation

The stripes we see when using a single color (with the cellophane in front of the flashlight) are caused by constructive and destructive interferences between two waves travelling in different directions. These two waves are formed when the light from the flashlight is reflected off two different surfaces. Reflections occurs on each of the surfaces between the glass slides, which are slightly separated when pressing the top slide at one end (Figure 1.4.3).

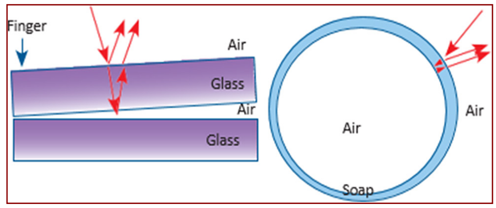

FIGURE 1.4.3 View of the forming of reflective waves, each on a different surface, creating the constructive and destructive interferences.

Source: Internally created.

Given that the top slide rises more where we are not pressing it, the path followed by the wave reflected on the second slide is different, depending on the position, which creates alternative construction and destructive interferences as it interacts with the other wave.

When using white light, we still see stripes, but they are different colors. This is because the constructive interferences for the different colors are produced for different thicknesses. This effect is also seen on the bubbles, as the thickness of the soapy layer is not even and also varies over time, making the colors "move".

In the soap bubble, the difference in the path followed by the second reflected wave compared to the first, assuming the incidence is normal, is

$$\text{Path difference} = 2 \times \text{bubble thickness} \times \text{refractive index of the soap bubble}$$

The constructive interferences occur when the maximum and minimum of the two waves coincide. This means that there is no gap, despite them following different optical paths. This happens when the difference in optical path is equal to the wavelength (λ) or a multiple thereof:

$$\text{Constructive interference} \rightarrow \text{path difference} = \text{multiple of } \lambda$$

So, when we see constructive interference of a color, we can find the relation to the thickness of the bubble:

$$\text{Bubble thickness} = \text{multiple of } \lambda \,/\, (2 \times \text{refractive index of the soap bubble})$$

For example, if we consider bubbles are primarily made of water (index $n = 1.3$) and we can see green colors ($\sim\lambda = 520$ nm) on the surface, the thickness of the soap in this case could be 200, 400, 600 nm, etc. However, if the surface of the bubble looks red ($\sim\lambda = 650$ nm), the thickness of the soap could be 250, 500, 750 nm, etc. This explains why we see different colors in different positions on the bubble where the thickness varies.

Tips

Try using different light sources (halogen lamp or fluorescent lamp). We will see different colors, as the emission spectrum for each bulb is different, even though together they both emit white light.

Review of what we have learned

- Why do we see light and dark stripes when using a single-color light?
- Why do we see different colors on different parts of the bubble?
- Why do we see different colors in a patch of oil on the road?

Related experiments

Experiment 5.3 Where do those colors come from?

1.5 Experiment

How Thick is My Hair?

30 min (+)

Diffraction, interference

OBJECTIVES:

Objective 1: Create a system for measuring the thickness of a hair.

Objective 2: Use diffraction to measure the thickness of very thin objects.

MATERIAL

- Card
- Scissors
- Laser pointer
- A long hair
- Ruler
- Measuring tape
- Adhesive tape

One of the most interesting behaviors of waves is that they can cause constructive or destructive interference. There are countless uses for this property. For example, sound-cancelling earphones use destructive interference on unwanted sound waves to isolate the user.

Another example is the use of electromagnetic wave interference to help us to measure very small distances with high precision. This is the characteristic we are going to use during this experiment to measure the thickness of a hair. The image shows an opaque object under a laser beam. The light diffracts on the edges of the object, creating two isolated sources that interfere at a certain distance. This pattern of interference depends on the size of the object, and this is what we will use during this experiment to measure the thickness of hair.

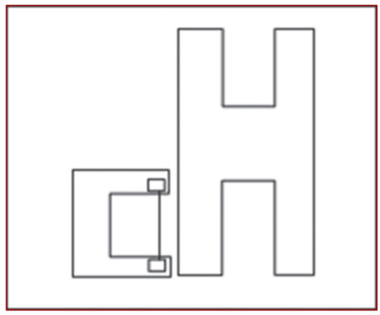

FIGURE 1.5.1 Frame for holding the hair.

Source: Internally created.

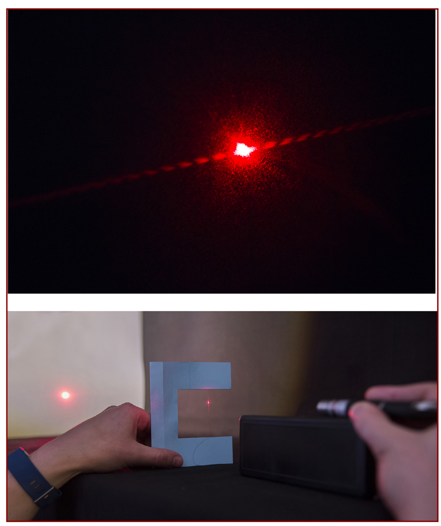

FIGURE 1.5.2 Setup of the experiment with the laser incident on the hair positioned over the card frame (top) and the interference pattern formed (bottom).

Photograph: Eliezer Sánchez González/Cultura Científica (CSIC)/IOSA.

Procedure

1. Make the frame by cutting a large "H" from a piece of card using the suggested template (Figure 1.5.1). The frame should measure approximately 20 x 10 cm. Fold the frame in half to make a "C" shape measuring 10 x 10 cm. Lay it down on its side.
2. Using adhesive tape, stick the ends of the hair to the prongs of the "C" shape, keeping it as vertical and tight as possible.
3. Switch off the light and shine the laser over the hair (remember not to look directly at the beam).
4. In order to gain a better measurement of the hair, it is advisable to do the experiment some distance from the wall where the laser will be projected. If you look at the spot on the wall, you will see a dotted line, the diffraction pattern.
5. Use the measuring tape to measure the distance between the frame holding the hair and the wall

where the laser is being projected. Try to set it at a distance of around 2 meters to obtain the diffraction pattern (Figure 1.5.2).

6. Use the ruler to measure the gap between the spots of light projected onto the wall. You need to measure the distance from the central patch of light and the next closest one (to the right or the left). Bear in mind that the intensity of the light spots may vary. If you can't see them, you may need to move a bit closer to the wall.
7. To calculate the thickness of the hair, use the formula thickness = (laser wavelength × distance from hair to screen/wall) / (distance between spots of light).

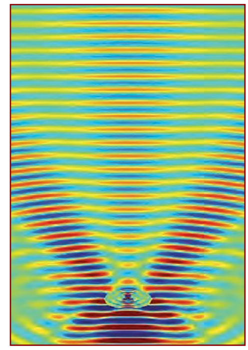

FIGURE 1.5.3 Intensity simulation of the diffraction caused by an object in the path of a laser beam.
Source: Juan Luis García Pomar.

Explanation

The phenomenon of diffraction occurs when a wave encounters an obstacle, whether it is a slit or an object of a certain size, and it passes through that obstacle or goes around it, creating new wavefronts that interfere with each other, forming a pattern of maximums and minimums of light if projected onto a screen (Figure 1.5.3). In this case, hair acts as an obstacle that the laser light travels around, forming two different sources of light that clash, creating the pattern of interference. As you will have noticed, this pattern consists of a central patch of light and a number of lateral ones. The spots closest to the center patch are called the first order of diffraction (in both directions).

The second, third and fourth spots of lights are known as the second, third and fourth order, respectively, and so on. In theory, diffraction patterns contain an infinite number of orders, but in practice we can only see a few.

The distance between the different orders is related to the thickness of the obstacle, as per the formula

$$a = n\,\lambda L/d_n$$

where a is the thickness of the hair, n is the order number we have used to measure the distance (d_n) from the central patch of light to the nth spot, λ is the wavelength of the laser used, and L is the distance between the hair and the screen where the light is projected.

Tips

- Try the experiment with naturally curly and straight hair to see if the thickness measurement changes depending on the angle of incidence. Straight hair is normally more homogeneous, while curly hair has a more oval-shaped section, which means the thickness will be different at different angles.
- You can also try using other material (e.g., dental floss).

Review of what we have learned

Can we see interference patterns when using other light sources such as sunlight or a lightbulb?

Related experiments

Experiment 2.1 Build your own spectroscope
Experiment 2.4 Extraordinary light: laser

1.6 Experiment

To Be or Not to Be a Particle!

40 min (+)

Refractive index, invisibility, interference

OBJECTIVES:

Objective 1: Observe the double slit interference process using light from a bulb and a laser light.
Objective 2: Observe the same phenomenon using sunlight.

MATERIAL

- Laser
- 2 fine aluminum sheets
- Awl
- Metal, PVC or cardboard tube
- Large cardboard box (e.g., shoe box)

In 1678, Christian Huygens put forward the theory that light was a wave phenomenon transmitted through a medium called ether. This theory was largely ignored until the first half of the 19th century, when Thomas Young resurrected it to explain the phenomenon of interference.

This research, together with the development of quantum physics in the 20th century, led to the discovery of the dual nature of light: wave and particle.

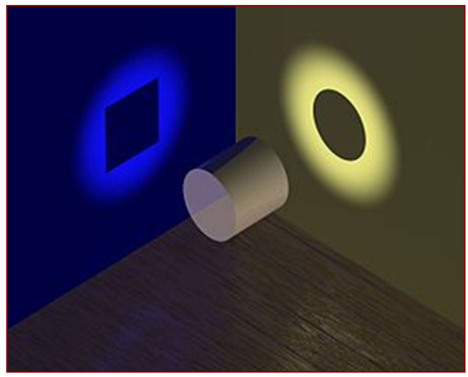

FIGURE 1.6.1 One single reality can be observed from two different viewpoints.
Source: Jean-Christophz Benoist, Wikimedia Commons.

Procedure

Experiment with aluminum sheets

1. Take the aluminum sheet and make two slits in it, less than 1 mm thick and less than 1 mm apart; if not, the pattern will form too close to the slits (Figure 1.6.2).
2. Take a shoe box and cut a hole in the lid a little smaller than the aluminum sheet (Figure 6.2). Similarly, cut a hole in the side of about 5 × 5 cm.
3. Place the aluminum over the lid of the box, lining it up with the hole.
4. Position the source of light (laser or lightbulb) at less than 5 cm from the aluminum across the slits so that both are illuminated by the beam.
5. Observe the strip pattern created though the side hole (Figure 1.6.3).

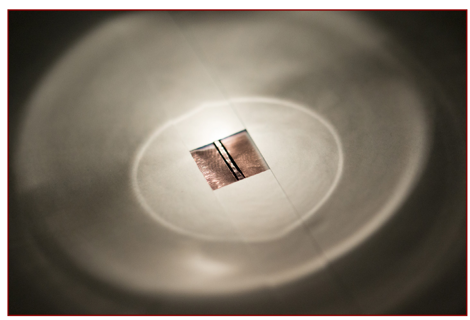

FIGURE 1.6.2 Two slits made in the aluminum sheet. The light is coming from a source of white light.
Photograph: Eliezer Sánchez González/Cultura Científica (CSIC)/IOSA.

Experiment with cardboard box

1. Punch two holes in the top of the box. The holes should be a few mm in diameter and positioned about 10 cm apart.
2. Line up one of the holes with the double slit aluminum sheet used in Procedure 1.
3. Turn the face of the box towards the sun. Look through the other hole in the box to observe the pattern formed by sunlight as it passes through the slits.

Experiment with a tube

1. Take the aluminum sheet and make two holes of at least 1 mm. The two slits need to be close (around 100 times the wavelength of the light used), otherwise the interference pattern will only form very close to the slits.
2. Take a metal, PVC or cardboard tube with a diameter of 6–10 cm and height of 15–20 cm, and place the aluminum sheet over one of the two openings like a lid. Cover the rest of the opening so that no light can get through that end, except through the two holes (Figure 1.6.4).
3. Look through the open end of the tube, turn it towards a source of light (beacon, bulb, etc.), and observe the pattern. What can you see?

FIGURE 1.6.3 Interference of two fronts of light created by two slits.

Photograph: Eliezer Sánchez González/Cultura Científica (CSIC)/IOSA.

Explanation

As the light from the two slits meets a screen, a series of stripes are created where you can see peaks and valleys in a regular pattern. This pattern originates from the wave-like nature of light. The waves reaching the slit are in phase. Based on the Huygens principle, each of these slits becomes a temporary source of waves that emit from them in the same phase, but the rays from each slit do not follow the same path until they reach the screen.

A connection can be made between the distance between the slits s, the wavelength λ, the distance of the slits from the screen D, and the width of the bands of interference (the distance between successive stripes) x:

$$\frac{\lambda}{s} = \frac{x}{D}$$

Tips

You will need two rubber balls and some wire to make two "maracas". Find a swimming pool, fountain or bathtub, i.e., somewhere with calm water. Gently tap the surface of the water with the balls at two points close to each other. Observe the undulations formed on the surface of the water and how the waves caused by each ball interfere with each other.

Review of what we have learned

- What differences can you see in the pattern created when you use natural light (sunlight) or laser light?
- What size should the slits be for the waves generated to be spherical temporary sources and for the effects of diffraction to be reduced through a single slit?
- What happens if one of the slits is covered?

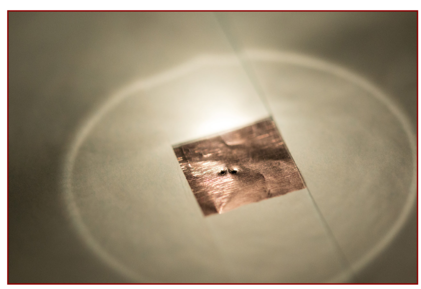

FIGURE 1.6.4 Zoomed-in view of holes over the aluminum sheet.

Photograph: Eliezer Sánchez González/Cultura Científica (CSIC)/IOSA.

Related experiments

Experiment 2.3 Detecting light with semiconductors

1.7 Experiment

Change of Wave! Polarization and Birefringence

50 min (+)

Polarization, Birefringence

OBJECTIVES:

Objective 1: Observe the behavior of polarizers.
Objective 2: To observe birefringence associated to photoelastic effect.

MATERIAL

- **2 large polarizers**
- **Plastic objects (fork, case)**
- **Glasses**
- **Transparent adhesive tape**

There are many substances (calcite, sugar) in which the speed of light depends both on the direction of travel of the light and on its state of polarization; it is said that such materials present anisotropic properties. In these materials, an electromagnetic wave breaks down into two waves, each affected by a different refractive index (ordinary n_o and extraordinary n_e). Among other effects, the division of the light, depending on polarization, into two beams can form a dual image. The polarization of the output light can also vary compared to the input light, which is why they are called optical dephasers.

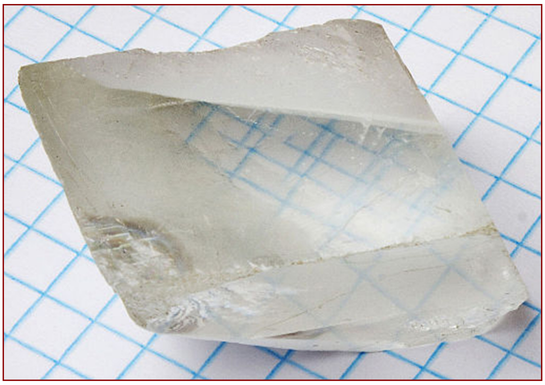

FIGURE 1.7.1 Ordinary and extraordinary component of light while passing through an anisotropic material. Dual image effect.

Photograph: APN MJM, Wikimedia Commons.

Procedure

Observation of light polarization using polarizing filters

1. Take two polarizing filters, one in each hand. Hold one in front of the other between your eyes and a source of light (e.g., a fluorescent ceiling light).
2. Keeping one of them still, turn the other through 90°. There will be a position where the intensity of the light you can see will be minimal; we'll call this the total extinction position.

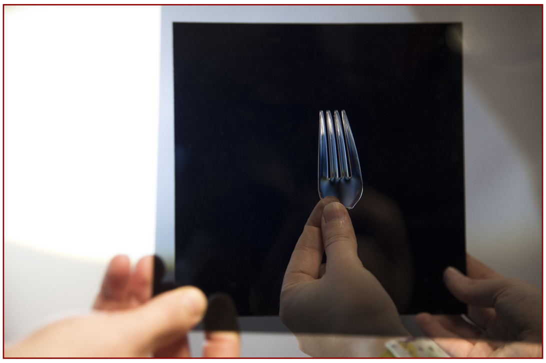

FIGURE 1.7.2 The two polarizing filters; one placed at 90° to the other blocks the light from behind.

Photograph: Eliezer Sánchez González/Cultura Científica (CSIC)/IOSA.

Observation of birefringence

1. Place the filters in total extinction position and hold an object between them (e.g. plastic fork).
2. Hold one of the filters in the same position and rotate the other. You will

FIGURE 1.7.3 Glasses between two polarizing filters in parallel (you may see colored interferences due to tensions inside the material of the lenses) (left) and with the filters crossed at 90°, blocking the light from behind (as the light passes through the plastic folder with tape across it, we can see colors associated to different tensions inside the tape) (right).

Photograph: Eliezer Sánchez González/Cultura Científica (CSIC)/IOSA.

see how the intensity of the light passing through both filters varies as you rotate (Figure 1.7.2).

3. Pay special attention to the object you placed between the filters and note down your observations, as what is happening is a birefringence effect due to possible tensions inside the material (Figure 1.7.3).

Explanation

In the first experiment, depending on the relative position between the filters, a greater or lesser amount of light will pass through. If you place both filters in the same direction, the maximum amount of light will pass through, as the first filter transforms natural light into linear polarized light and the second allows it all through as it is in the same position. If you turn the second polarizer 90°, the light will be completely blocked.

By placing glasses or another clear plastic item between the filters, you can see how some materials become birefringent as they have been subjected to tension or force during manufacturing. This is known as photoelasticity (Figure 1.7.3). This means that the polarization of the light is changed as it passes through the glasses. As the tension or force is not applied evenly, the birefringence caused by the photoelastic effect will also be uneven.

Tips

- Try the same experiment using different people's glasses and different kinds of frames (or frameless glasses). You will see greater or lesser tension depending on the manufacturer or the type of frame/lens.

Review of what we have learned

- What is the difference between natural light and polarized light?
- Why do glasses placed between polarizing filters show different colors rather than just one?

1.8 Experiment

Photons Give You Wings!!! The Photoelectric Effect

30 min (+) Radiation, photon energy

OBJECTIVES:

Objective 1: Discover the charge of different objects and how they attract or repel depending on that electric charge.
Objective 2: See how exposure of an object to light can remove its charge on releasing electrons.

MATERIAL

- Balloons
- String or thread
- Aluminum foil
- PVC tube
- Cotton cloth
- Wooden stand (pencil)
- Source of ultraviolet light

The photoelectric effect consists of the emission of electrons by a material when electromagnetic radiation meets it (generally visible light or ultraviolet light). Photons have a characteristic energy, determined by the frequency of the light wave. If an atom absorbs energy from a photon, has more energy than needed to expel an electron from the material, and is also following a trajectory towards the surface, then the electron may be expelled from the material. If the photon energy is too low, the electron cannot escape from the surface of the material.

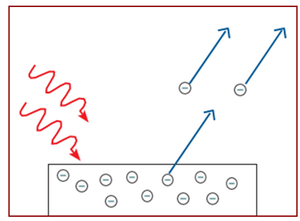

FIGURE 1.8.1 Diagram of the photoelectric effect.
Source: Internally created.

The photoelectric effect was discovered and described by Heinrich Hertz in 1887, who saw the arc between two electrodes connected to high-voltage currents covered greater distances when illuminated with ultraviolet light than when left in darkness. The theory was explained by Albert Einstein in 1905; he received the Nobel Prize for Physics for this theory in 1921.

Procedure

Experiment with balloons

1. Blow up two balloons and tie each one to a different string.
2. Rub one of the balloons on your hair. Next, hold this balloon close to the other one; you will see that they are attracted (Figure 1.8.2, left).
3. Now rub both balloons on your hair and bring them together again. This time, you will see how the balloons repel (Figure 1.8.2, right).

Experiment with aluminum foil

1. With the aluminum foil, make a "curtain" of strips connected at the top. Fix this curtain to a wooden support.
2. Rub the PVC tube with the cotton cloth. Bring it close to the aluminum curtain. You will see that the strips move, repelling each other as they are charged, as shown in the image (Figure 1.8.3).

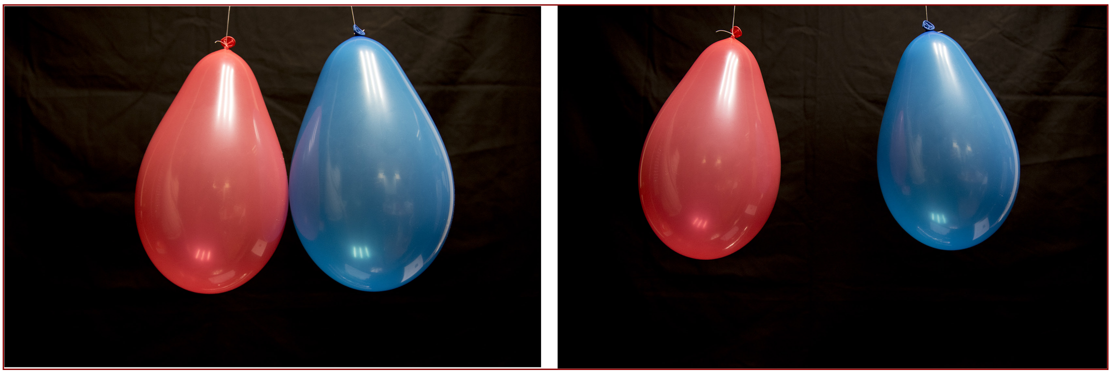

FIGURE 1.8.2 Balloons hanging from a string, one not rubbed (left) and both rubbed and therefore electrically charged with the same charge (right).

Photograph: Eliezer Sánchez González/Cultura Científica (CSIC)/IOSA.

3. Touch the metal frame to discharge the aluminum curtain with your body.
4. Charge the curtain in the same way as in Step 2.
5. Now shine an ultraviolet light on the curtain. Does it also discharge?

Explanation

Matter is made of atoms, in turn consisting of protons (positive charge), electrons (negative charge) and neutrons (no charge). Atoms normally contain more protons than electrons, and so the positive and negative charges cancel each other out. The balloons are fundamentally in this state. When you rub a balloon against your hair, your hair gives up electrons to the balloon, which becomes negatively charged: it has more electrons than protons. This is how the attraction effect occurs: when one balloon is negatively charged and the other one is neutral; repulsion occurs when both balloons are negatively charged.

In the case of the aluminum strips, which are negatively charged by the PVC object, i.e., they have more electrons than protons, we see how they repel each other.

FIGURE 1.8.3 Charged curtain made from aluminum foil using a charged PVC tube.

Photograph: Eliezer Sánchez González/Cultura Científica (CSIC)/IOSA.

Under ultraviolet light, the energy of the photons is absorbed by the electrons of the aluminum strip so that they take on the necessary energy in order to escape the material, i.e. the photoelectric effect takes place. This process discharged the aluminum strips. They then have the same number of electrons as protons, and the strips therefore do not repel each other.

Tips

- If you want to make it more fun, rub the balloon against your shirt, or another cotton garment. Hold the balloon to the strips and see how they are attracted to it. In the same way, if you hold the negatively charged balloon near to your hair, you will see how it stands on end.
- If you shine an ultraviolet light on the balloon, it will be discharged and no longer have the same effect on the strips or your hair.

Review of what we have learned

- How can a material be negatively charged?
- Is an electron always released when a photon strikes a material?
- Is it easier to release an electron with ultraviolet light than with infrared?

Related experiments

Experiment 6.6 Obtaining electricity from the sun: build a photovoltaic cell