

Library of Congress Control Number: 2020944342

ISBN: 978-1-5106-3936-2

e-ISBN: 978-1-5106-3935-5

DOI: 10.1117/3.2579764

English translation of Descubriendo la luz: Experimentos divertidos de óptica

Copyright © 2018 CSIC

Translated by Alexandra Stephens and Craig Cavanagh



GOBIERNO
DE ESPAÑA

MINISTERIO
DE CIENCIA
E INNOVACIÓN



ISBN: 978-84-00-10789-5

e-ISBN: 978-84-00-10790-1

NIPO: 833-21-043-3

e-NIPO: 833-21-044-9

DL: M-11258-2021

In cooperation with the OSA Foundation

Published by

SPIE

P.O. Box 10

Bellingham, Washington 98227-0010 USA

Phone: +1 360.676.3290

Fax: +1 360.647.1445

Email: books@spie.org

Web: <http://spie.org>

Copyright © 2021 Society of Photo-Optical Instrumentation Engineers (SPIE)

Cover image courtesy of Francesca Gallazzi

All rights reserved. No part of this publication may be reproduced or distributed in any form or by any means without written permission of the publisher.

The content of this book reflects the work and thought of the authors. Every effort has been made to publish reliable and accurate information herein, but the publisher is not responsible for the validity of the information or for any outcomes resulting from reliance thereon.

SAFETY NOTE: All of the experiments in this book are intended to be performed under adult supervision. Appropriate and reasonable caution is required at all times, and the recommendations in the activities in this book cannot replace sound judgment. The authors and publisher disclaim all liability for any damage, mishap, or injury that may occur from engaging in the activities featured in this book.

Printed in the United States of America

First edition

For updates to this book, visit <http://spie.org> and type “PM324” in the search field

SPIE.

Introduction

Light is an element that draws together many areas of human knowledge (physics, chemistry, biology, astronomy, engineering, art, etc.); moreover, optical phenomena and the technologies based on them are widespread in our daily lives. However, it can be difficult to understand or explain these phenomena.

What is light? Where are optics and photonics present in our lives? What lies behind different optical phenomena? What is an optical instrument? How does the eye resemble an optical instrument? How can we explain human vision? What are everyday optical technologies based on? Where is optics found in nature? The book you are holding, written by a group of young scientists, attempts to answer these questions and many more, and help you to get to know the exciting world of optics and photonics.

Our aim is to look at optics from all sides, covering both basic phenomena occurring in nature and the very latest applications and technologies. Although we want to reach out to anyone interested in science, we have taken care to include experiments and explanations covering the light-related topics on the syllabus for high school level. Our experience in performing demonstrations at primary and secondary schools, as well as the general public, has taught us that the best way to reach our goals is through experimentation and interpretation of results. We have developed a set of exercise cards to help you complete the different experiments step by step (color-coded by level of complexity), after which the challenge is to show what you have learned. We provide help to fully understand the experiments, with an introduction to all the necessary concepts at the beginning of each chapter, as well as plenty of interesting facts.

Chapter 1 looks at the physical properties of light, how it is described, how it travels and how it behaves on interaction with different materials. Some of the key words in this chapter are wave, photon, reflection, refraction, diffraction and interference.

In Chapter 2, we explore the different sources and detectors of light that are so commonplace in our daily lives. It includes experiments using extraordinary light emitters like lasers and building “invisible” light detectors.

Chapter 3 shows how you can use simple optical elements such as lenses, mirrors and prisms to build different optical instruments. We will focus on understanding how light travels and images are formed using these items and how we can manipulate light using optical instruments such as cameras, microscopes and telescopes.

Chapter 4 deals specifically with human vision. It contains experiments to show you how our eyes work and how they compare to complex optical instruments, their enormous capacity (color vision, depth of vision, etc.), as well as their defects (short sight, long sight, etc.).

In Chapter 5, we show you how to recreate optical phenomena in your laboratory (home or classroom) that happen every day in nature, such as mirages, rainbows, or star-gazing.

Finally, in Chapter 6 you will finally be convinced of the importance of optics in our daily lives; you will learn about technologies where light is essential, such as telecommunications, energy generation or even the food industry.

We hope you enjoy the book and that you have fun with optics and photonics.

The Authors

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

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).

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 1.6 Example of how a difference in the refraction index causes a diversion of light.

Photograph: in house.

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**).

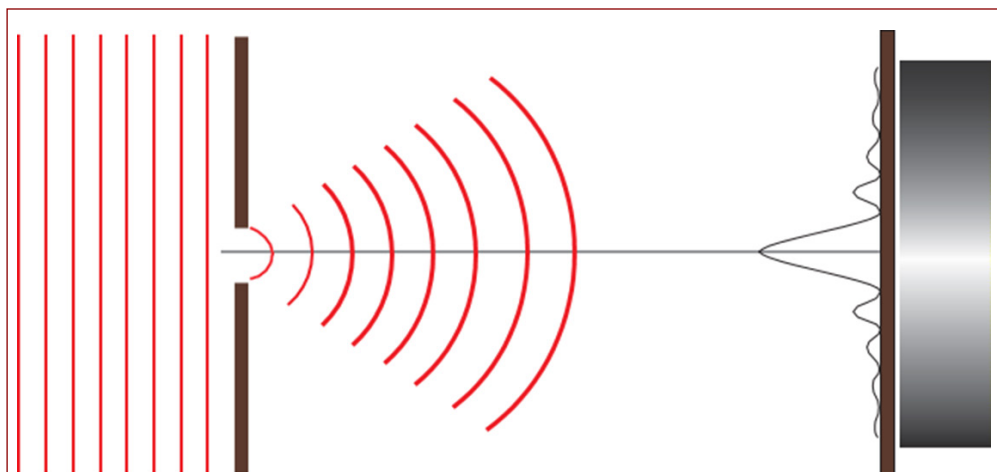


FIGURE 1.12 Diffraction of a wavefront through a small aperture. On the right, the diffraction pattern (distribution of light intensity) is formed after passing through the aperture.

Source: Internally created.

1.5 Experiment

How Thick is My Hair?

Diffraction, interference

30 min (+)



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.

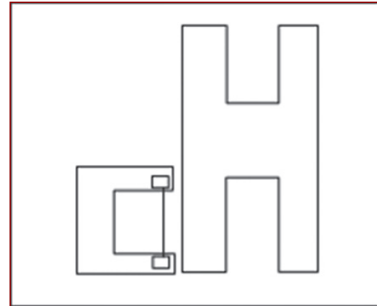


FIGURE 1.5.1 Frame for holding the hair.

Source: Internally created.

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

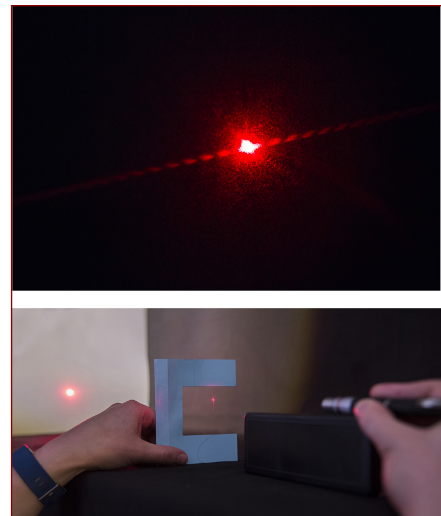


FIGURE 1.5.2 Setup of the experiment with the laser incident on the hair positioned over the card frame (top) and the interference pattern formed (bottom).

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

Light sources and detectors

Now that we know what light is and its properties, in this chapter we will focus on understanding how we have learned to generate and detect it, as all artificial light sources of light require the conversion of some kind of energy into electromagnetic radiation. The main thread of this chapter is understanding how this conversion takes place, identifying the part of the electromagnetic spectrum where the different types of light sources have the best properties and discovering which are the most efficient of them. At the end of the chapter, we will focus on the optical systems that can detect light and their recent application to artificial vision.

What is a source of light? What kind of light sources are there?

The simplest definition of a source of light is “any object that emits light”. There are *natural* sources of light (sun, stars, some plants or animals via *fluorescence*, or via *luminescence* in the case of the firefly) and *artificial* ones (e.g., a lightbulb, as in [Figure 2.1](#)). In this section, we will look exclusively at artificial sources of light, ranging from *incandescent* (emission of light due to temperature) to *luminescent* (e.g., electro-luminescence, the emission of light in response to an electrical current).

What are the different ways of generating visible electromagnetic radiation (light)?

Before getting into more detail, it is important to understand the different processes we have for generating *radiation* (light, in the case of visible radiation).

In broad terms, we can differentiate between two ways of emitting light: applying heat to a substance (thermal emission or *incandescence*), such as a lightbulb, or using other means that do not involve heating the substance (*luminescence*), such as in fluorescent lighting or in nature; fireflies are a good example of this. Another type of luminescence is atomic emission, which is a form of radiation in which it is not necessary to increase the temperature of the material.

Thermal emission: incandescence

All bodies at a temperature above absolute zero (0 K) emit energy in the form of electromagnetic radiation ([Figure 2.2](#)). If we study their corresponding *emission spectrum*, we can see that it is

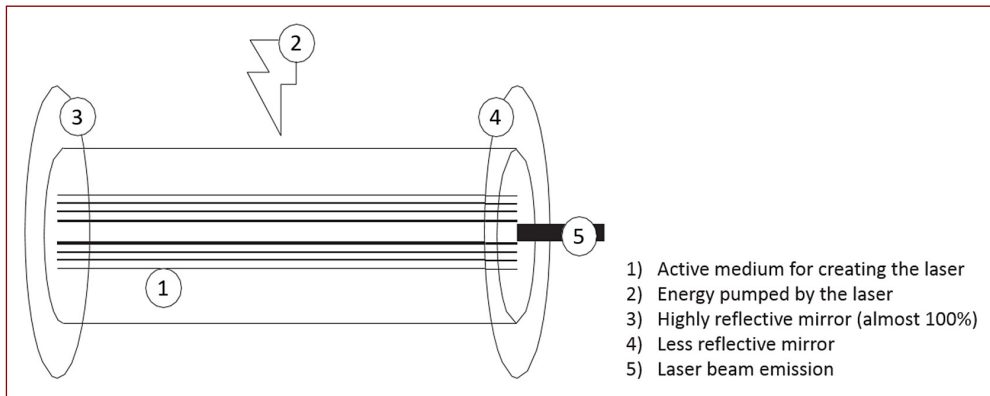


FIGURE 2.11 Operation of a laser (upper). Red laser passing through two LEGO pieces (lower).

Source: Internally created. Photograph: Martin Kenny Seguir, Flickr.

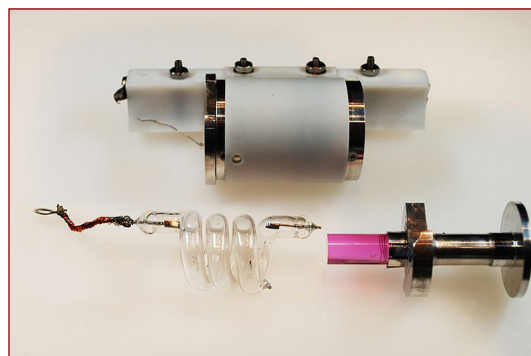


FIGURE 2.12 Image of the first ruby laser system developed by T. Maiman in 1960.

Photograph: Guy Immega, Wikimedia Commons.

Did you know...?

The *Star Wars* movies contain a number of scientific inaccuracies. One example is the epic space battles using laser weapons.

A laser beam is actually invisible: we can see the projected spot of light but not its path, unless the beam is dispersed by smoke or other particles in the air... which does not appear to be the case in most of the *Star Wars* scenes!

2.2 Experiment

Reinventing Edison: Build A Lightbulb



Light sources, continuous spectrum, incandescence

OBJECTIVES:

Objective 1: Understand how an incandescent bulb works.

Objective 2: Re-create a lightbulb similar to the first ones sold by Edison.

MATERIAL

- Glass jar with lid (airtight)
- 1.4-mm graphite pencil leads and aluminum foil
- 2 4R25-type 6V batteries or a 12V, 8Ah lead-acid battery
- Switch, wire and crocodile clips
- 2 pliers
- Metal paper clips (not coated)
- Bathroom sealant
- Small candle or small piece of a large candle
- 2 screws, 4 washers and 8 nuts (4 for "security"). Diameter ≥ 4 mm
- Plastic adhesive / hot glue gun
- Safety gloves
- Manual drill and metal drill bits
- 1 cork

Have you ever looked at an old incandescent lightbulb and thought it didn't seem too complicated? The truth is you are right! In this experiment, we'll show you how to make your own lightbulb with a graphite filament. The principle is simple: passing electricity through a material to heat it up and make it emit visible light.



FIGURE 2.2.1 Materials.

Photograph: in house.

Procedure

1. Find an airtight glass jar. Check that it is airtight by heating it (in a warm oven or with steam) without the lid. Next, place the lid, taking care not to burn yourself, and then leave it to cool. If once the jar is cold the lid has been sucked downwards and does not go "plop" when you press it, the jar is airtight. If not, you need to find another one.
2. Start by marking and drilling the holes in the lid for the pieces of cork, as shown in the image (Figure 2.2.2). Try to ensure that they are far enough apart and not too large.
3. Next, cut the cork in half and drill a hole in the center of each half to feed the screws through. It is important to drill a hole slightly smaller in diameter than the screws so that they are firmly held in place. Now you can insert them into the holes in the lid of the jar and seal them with hot glue or bathroom sealant.
4. Strip, braid and wind a piece of wire around the head of each screw. If you or anyone you know can solder, you can solder the wire onto the screw for a stronger connection (as shown in the images). If not, just leave them wound around the head. Now you can screw them into the cork pieces in the lid of the jar.
5. Next, take the pencil lead, being careful not to snap it or damage it. You must use gloves for this stage to protect the lead and prevent it from becoming greasy. Now

2.5 Experiment

Beyond the Visible: IR Radiation



30 min (+)

Infrared light,
Herschel's experiment

OBJECTIVES:

Objective 1: Repeat the experiment Herschel used to discover infrared radiation.

Objective 2: Understand the relationship between temperature and radiation.

MATERIAL

- Glass prism
- 3 alcohol thermometers (for measuring air temperature)
- Permanent black ink or marker, or black insulating tape.
- Carboard box (or something similar to use under the prism)
- Adhesive tape
- Scissors

In the year 1800, William Herschel realized, while observing the spectrum of sunlight through different filters, that depending on their color, the amount of heat transmitted was different. It was while he was trying to understand this phenomenon that, by chance, he discovered infrared radiation, a type of radiation on the electromagnetic spectrum located “beyond red”, which cannot be seen with the naked eye.

Herschel managed to detect it because it is associated with thermal radiation: part of the radiation is emitted in the form of heat, which can be measured using a thermometer, as we will do in this experiment.



Procedure

1. This experiment should be completed outside or close to a window on a sunny day without clouds or mist, as this might reduce the chances of seeing the phenomenon.
2. Color or paint the thermometer bulbs or cover them with black tape so that they absorb more heat. Stick them together with adhesive tape, with all the temperature gauges lined up.
3. You will need to create a support for the prism on the side of the box nearest the sun. Cut out a piece from the top edge, slightly shorter than the largest axis of the prism and quite deep to allow the prism to spin. You can create a different kind of frame for the prism if you prefer.
4. Place the prism on its support frame. Adjust its position to obtain the widest possible spectrum (you already know how a prism works): you can direct the spectrum into the shadows inside the box, but it is easier to get a wider spectrum if you project it a bit further, e.g., onto the floor or a table. Make sure that the prism is not moving.
5. Place the thermometers in the shade to measure the ambient temperature.
6. Next position the thermometers where the spectrum spreads out, so that the first bulb lines up with blue, the middle one with yellow

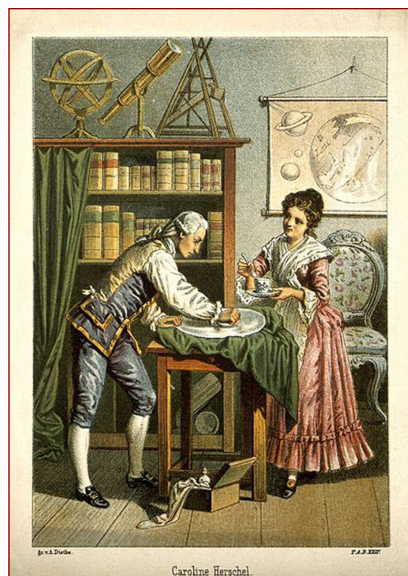


FIGURE 2.5.1 Sir William Herschel and Caroline Herschel. William is polishing a telescopic instrument, probably a mirror, while Caroline Herschel adds lubricant.

Source: Color lithograph by A. Diethe, c 1896. R. Burgess, Portraits of Doctors & Scientists in the Wellcome Institute, London, 1973, no. 1379.10.

Optical instruments

In this chapter, we will find out how rays of light behave when they pass through the different elements that make up an optical system: lenses, mirrors and prisms. In other words, we will look at the deviation of the rays of light as they pass through different items. This examination helps us to predict the characteristics of an image formed by the combination of certain optical elements, e.g., in the case of a microscope, where the image is inverted and larger than the real size object we are looking at.

This means that we will not be looking at phenomena related to the behavior of light as a wave, although they may actually be present (interference, diffraction, etc.). Nor are we going to take into consideration the intensity of light; we will concentrate on describing these properties based solely on the path followed by the rays of light. We will do this using what is known as *geometrical optics*, with calculations, or graphs, to work out the path of light through certain optical elements or a combination of these (*optical systems*).

Using geometrical optics, we will discover the key characteristics of basic optical elements and systems, as well as more complex systems made from a combination of different simple ones, such as cameras, telescopes and microscopes.

Basic concepts

It is very important to know what type of *image* an optical element will form of an *object*, as it helps us understand how the world will look through that instrument.

An *object* either emits light (light source) or reflects light from a separate light source in the form of rays. These rays travel in a straight line through a *homogeneous and isotropic* medium, which is most common, until they reach a medium with a different index of refraction. As we saw in Chapter 1, the surface between the two media with differing indices of refraction will refract or reflect the rays of light that have not been absorbed; they will change direction according to the law of refraction (Snell's law) or the law of reflection (*angle of reflection = angle of incidence*), respectively.

When we study the *image* formed of an object by an *optical element*, it is not enough to examine a single ray of light. We need to study at least two rays as the image will form at the point where two rays leaving the same point on the original object cross over, having passed through all the elements making up the optical system in question. In reality, not only two rays leave each point on the object but also what is known as a stroke of light, i.e., many rays of light from the same point on the object that fill up the optical element as they pass through it and then reflect or refract to form the corresponding image. Studying the propagation of these strokes of light, made up of rays, allows us to predict that the

The human eye: a biological photo camera

The human eye is an optical instrument offering incredible performance: not only is it capable of forming an image focused on its sensor (the *retina*) but it also has the ability to focus at different distances and work under a wide range of light levels boasting optical quality that is optimized for its functions. This is why for years it was the weak point of Darwin's theory of evolution, as he himself acknowledged:

How is it possible that simply through the process of natural selection, such a perfect biological optical instrument had been created?

Yet the ability to see does not belong solely to the eyes; rather, it is a complex process (Figure 4.1) that occurs throughout differentiated phases where visual information is perceived, recognized, transformed and processed, over three stages: optic, retinal and neuronal. Our eyes form the image of the outside world, the brain interprets the image from each eye "in real time" and vision is the incredible result of highly coordinated teamwork.

The eye, the biological optical training system of images

The first stage of the visual process is the optical stage, where the eye is the main protagonist when collecting light from objects in our environment. If a distant object is observed, we can consider that the propagation of light is rectilinear and parallel to the position of our eye and that it travels through the air, a homogeneous medium with an index of refraction with a value of 1. When light enters the eye, it changes from the air to an aqueous medium (with an approximate refractive index of 1.334), in which its transmission speed changes, producing the phenomenon of refraction. Furthermore, the eye is formed by different tissues that include transparent biological structures that function as converging lenses (*cornea* and *lens*, the latter is a variable power lens), transparent fluids that provide nutrition and support (*tear*, *aqueous humour* and *vitreous humour*) and a diaphragm capable of offering openings adapted to ambient light (*iris*), which change the trajectory of beams of light by gathering them in the position of our retina in the same way as the lenses of a camera project the image on the digital sensor, as shown in Figure 4.1.

Finally, our eyes are wholly protected by the *sclera*, *eyelids* and bones of our *eye orbit*. This specialist design responds to the requirement to capture almost infinite information from the outside world and focus it on our biological sensor, the *retina*. As can be seen, this layout can resemble that of a camera (Figure 4.2), with its lens and eyepiece, sensor and housing, but let's see more of its components in detail.

The *cornea* provides the greatest part of the eye's refractive power, since it contributes approximately 2/3 of the eye's total power. This major contribution is due to the shape of the corneal surface (convergent *meniscus* type lens) and the difference in the *refractive*

4.1 Experiment



How Does the Human Eye Work? And that of Other Animals?



60 min (+) Anatomy of the eye.

OBJECTIVES:

Objective 1: Mount the eye of the nautilus.

Objective 2: Build and identify the parts of a human eye and compare them with the parts of a camera.

MATERIALS

- Plastic ball
- PVC or sturdy cardboard tube
- Convex lens (magnifying glass)
- Flashlight
- Circular piece of transparent plastic with a diameter somewhat larger than the PVC pipe
- Piece of onion paper the same size as the circular piece of plastic
- Craft knife, scissors, glue and adhesive tape

The sight process is complex and needs three basic elements: eye, brain and light. Without light, we are unable to see. However, in many cases it is the optics of the eye that determines the type of vision.

In this experiment, you can mount two different eye models, in which various optical elements are involved: a pinhole and a lens. Of course, the quality of the image that reaches the retina is not the same.

Try for yourself!

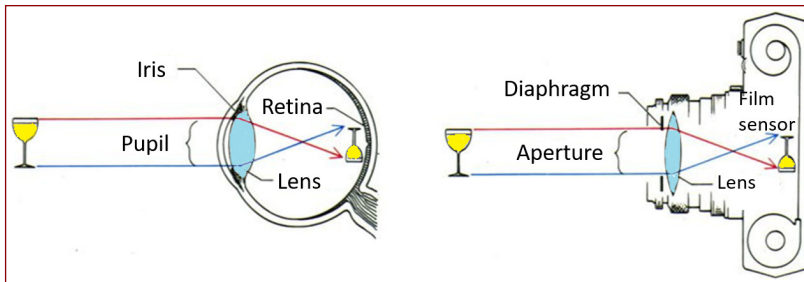


FIGURE 4.1.1 Formation of a image in the eye and in a camera.

Source: In-house



Procedure

The nautilus

The nautilus has the simplest visual system you can imagine: a simple pinhole that regulates the amount of light that enters, and no lens.

1. Make a small hole in some cardboard. You can draw the animal on the cardboard!
2. Illuminate a slide so that the image passes through the pinhole. Place a white cardboard behind the nautilus to see how the image is formed.

The human eye

1. Take the transparent circular plastic and stick it to one end of the PVC pipe.
2. Glue the piece of onion paper over the clear plastic. This is where the image will be projected, that is, the retina.

Light in nature

Optical phenomena in nature are generally caused by interactions between sunlight and the atmosphere, clouds, water, dust and other particles and materials, animals and plants, and even objects, both natural and man-made. From sunsets to the rainbows, passing through the blues and green of the oceans and the astounding variety of colors of animals and plants, nature unveils many examples of optical phenomena.

Some are a consequence of the dual behavior of light as a particle and wave. Some are easily observable, such as rainbows, and others can only be observed and measured by precise scientific instrumentation, such as the curvature of a star by the sun during a solar eclipse, demonstrating the curvature of space as predicted in the theory of relativity.

Reflection and refraction

As has been seen in previous chapters, light propagates along the fastest and straightest path in a transparent and homogeneous material. Its behavior is basically governed by the laws of *reflection* and *refraction*.

What are mirages?

Mirages are phenomena associated with the propagation of light in non-homogeneous mediums, where the refractive index (n) varies continuously with height and the light describes curved paths. These curves feature a concavity in the direction of the increase in the refractive index. That is, the light curves towards the middle with a higher refractive index. In a mirage, light changes trajectory (bends) as it passes through the layers of air at different temperatures. Popularly, mirages are associated with hallucinations, but this is not the case. Mirages are real optical phenomena where the true position of the object is subject to human interpretation, since the formation of the image is conditioned by the refraction of light. Mirages (see **Experiment 5.1**) can be classified as lower and upper.

Lower mirages occur on hot days, when the layer of air that is directly on the ground is hotter than the upper layers, producing a thermal gradient that has a refractive index gradient associated with it. The index of the layers near the ground is lower (hotter, less dense areas) than that of the upper layers (denser areas). As a consequence, the light rays are curved so that they appear to be reflected on the ground (**Figure 5.1**, upper part).

beings. A simple definition of this phenomenon is “all the artificial light that escapes outside the perimeter or area that is intended to be illuminated” (see **Experiment 5.7**). The consequences of light pollution are numerous. The main one is that the sky is no longer black enough to adopt the color of artificial urban lighting. While this aesthetically affects the visibility of beautiful starry skies, it is also felt in the pockets of electric power consumers. Yet light pollution can be reduced, improving the design of lamps and lanterns to avoid sending unnecessary excess light to the sky, where nobody needs it, optimizing the emission spectrum of these sources and, of course, streamlining the use of light sources ([Figure 5.17](#)).

Can we see artificial satellites with the naked eye?

The moon is the natural satellite of the Earth and can sometimes be seen with the naked eye by day, although apparently it is not very bright, and at night, when it seems that its brightness increases considerably, although it is the same. Although it looks bright, with a color somewhere between silver and white, the moon is composed of an almost black



FIGURE 5.17 Example of light pollution: aerial view of the large city of Madrid (left) and the much smaller town Santiago de Compostela (right).

Photography: in house.

Did you know...?

Astronomical observatories have agreements with nearby cities to regulate light pollution and thus not interfere with their measurements. Eclipses can be observed irrespective of light pollution.

5.4 Experiment: The Light Hidden by Nature



Tricks

Now you know why in some supermarkets they illuminate with a purple lamp the banknotes you use to pay. The purple lamp is ultraviolet and...they are checking that the notes are not fake! If you do not have an ultraviolet lamp and you cannot buy one, take advantage when you go to the supermarket and ask them to let you see it in action.



Let's see what you have learned

- Why do gin and tonics shine in nightclubs?
- How is fluorescence different from phosphorescence?
- Why do you have to bend the light strip to emit light?
- How is it possible that we observe yellow or red figures on our banknotes and passports with ultraviolet light?



Related experiments

Experiment 5.5 Chlorophyll, green?

Experiment 6.4 Does my olive oil have antioxidants?



FIGURE 5.4.4 Glow sticks.

Photography: in house.



FIGURE 5.4.5 Banknotes illuminated with white light (standard) and with ultraviolet light.

Photography: in house.

5.6 Experiment

Artificial Sunset: Scattering of Light in Our Atmosphere



15 min (+)

Mie scattering, Rayleigh scattering, sunset, sky blue color

OBJECTIVES:

Objective 1: Produce the scattering of light in a controlled way to generate a color change of the white light coming from the flashlight and reproduce the blue light of a clear day and the reddish light of a sunset.

MATERIALS

- Transparent container with water
- Milk
- White light flashlight
- Spoon

As we explained in Chapter 1, light travels in a straight line unless the materials in its path modify its trajectory. In the case of sunlight, which we could call white light (it contains all colors, including red, yellow, green, blue), when it enters the atmosphere it undergoes color changes, giving the violet-blue color to the sky in a clear day and the typical reddish color at sunset. What happens is that the light interacts with the gas molecules in our atmosphere and they scatter the light. Because the wavelengths of the violet-blue colors are the shortest (400 nm), they scatter about ten times more than the yellow-red light (in addition to a resonance effect with the molecules of the atmosphere that favors the blue light emission).

On the other hand, when the sun is on the horizon, at sunrise or sunset, light travels a longer way through our atmosphere, so most of the light of other colors is scattered, leaving mainly red, orange and yellow colors found at sunrise and sunset.

In this experiment we will try to simulate the particles of the atmosphere to get the effect of a blue sky and a reddish sunset. So let's start!



FIGURE 5.6.1 The dispersion of the rays of light coming from the sun in the particles of the atmosphere produces the typical reddish color of the sunset.

Photography: Pexels.

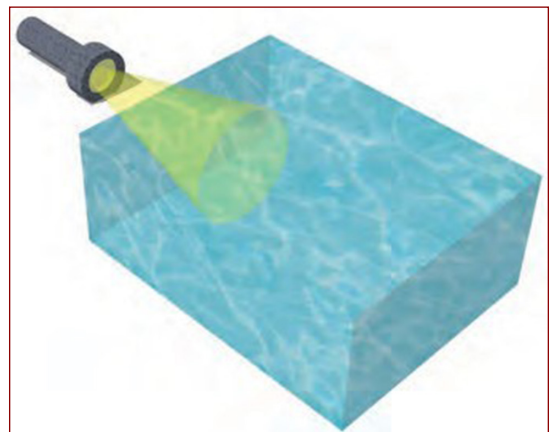


FIGURE 5.6.2 Experimental setup.

Source: Camilo Florian Baron.

Procedure

1. You must do the experiment in a dark and closed space, with the lights off.
2. Put enough water in the transparent container, but do not fill it to the brim because then you must shake it, and you must avoid it spilling.

Review of what we have learned

Chapter 1 | What is light?

Experiment 1.1 Does light travel in a straight line?

Why do hydrogel beads become invisible in water?

If you look at one of the hydrated hydrogel beads between your fingers, it seems to work like a magnifying glass. The reason is that, in addition to having a curved surface, its index of refraction is different from that of air, and thus it deflects the beams as if it were a lens. However, once you put it in the glass with water, as the hydrogel bead is hydrated with water, the difference in refractive index is so low that it does not deflect the beams that pass through it. It's like having an air-to-air lens: no matter how much curvature you have, the beams will not be deflected since the refractive indexes match.

How can it be observed that the refractive index of ethyl alcohol is lower than that of sunflower oil?

A very simple way to verify differences in the refractive index of different liquids is to put them in the same container and then introduce a pencil or a straw, for example. When you look at the sides, you will see that the light is refracted differently in each liquid, making the pencil appear discontinuous. If you see that the image of the pencil does not change when the two liquids pass through, then they have the same refractive index; but if you notice a discontinuity (as if the pencil were broken), then its index of refraction is different. Image 1.1.3 illustrates three liquids with different refractive indices. The most drastic change in index can be observed between air and water, since the straw seems wholly broken (Figure 1.6).

Experiment 1.2 Breaking light: Newton's prism

Why don't we see the decay in colors when we look through the window, which is made of glass?

When we look through a window, the surface where a beam of light arrives and where it comes from are parallel. This indeed makes a slight deviation of the position of the refracted ray with respect to the incident when the angle of incidence is different from normal to the surface. In this case, the difference of roads is so short that, practically,

Experiment 2.4 An extraordinary light: The laser

What are the main characteristics of the light generated by a laser that distinguish it from other light sources?

Unlike the other light sources, the laser light is monochromatic (it has only one wavelength), collimated (the beams travel in parallel) and coherent (the waves have the same phase relationship). Thanks to these properties, we obtain a highly energetic light source.

Experiment 2.5 Beyond the visible: IR radiation

Try to repeat the experiment at different times of the day or by slightly changing the position of the thermometers with respect to the spectrum. Do you notice any difference? What conclusions can be drawn?

The temperatures recorded by the thermometers will always be lower in blue and higher towards red and infrared regardless of the time of day at which the experiment is performed. The big difference at different times during the day is the maximum temperature that the thermometers will reach. Surely, if you did it the first time in the morning or late afternoon, you would get lower temperatures than at noon. This is because at noon the layer of the atmosphere that has had to pass through the sunlight is smaller than the one that must pass through in the morning or in the afternoon, thus obtaining higher temperatures, especially in the red and infrared.

What is the relationship between temperature and color (or, rather, electromagnetic spectrum, since we cannot see it completely)?

Each color of the light (or part of the EM spectrum) has its own wavelength (or frequency) and each frequency (ν) corresponds to a certain energy (E) according to the Planck equation $E = h \cdot \nu$, where h is a constant (Planck's constant). Color is only one type of energy.

Chapter 3 | Optical instruments

Experiment 3.1 Catch me if you can!

How do you think the image must appear on the tablet or mobile for you to see it properly?

The part of the mirror resting on the tablet or mobile will be at the bottom of our hologram, and the images must be placed facing that direction. The reflection is directed on each of the walls, and therefore, if the direction changes, it will be rotated.

What would happen if there were only one image on the tablet or mobile?

We would not achieve the same effect. In that case, the image is reflected only in the side that is facing the image, and therefore, we would only see the “hologram” from the side. Turning the phone or tablet would have no three-dimensional effect.

Experiment 3.2 There is nothing beyond my reach!

Why is it important for mirrors to internally form a 45° angle with the sides of the box?

The mirrors are located in the tube parallel to each other and at an angle of 45° with the axis of the tube. The mirror at the top is the one that reflects the objects that are located outside the area of our vision and we wish to observe. When it affects the surface of the