The Importance of Light in our Lives[1]

An overview of the fascinating history and current relevance of Optics and Photonics

Lecture Notes

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[1] This subject is included in the University of Cantabria's Senior Program.

Figure 0. An engraving which depicts Archimedes' supposed defense of Syracuse using a mirror system for focusing the sun's rays. License: Public Domain.

The Importance of Light in our Lives

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Course Structure

This course is divided into 8 chapters and aims to provide an introduction to the main concepts of optics and photonics: from the use of the first magnifying glasses to the use of laser in a multitude of present-day devices and applications.

- **Chapter 1: The Historical Evolution of Optics and Photonics**

  With reference to the discoveries of key personalities such as Archimedes, Newton or Einstein, this chapter traces the fascinating history of the evolution of Optics through to Photonics, with the invention of the omnipresent laser and optical fiber.
- **Chapter 2: What is Light? Waves and Particles**

  This chapter aims to provide a clear and simple explanation of one of the "mysteries" that have most greatly concerned and occupied hundreds of scientists throughout the centuries: What is Light? Is it a wave or a particle?
- **Chapter 3: Sun, Light and Life: how the Sun and photosynthesis work**

  Life on our planet would not exist without the Sun and the energy it provides every second. Likewise, photosynthesis or the conversion of inorganic substances to organic compounds in plants, takes place thanks to the energy of light.
- **Chapter 4: The light that revolutionized the digital era: the laser and optical fiber**

  Today's society would not be the same if, back in 1958, the laser had not been invented and, thereafter, optical fiber. The Internet, the great communications phenomenon that has revolutionized our lives, is simply light (laser) travelling around the world through optical fiber. We will briefly review the invention of the laser, optical fiber and their fundamentals.
- **Chapter 5: Measuring the world using light: from biomedicine to civil work**

  Light not only serves for high speed communication via the Internet, but can also help us in a variety of applications: from precisely delimiting cancer cells to real-time monitoring of a bridge or dam. This chapter provides a brief explanation of some important examples that help us to better understand this "hidden" facet of light.
- **Chapter 6: The phenomenon of vision: how humans and animals see**

  This introduction to the world of light would not be complete if we were not to explain how one of the most incredible parts of our body works: the eye and the sense of sight. Furthermore, we will explore the differences between our sense of sight and that of other members of the animal kingdom.
- **Chapter 7: Photonics: current situation and future perspectives**

  This final chapter reviews some of the most recent advances in the world of optics and photonics and other possible future applications of this field of knowledge, which is fundamentally important today and will undoubtedly continue to be so in future decades.
- **Chapter 8: Experiments with light that you can do at home**

  Finally, we suggest a series of simple experiments that students can do to help assimilate the concepts explained during the course.

Table of Contents

Chapter 1

The Historical Evolution of Optics and Photonics

1.1. Where shall we start?

At the beginning! Admittedly, without becoming "philosophical", it is not easy to say when the history of Optics began. Maybe it would be easier to start by defining what we mean by Optics:

"Optics is the branch of physics which involves the behavior and properties of light, including its interactions with matter and the construction of instruments that use or detect it" (Wikipedia)

We will start at the end, as we could say that Optics begins when human beings manufacture the first instruments for using the properties of light:

The first known optical "objects" are probably metal mirrors found in Egyptian tombs most likely used to divert the sun's rays; as well as lenses found both in Pompeii and Mesopotamia (3000 BC) and Crete.

The first glass vessels [1] [2] and artistic enamels made of this material appeared in the **15th Century BC**, during the reign of Thutmose III.

In the 6th Century BC Confucius (China between 551 and 479 BC) talked about a cobbler who used "glasses" on his eyes. This suggests that this material was used for decorative or medicinal purposes and Empedocles of Akragas (Sicily around the year 495 BC) mentioned the field of vision for the first time.

[1] Glass is an amorphous material obtained by fusing silica sand (SiO_2), sodium carbonate (Na_2CO_3) and limestone ($CaCO_3$) at about 1500 °C.

[2] The term crystal is often used as a synonym of glass, although scientifically-speaking this is incorrect as glass is an amorphous solid (its molecules are not arranged in a regular pattern) and not a crystalline solid.

Figure 1. Wood and copper Egyptian mirror, exhibited in the Louvre museum. Source: Wikimedia Commons (CC BY-SA 1.0). https://bit.ly/2S12utj

The first written references to the existence of lenses are quite ancient. A historical account affirms that a convergent rock crystal lens was found amongst the ruins of Nineveh. Also Aristophanes, in his play "The Clouds" dating back to 423 BC, mentioned the existence of lenses: in the play, Strepsiades plans to use a burning glass for focusing the sun's rays on a wax tablet in order to melt the record of a debt incurred through a bet.

In the 5th Century BC the Greeks, Romans, Arabs... were aware of the properties of mirrors, they cauterized wounds with positive lenses and they used glass spheres filled with water called "lighting crystals" for lighting fires. Perhaps the first lens ever to exist in the world was that built by Aristophanes in the year 424 BC with a blown glass globe filled with water. However, his objective was not to magnify images, but to focus the sun's rays.

It was during the time of Ancient Greece when the first attempts were made to explain the phenomenon of vision, proposing a variety of theories in which concepts of **light** and **vision**, were intermingled [1].

Thus, for example, the **school of Pythagoras** suggested that vision is caused by the **projection of images emitted from objects** towards the eye.

On the other hand, **Euclid and Plato** followers believed that vision occurred when "ocular beams" emanating from the eyes hit objects.

A third explanation upheld by Aristoteles, contrary to the previous theories, suggested that when the medium situated between the eye and the object is at rest, there is darkness. However, if the medium is excited by the object's "fire", the medium is transformed into an active state and thus becomes transparent. In this way, the object's colors can travel to the eyes, and the colors that are really transmitted depends on the medium's characteristics.

[1] Breve Historia de la Óptica (José Villasuso) http://bibliotecadigital.ilce.edu.mx

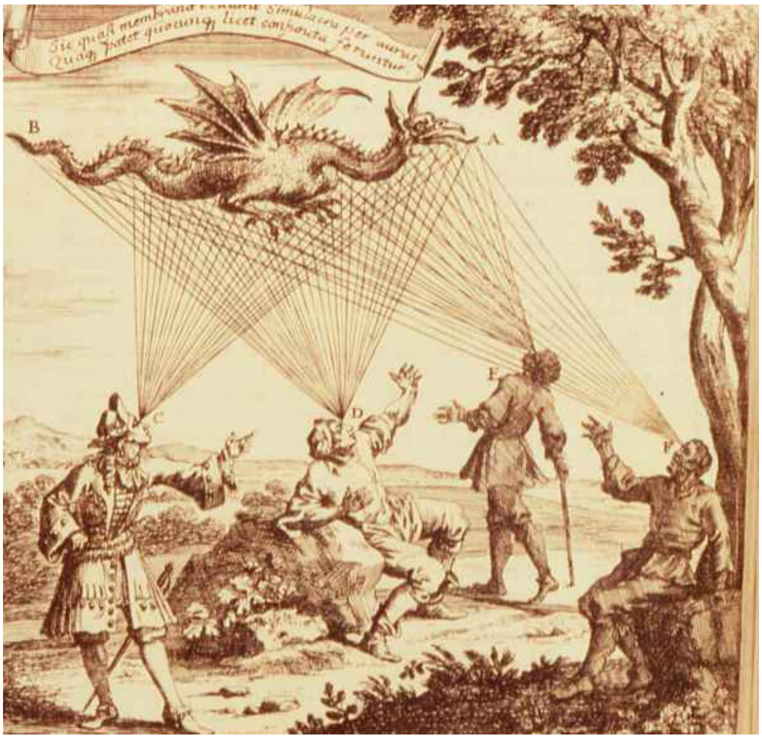

Figure 2. Medieval illustration representing the Platonic explanation of the phenomenon of vision. License: Public Domain. Source: `https://bit.ly/2Ssfqh2`

Apart from explaining the phenomenon of vision, Greek mathematicians were also interested in the geometric aspects of optics. Amongst the different contributions, of particular note are those made by **Euclid**, who defended the rectilinear propagation of light and the equality of the angles of incidence and reflection[1].

1.2. Archimedes and the defense of Syracuse

Owing to his supposed defense of Syracuse using a system of large mirrors, Aristoteles could be considered the precursor of **solar thermal power**, in which, by means of a mirror system, the sun's energy is used to heat certain fluids and subsequently generate electric energy. This technology is also sometimes referred to as solar thermoelectric power or CSP: Concentrating Solar Power.

Even though using mirrors to cauterize wounds and for other purposes goes back to earlier times, **Archimedes** may be looked upon as one of the "fathers" of solar thermal power, or at least according to legend, as the historical veracity of his supposed defense of Syracuse from being attacked by the Romans using **a system of large mirrors capable of concentrating the Sun's energy** and setting the Roman ships on fire, is not very clear. Apart from the system's supposed technical viability, doubts also arise owing to the fact that the first historical sources to mention the event are from a much later date.

However, several attempts have been made to replicate this supposed system (which, if it

[1]When the light strikes a surface, for example a mirror, and is reflected, the angles that form the incident "rays" and those reflected by the reflective surface, are identical.

Figure 3. An engraving which depicts Archimedes' supposed defense of Syracuse using a mirror system for focusing the sun's rays. License: Public Domain.

existed, was not very successful as Syracuse eventually surrendered, and Archimedes was killed by a Roman solider): from the "Myth Buster" program[1] to the very MIT (Massachusetts Institute of Technology)[2], with varying results.

Important 2.1: The death of Archimedes

Archimedes was a great scientist, with noteworthy contributions to mathematics, physics, engineering and astronomy. Amongst his greatest contributions are those made to integral calculus, to estimating the value of pi, to formulating the law of the lever and designing the compound pulley and to founding the law of hydrostatics.

Archimedes died during the Roman conquest of Syracuse, even though the military authorities had given orders that he should not be harmed. Although there is more than one version of the event, it seems that his death may have been caused by his "genius" character, since he refused to follow the instructions of a Roman soldier whilst busy working on a problem.

Archimedes' work later influenced a great number of scientists and certainly changed the field

[1] You can see the video at the following link: `https://youtu.be/kAWBvZcBZOU`

[2] You can consult information about the MIT experiment at the following link: `http://bit.ly/1md1NdI`

of optics. There was Heron, for example, who studied different forms of mirrors, both concave and convex planes.

Question 2.1: The death of Archimedes

As an activity, investigate the alleged truth about the defense of Syracuse with large mirrors. With the sources that you have consulted, draw your own conclusions: Do you think that Archimedes' story was real?

1.3. Understanding reflection and refraction

Using this historical overview a pretext, we will now briefly pause at the figure of **Claudius Ptolemy** in order to explain two interrelated and fundamental phenomena that form part of optics and our daily life: the **reflection and refraction** of light.

Ptolemy, who lived in Egypt during the 2nd Century AD, it is believed working at the famous Library of Alexandria, made noteworthy contributions to various fields. Probably his greatest contributions were those concerning astronomy, in particular his proposal of the famous geocentric universe model, situating the Earth, motionless, at its center with the remaining celestial objects orbiting it.

Figure 4. Drawing of Claudius Ptolemy from a 16th century book. License: Public Domain. Source: `https://bit.ly/2OUONoy`

However, he also carried out studies and work in the fields of geography, music, astrology and, of course, optics. In this latter field, he endeavored to study the properties of light, more specifically the phenomena of reflection and refraction. In one of his books on optics, he writes about the construction of a device to precisely measure the angles of incidence and refraction, in an attempt to find a relationship between the two, although he was not able to formulate a law in this respect.

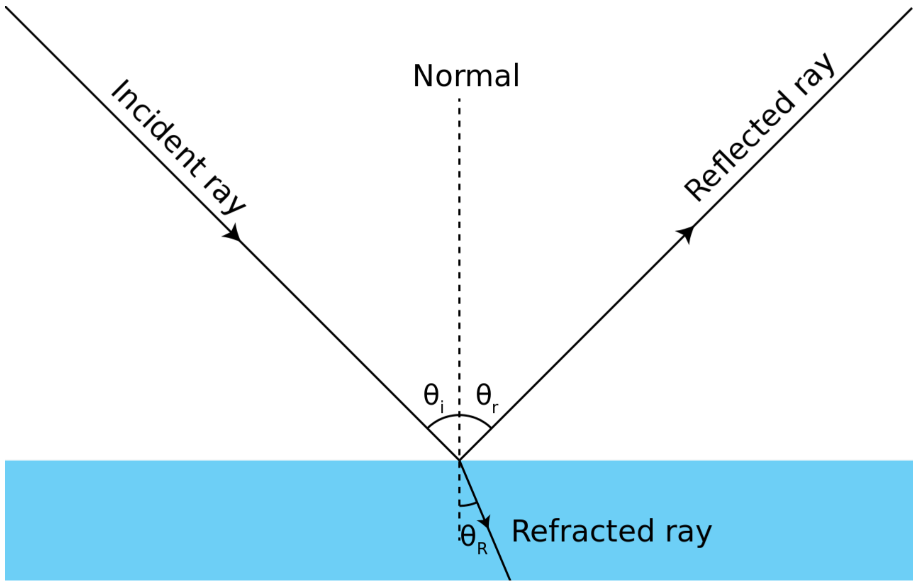

Figure 5. Diagram showing the phenomena of the reflection and refraction of light. License: (Public Domain (modified)). Source: `https://bit.ly/2RgvHUS`

In this sense, he wrote tables with values of angles for several different transparent media and he went as far as to affirm that the rays coming from the stars are refracted in the air, which is why the path (of light) observed is different from the real path.

1.3.1. The reflection of light

How can we explain the phenomena of the **reflection and refraction** of light? Let's start with the first one, which we are familiar with and would probably be capable of explaining intuitively: the **reflection** of light is the phenomenon produced when propagating light hits a "different" medium (or a medium of a different nature), changing and inverting its direction of propagation.

We see this phenomenon of reflection on a day to day basis, for example every time that we look in a mirror. Another example of this is when light traveling through the air hits water, for example the sea. This situation is represented in Figure 6, where we can see the reflection produced in the temple's water (situated in Singapore).

A final (and interesting) example that we are used to seeing is the reflection of light in people or animals in photographs. Figure 7 illustrates this with the example of a friendly cat. Why do its eyes shine so brightly? This is due to the reflection of light: the light that penetrates into the eyes of dogs or cats reaches the retina and is detected there by photoreceptors (cells specialized in converting light into electric signals which can be interpreted by the brain). However, a large part of the light is not detected and hits the back wall of the eye. In dogs and cats, this surface reflects the light, thus increasing the possibilities of the light being detected on the way back. All the light that is not absorbed by the photoreceptors emanates from the eye, causing this interesting effect shown in the picture.

To conclude this brief explanation on the reflection of light, it remains to say that the angle at which the ray is reflected by the surface is identical to the angle that the incident ray forms with that surface. This is clearly shown above in Figure 5.

Figure 6. Example of the reflection of light in water (Singapore Temple). License: (Public Domain). Source: `http://bit.ly/2BJaVWS`

Important 3.1: The refractive index

As previously commented, light is reflected (or refracted) when it hits a “different” medium or a medium of a different nature. A more technical explanation could be that light undergoes these phenomena when it encounters a medium whose refractive index is different from the index of the medium through which is travelling.

The refractive index n gives us an idea of the speed at which light travels in a medium. For example, the refractive index of air is $n = 1$, whereas that of water is $n = 1{,}33$. Light travels faster in air than in water, so we can see that the speed of propagation of light in a medium is inversely proportional to that medium’s refractive index. Intuitively we could say that **the denser the medium, the slower light travels in it**.

Important 3.2: The speed of light

Are you surprised by what we have just said? Maybe you thought that the speed of light was constant and what is more, as Albert Einstein postulated, was the maximum possible speed of travel in our universe, $c = 3{\cdot}10^8 m/s$. In fact, that is the speed of light in vacuum. As just pointed out, the speed of light depends on the characteristics of the material through which it travels. For example, the refractive index of diamond is 2,42, thus the speed of light in diamond is $v = c/2{,}42$.

Figure 7. Example of the reflection of light in the eyes of a cat. License: (CC BY-SA 3.0). Source: `https://bit.ly/2D8TVxb`

1.3.2. The refraction of light

Although reflection is probably a more intuitive phenomenon, we are all also used to observing the phenomenon of the refraction of light in our everyday lives. Look at the example in Figure 8: when we see a pencil placed inside a glass of water, the part of the pencil immersed in the water looks "bent" or "twisted" in comparison with the part above the water.

Figure 8. Example of the refraction of light with a pencil and a glass of water. License: (CC BY-SA 4.0). Source: `https://bit.ly/2PzbAUs`

Why does this happen? Because of the phenomenon of **refraction**, which occurs when the light passes from one medium to another, for example from air to water, these being media with different "optical densities" or refractive indexes. When light passes from air (with a refractive index of 1) to water (with a refractive index of 1.33), it experiences a change in speed and consequently direction. Why does the pencil look bent? We will try to explain this with Figure 9. The rays of light travelling from the part of the pencil not immersed in the water to the eye, travel in a straight line. However, the rays of light travelling from the part of the pencil immersed in water to the eye, travel along a "bent" path. If we take the end of the pencil as a reference, point **X**, we can see how the light rays set off in one direction, but when they reach the boundary between water and air, they undergo a deviation from their original path and travel ultimately to the eye. Thus the eye thinks that the end of the pencil is really at **Y**, that being the direction of the light rays that reach it.

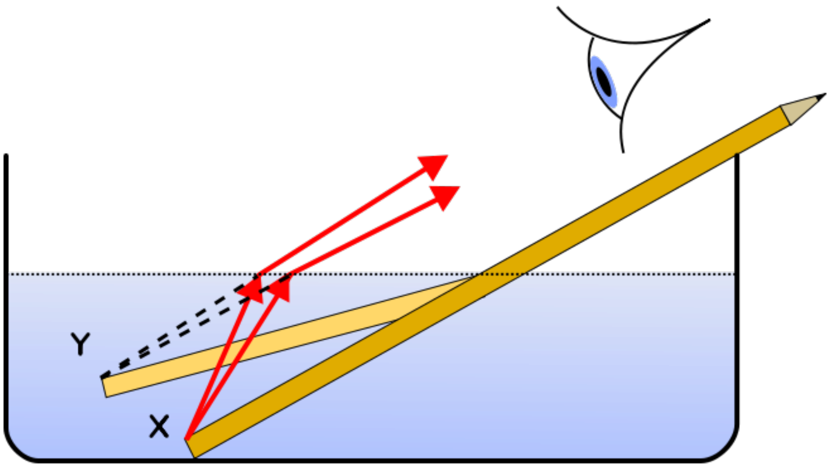

Figure 9. Observing the phenomenon of the refraction of light using a pencil and a glass of water. License: (CC BY-SA 3.0). User: Theresa knott. Source: `https://bit.ly/2ABEfQv`

The diffraction of light explains an infinity of processes, from human vision (how light is focused on the retina), to the functioning of eyeglasses or lenses for vision or the formation of a rainbow. We will return to this topic in subsequent chapters, but for now we will continue with the theme of this chapter: the History of Optics and Photonics.

1.4. Al-Hazen: the father of modern Optics

Al-Hazen (965-1039 d.C.) is a fascinating figure, like someone out of a far-fetched movie. Alhazen (or Alhacen) was born in present-day Irak around the year 965 AD. He had a strong inclination towards the sciences and made important contributions to mathematics, geometry and astronomy. Alhazen arrived in El Cairo during the reign of Al-Hakim, a Caliph who was greatly interested in astronomy and had one fundamental objective, to control the flooding of the Nile that caused so much harm to the region. Alhazen offered to solve the problem by building a dam at the current site of the Aswan dam, but he soon realized the impossibility of the project and gave up.

Legend has it that Alhazen, fearing the Caliph's ire who could have sentenced him to death for not fulfilling his task, feigned madness. Thus he escaped death, but was imprisoned between the years 1011 and 1021. Making the most of his reclusion, it was precisely during this period that he made certain observations concerning light that led him to make surprising contributions in fields such as:

Figure 10. Representation of Alhazen imprisoned from the documentary "Light Fantastic" by the BBC. Source: YouTube. Standard YouTube License.

Optics of lenses and mirrors He made lenses, he built parabolic devices like the ones now used in modern telescopes and he studied the focusing properties that they produce. He was on the verge of discovering the magnifying glass theory that was developed in Italy three centuries later. He studied the property of curved glass surfaces in increasing the dimensions of objects and tested the refraction of rays in a transparent medium[1] using glass decanters filled with water.

The nature of light He studied shadows, eclipses and the nature of light.

Dispersion He also carried out the first experiments on the dispersion of light into its different colors.

The human eye and the process of vision He was the first person to provide a precise description of the parts of the eye and to give a scientific explanation concerning the process of vision. Contradicting the theory of Ptolemy and Euclid that the eye emits ocular beams to objects, he instead believed that light rays go from the objects to the eye.

Camera obscura He was the first person to correctly analyze the principles of the camera obscura (the pinhole image) that consists of a dark room or box with a small hole in one of its walls. An inverted image of the objects outside is formed on the opposite wall. This device is the antecessor of the modern photographic camera.

Speed of light He anticipated a fundamental discovery that light travels at a finite speed.

[1] https://bit.ly/1IF1aDH

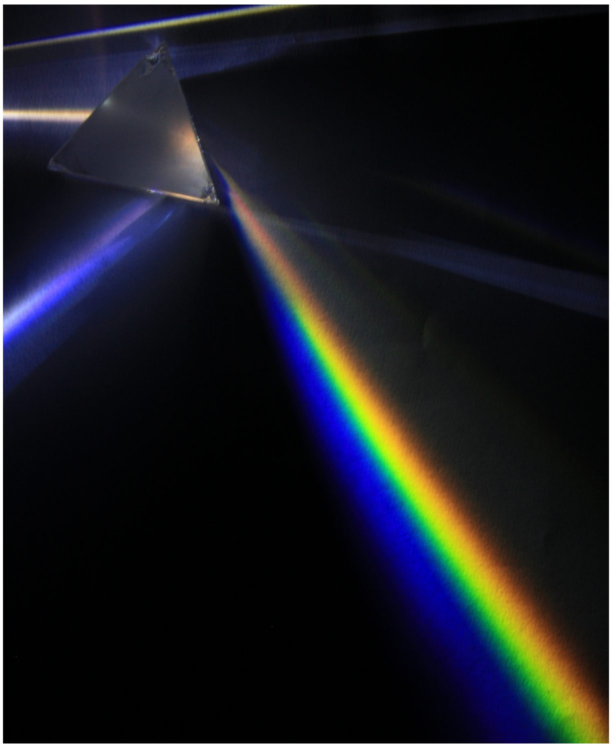

Figure 11. The dispersion of light caused by a prism. Source: Wikimedia Commons. License: CC-by-SA 3.0. `https://bit.ly/2qIEW4R`

Important 4.1: Dispersion of light

Dispersion was mentioned in the aforementioned list as one of the contributions made by Alhazen: Do you know what that means?

The **dispersion of light** is the phenomenon produced when a light ray (let's imagine from the sun) crosses a "dispersive" medium, for example a prism (see Figure 11). We are probably familiar with this image, in which light is "broken down" or "dispersed" into its different colors. This phenomenon is directly related to refraction, as it occurs because each "color" travels at a different speed in the material and, therefore, undergoes a different angle of refraction. This occurs because the material's refractive index is dependent on the wavelength or frequency of light.

Don't worry, we will explain this concept again further on. Let's continue with our fascinating overview.

Question 4.1: Observe dispersion at home!

Even if you don't have a prism like the one in the picture, it is in fact very easy to observe this phenomenon at home. Have you got a CD handy? If you have, take it and tilt its underside towards a source of light in your home, for example a fluorescent lamp. Move it slightly and if you're lucky you'll see how different colors appear.

In short, from what we have said, it is evident that Alhazen has been fundamentally important in our understanding of different phenomena concerning light and vision. His work also considerably influenced other scientists such as Roger Bacon or Leonardo Da Vinci.

1.5. 1.5. Roger Bacon: philosopher, theologian and scientist

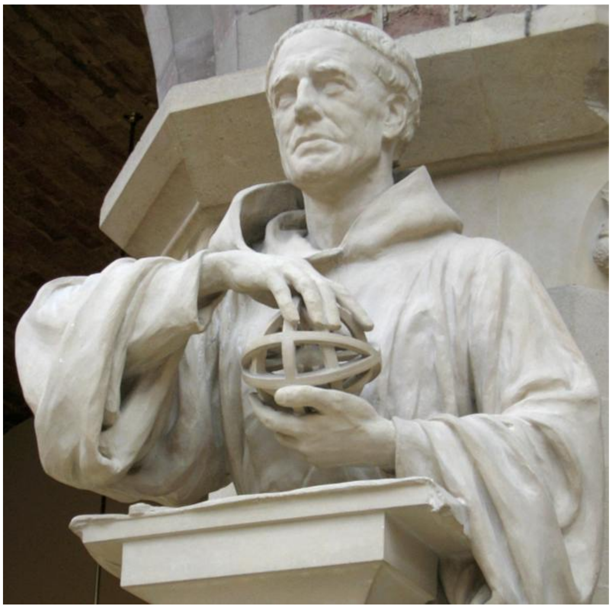

Figure 12. Statue of Roger Bacon at the Oxford University Museum of Natural History. Source: Wikimedia Commons. License: CC-by-SA 3.0. Source: `https://bit.ly/2DdsylK`

The name of the Franciscan friar Roger Bacon (1214-1294) is usually rapidly associated with the modern scientific method, as he was one of the first thinkers to propose and defend this approach. Besides his contributions to philosophy and theology, Bacon is commonly considered to be the father of lenses or spectacles, by quoting in one of his works that a piece of glass allows observing objects with magnification, which could assist weak eyes or the vision of aged persons.

Bacon, who also foresaw the use of the microscope and telescope, was clearly influenced by the work of Alhazen as regards his contributions to optics, although he also contributed studies in mathematics, astronomy and alchemy.

Unfortunately, Bacon was persecuted and imprisoned by the church for 14 years and his writings were censured. The fact that Pope Clement IV was a great admirer of Bacon probably prevented his work from being lost and his life from being sacrificed before time[1].

Important 5.1: Lenticular lens

Roger Bacon is believed to have made the first lenses in 1266. The name lens derived from its shape in the form of a lentil: interesting!

[1] https://bit.ly/2OhusTw

Important 5.2: Eyeglasses

Quartz and sea water were used to make the first eyeglasses, but as their demand increased it was necessary to manufacture optical glass which breaks easily and is therefore dangerous. Since then, glasses have evolved according to society's needs.

1.6. The evolution of lenses and glasses

The development of the first lenses is usually associated with the glassmakers of Venice and more precisely with the area of Murano Island. These lenses, originally intended for just one eye, were carved at the workshops of these famous glassblowers.

Once lenses had been developed, the following step consisted in adding a frame, which occurred approximately between the years 1285 and 1300. This configuration is attributed both to **Alexandro della Spina** (Dominican monk from Pisa) and **Salvino de Armati** (Florence).

It is important to emphasize that the first known lenses were convergent, in other words, they focused the rays or beams of light incident on the lens on one single point (as the human eye does), whereas divergent lenses disperse the beams in different directions. This is clearly shown in Figure 13.

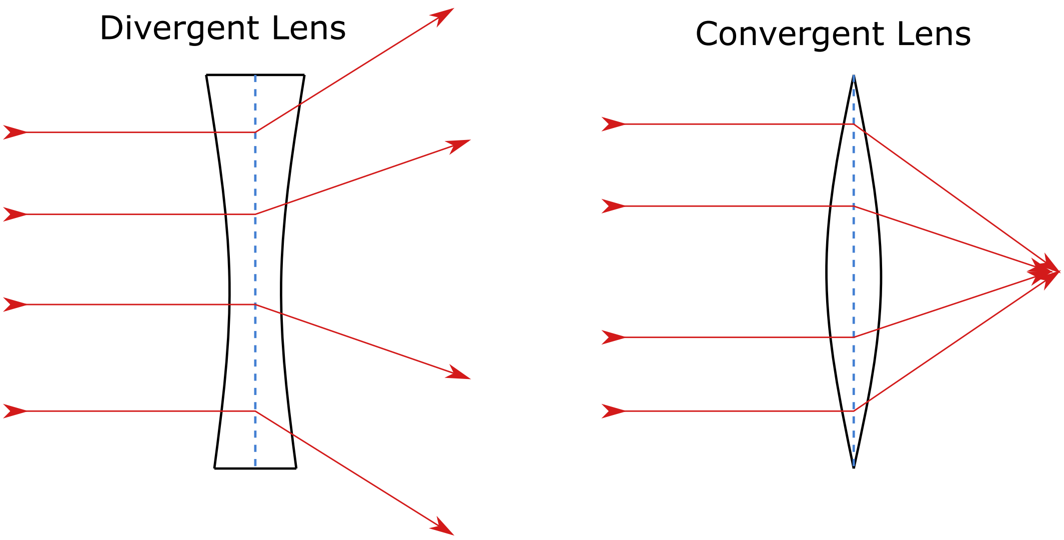

Figure 13. A diagram showing convergent and divergent lenses. Source: Author's own work.

At a later date, written references to the use of lenses for aiding vision appeared. The book "Liliban Medicinae" (1299) indicates the use of lenses sent from the East to Europe (in this case Italy) as a remedy for vision. **Francesco Petrarca** (1304-1374) expresses in his *Letter to Posterity* that at the age of 60 he needs glasses for reading. The first painting (by Tomasso da Modena) to depict a person wearing eyeglasses dates from the year 1352, that person being Cardinal Hugh of Provence. The painting (see Figure 14) can be seen in the Church of St. Nicholas in Treviso.

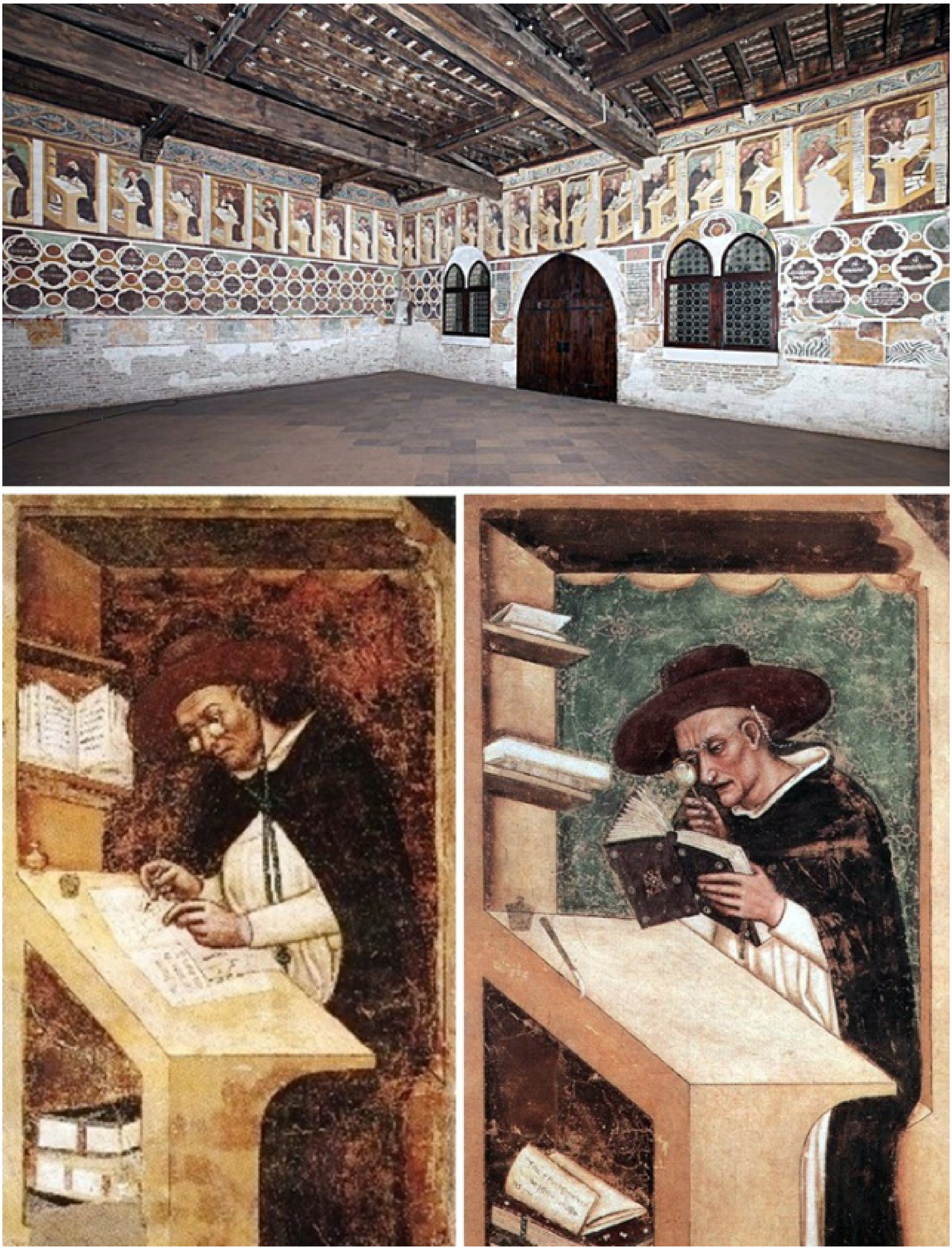

Figure 14. The Church of Saint Nicholas in Treviso (Above) and paintings of Cardinal Hugh of Province. Source: Histoptica.com. `https://bit.ly/2SwU9Tc`

Important 6.1: The Name of the Rose

In the movie **The Name of the Rose**, based on the novel of the same name by Umberto Eco, the main character (William of Baskerville, played by Sean Connery, a Franciscan friar and former inquisitor who has great "detective-like" attributes) uses spectacles to consult texts concerning crimes that occur at the abbey. In fact, these spectacles are stolen from him at one point, greatly hindering his investigations.

Figure 15. Sean Connery in a scene of the movie **The Name of the Rose**. Source: radicalbarbatilo.blogspot.com.es. https://bit.ly/2OdLBgF

Question 6.1: Myopia and Presbyopia

What are the principles behind using lenses (glasses, contact lenses) for correcting the effects of myopia and presbyopia on vision?

Briefly explain the two pathologies and indicate what kind of lens must be used to correct vision in each case.

1.7. Leonardo da Vinci

In our journey through the history of optics, we have now come to one of the greatest scientific geniuses of all time: the great Leonardo da Vinci.

Da Vinci (1452-1519) has made an overwhelming number of contributions to a great number of different fields. This is evident from the following Wikipedia[1] extract:

[1] https://bit.ly/1N1dPZI

"Leonardo da Vinci.....was an Italian polymath of the Renaissance, whose areas of interest included invention, painting, sculpting, architecture, science, music, mathematics, engineering, literature, anatomy, geology, astronomy, botany, writing, history and cartography."

As regards his contributions to optics, Leonardo studied the **structure and functioning of the human eye**, although, like his predecessors, he believed that the ability to see fundamentally resided in the crystalline, instead of in the retina. To support his theories on vision, he made use of the functioning of the **camera obscura**[1]. Figure 16 shows a diagram of a camera obscura from the time, as well as sketches by Canaletto drawn with the help of a camera obscura.

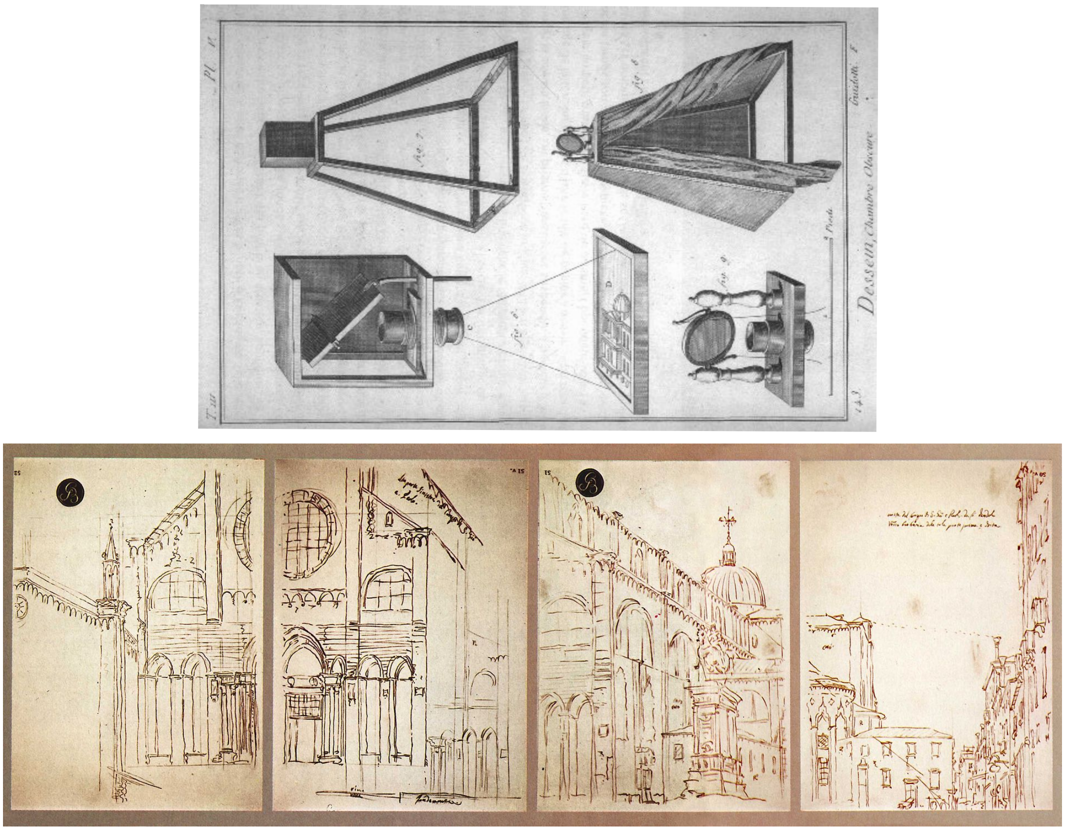

Figure 16. Diagram of a camera obscura (top) and sketches obtained using a camera obscura (Canaletto: The Basilica of Saints John and Paul, Venice). Source: Wikipedia. License: Public Domain. `https://bit.ly/2dfTWDW`

Leonardo also designed various machines intended for the manufacture of large mirrors (probably influenced by the story of Archimedes' defense of Syracuse), although he never built any of them. Furthermore, he was also the first person to suggest using contact lenses for correcting vision problems.

[1]Instrument commonly used by painters of the time, which basically enabled projecting an external image on a flat surface.

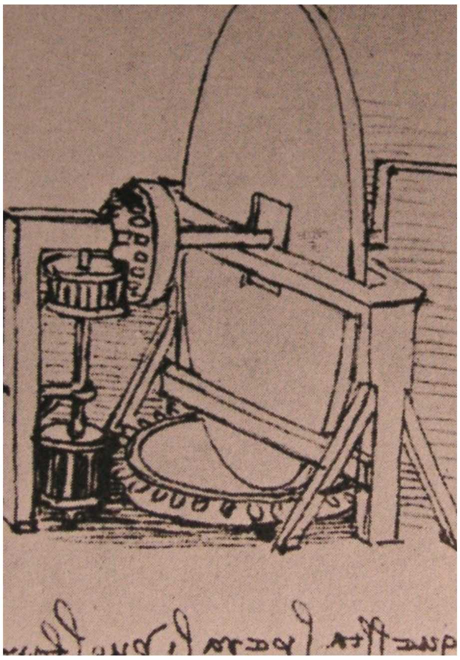

Figure 17. Sketch of a machine designed by da Vinci for manufacturing large mirrors. Source: Wikipedia. License: Public Domain. `https://bit.ly/1N1dPZI`

1.8. Telescope: “spying” at a distance

The invention of the **telescope**, at the end of the 16th century or the beginning of the 17th century, is enshrouded in controversy and mystery, as we do not know exactly who the real inventor was. The first candidate is the Italian **Gianbattista della Porta** who, in 1589, wrote a description of what appears to be a telescope in his book Magia Naturalis. The second candidate is the Dutch **Zacharias Janssen** in 1590, as writings have been found affirming this. However, the most probable inventor of this instrument is a Dutch spectacle-maker called **Hans Lippershey** as, according to thorough historical research, he built a telescope in the year 1608.

These discoveries are found in his book “Sidereus Nuncius”, (”The Starry Messenger”). Following its publication, it sold out in just a few days and spectacle-makers began to make increasingly bigger and more powerful telescopes.

However, the story of the telescope’s invention does not end here: some years ago, research carried out by Nick Pelling (a British computer programmer and historical investigative journalist) was published in the magazine History Today. According to this study, the telescope was really invented in 1590 by a man from Girona called Juan Roget. This theory claims that Zacharias Janssen had copied Roget and tried to patent the invention. However, Hans Lippershey also tried to patent it in Holland, after carrying out a demonstration to Prince Maurice of Nassau in the middle of the civil war; and even two other Dutch craftsmen. This “conflict” dissuaded the Dutch authorities from granting the patent.

Important 8.1: The invention of the telescope

This article from “El País” further explores this fascinating story:

`https://bit.ly/2z3ayHa`

1.9. Galileo: and yet ...

... it moves! This is the phrase (allegedly) muttered by Galileo (1564-1642) following his adjuration associated with the legal action initiated by the church against him for his heliocentrist postulates. But let's start at the beginning: Galileo Galilei was an Italian philosopher, astronomer, physicist, mathematician and engineer. In 1583, he decided to focus on this vocation for mathematics and began a successful scientific career with important contributions, such as the law of uniformly accelerated motion.

Figure 18. Galileo showing the telescope to the Doge of Venice. Source: Wikipedia. License: Public Domain. `https://bit.ly/1NFSeCx`

In 1609 he learned about the telescope and immediately manufactured various models (simply from a description of the invention) whose characteristics he gradually improved, mainly their magnification[1][2]. With his telescopes, Galileo began to make several observations and discoveries that convinced him that his intuition was right: the geocentric model is incorrect and the Earth is not the center of the Universe.

What discoveries did Galileo make that supported the heliocentric model or the Copernican theory?

1. Mountains on the moon

2. New stars

[1] Actually Galileo did not master the optical theory, which meant that many of his telescopes were not really useful.

[2] Galileo bequeathed the rights of the telescopic to the Venetian Republic, highly interested in its military applications.

3. Jupiters'moons
4. Sun spots
5. Venus'phases
6. Tide theory[1]

With his claims, Galileo earned considerable scientific recognition. However, as we all know, he faced opposition from the Church which brought him to trial in 1633 and, under the threat of torture, he confessed and recanted his theories, which allowed him to remain under house arrest, instead of in prison. Galileo died at the age of 77 and the Church, over the years, slowly accepted his work. In the 18th century, Benedict XIV authorized the works on heliocentrism and in the 20th century, from Pius XII onwards, tribute started being paid to Galileo.

Figure 19. Galileo before the Holy Office, by Joseph-Nicolas Robert-Fleury. Source: Wikipedia. License: Public Domain. `https://bit.ly/1NFSeCx`

Pope John Paul II asked for forgiveness for the errors made by the Church in the past. As for the Galileo case, in 1979 he expressed his wish for there be a sincere and impartial re-examination of the matter, but the Commission that he appointed for this purpose in 1981 and which reached its conclusions 1992, once again confirmed the thesis that Galileo lacked scientific arguments to prove heliocentrism and maintained the innocence of the Church as an institution and Galileo's obligation to recognize and yield obedience to its Magisterium, justifying the sentence and avoiding a full rectification[2].

[1] For more information on these matters, go to: `https://bit.ly/1NFSeCx`
[2] `https://bit.ly/1NFSeCx`

Important 9.1: Galileo: Documentary

If you want to further explore the figure of Galileo, you can consult the documentary at the following link:

`https://bit.ly/2z5X1yh`

1.10. Snell's Law

Although it may sound like the title of a Clint Eastwood movie, the law postulated by **Willebrord Snell** (1581-1626) is fundamental in the world of optics. Snell's law is simply the law that explains the refraction of light. As mentioned earlier, this was something that greatly occupied early scientists. With his measurements of the angles formed by the rays refracted and reflected at the interface[1] between two media like air and water, he was capable of deducing the law that defines, generically, the refraction and reflection of light.

The formula, shown below, is very simple:

$$n1 \cdot sen(\theta_1) = n2 \cdot sen(\theta_2) \tag{1.1}$$

The law's explanation is also very simple as we can see in Figure 20. The angle θ_2 at which the light ray will be refracted when changing from medium 1 to medium 2, will depend on the angle of the incident ray (θ_1) and the refractive indexes of the two media n_1 and n_2.

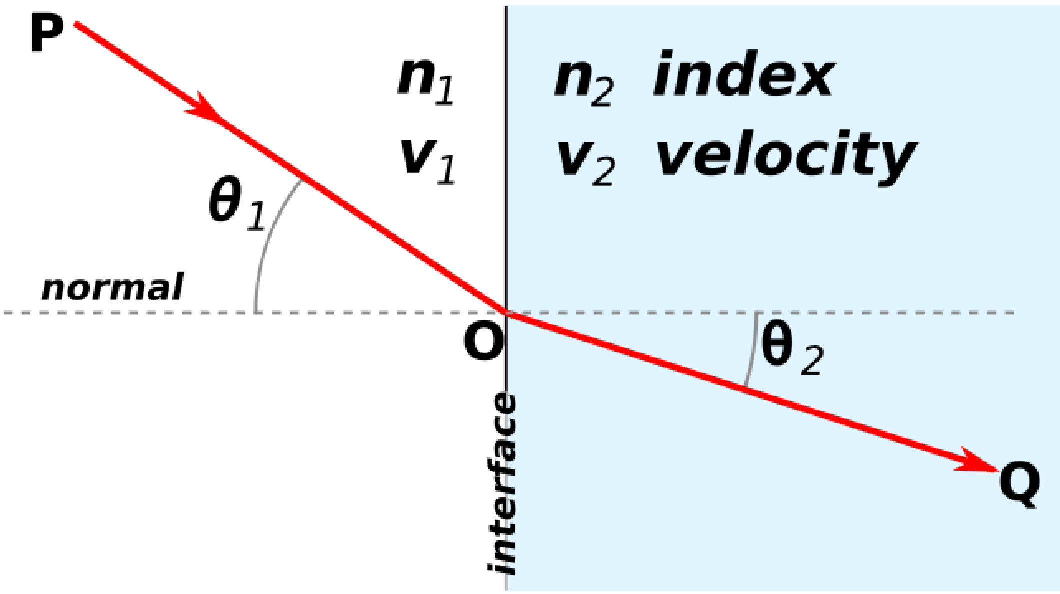

Figure 20. Law of refraction or Snell's law. Source: Wikipedia. License: CC-by-SA 4.0. `https://bit.ly/1QwXLkM`

[1] By interface, for example between air and water, we refer to the point (surface) where the two media come into contact.

Important 10.1: Equations?

Don't worry! We're not going to see many equations in this course.

By the way, if you can't clearly remember the concept of the refractive index, you can look back at point 1.3 of this document.

1.11. The microscope and the father of microbiology

In the world of science, we often come across interesting people, real "renaissance men" like da Vinci or Galileo or people who, like **Antonie van Leeuwenhoek** (1632-1723), are capable of making fundamental inventions, without having any formal academic knowledge of the matter.

Van Leeuwenhoek was a Dutch businessman involved in the textile business, with a keen interest in the manufacture of lenses, so much so that he constructed his own microscopes. However, the invention of the microscope can probably not be attributed to Leeuwenhoek, the person worthy of this honor most likely being the aforementioned Zacharias Janssen.

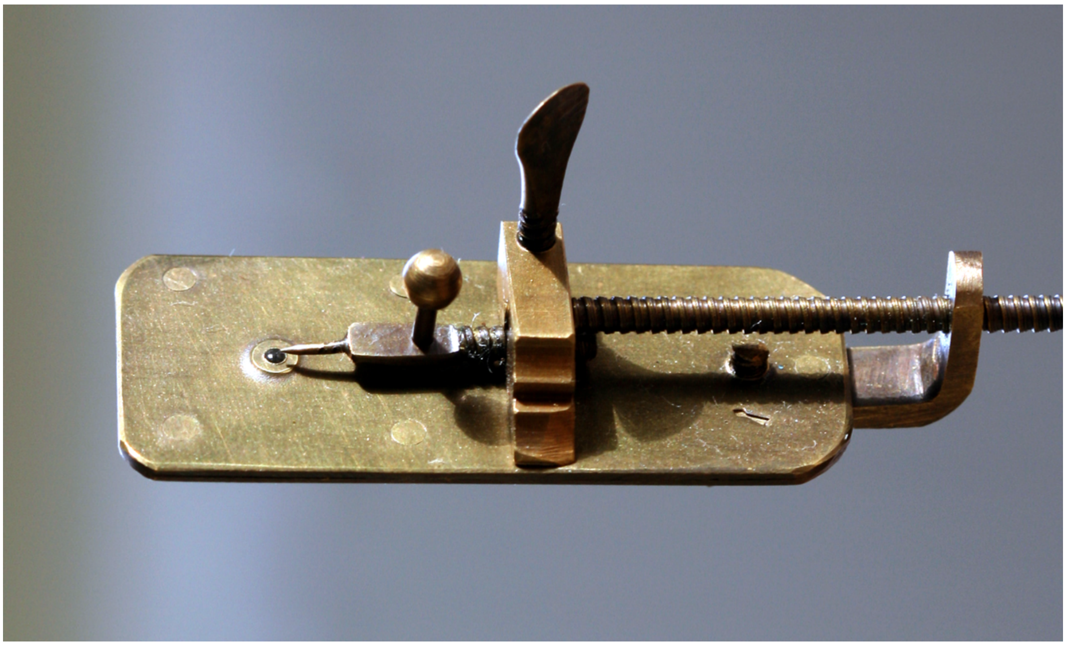

Figure 21. Replica of a microscope by van Leeuwenhoek. Source: Wikipedia. License: CC-by-SA 3.0. https://bit.ly/2eCJeo4

However, there is doubt that van Leeuwenhoek is considered to be the father of microbiology thanks to his astonishing observations: he was the first person to observe protozoa and bacteria (what he called "animalcules") and he was also the first person to see red blood cells and spermatozoids. These observations were possible owing to his microscopes with up to x200 magnifications. Van Leeuwenhoek is believed to have built more than 500 microscopes, a few of which have survived to this today.

Important 11.1: Van Leeuwenhoek's microscopes

In 2009, an original silver microscope made by Leeuwenhoek sold for £321,237.50 at the famous Christies's auction house[a].

[a] https://bit.ly/2ed0h19

Important 11.2: More about Van Leeuwenhoek

You can find out more about the life and work of the father of microbiology at the following links:

http://bit.ly/2ed0h19

https://youtu.be/0niSF8QrHac

1.12. Fermat's principle

Figure 22. Pierre de Fermat. Source: Wikipedia. License: Public Domain. https://bit.ly/2FhzmR3

Pierre de Fermat (1601-1665) was a distinguished French mathematician who made a great number of contributions to his discipline, such as differential calculus or probability theory. However, with regard to optics, his most celebrated contribution is **Fermat's Principle**, which states that:

"Light travels between two points along the path that requires the least time."

Former scientists, like our famous Alhazen, got close to this principle, which can be explained graphically using the lifeguard example (see Figure 23).

The picture shows a lifeguard on the beach who has to save a swimmer (represented by the ring buoy) who is being attacked by a ferocious shark. The simplest option for the lifeguard would be to go in a straight line to save the swimmer. However, everyone can run faster than they can

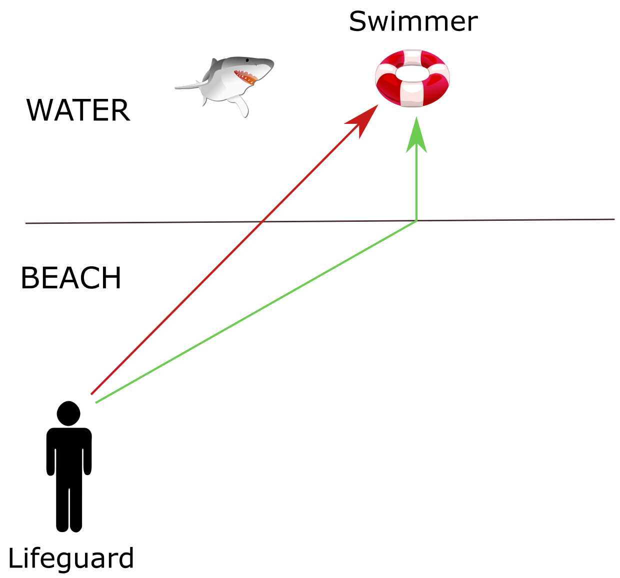

Figure 23. Diagram illustrating Fermat's Principle. Source: Author's own work.

swim, so this option means that the lifeguard would be wasting valuable time. The best option would be to minimize the part involving a lower speed, in other words, the part the lifeguard would have to swim. This option is shown in the picture by a green arrow.

This is precisely the strategy that light always follows: to follow the "optimal" path that minimizes the time it takes to go from one point to another. In fact, in the example shown, light would also follow the path indicated in green, since, just like the lifeguard, light travels faster in air (refractive index in air $n_{air} = 1$) than in water ($n_{water} = 1{,}33$), the speed of light being:

$$v = \frac{c}{n}, \tag{1.2}$$

where $\boldsymbol{v}$ is the speed of light in a certain medium, $\boldsymbol{c}$ the speed of light in vacuum[1] y $\boldsymbol{n}$ and n the medium's refractive index.

1.13. Huygens and Newton: waves and particles

In the previous sections we have seen how, as the years went by, knowledge concerning light and its associated phenomena gradually increased. However, in the 17th century the opinions of scientists were divided as regards one fundamental question: What is light: is it a wave or a particle?

Advocates of the **wavelike nature of light** included **Christian Huygens** (1629-1695). However, to understand this approach, maybe it would first of all be appropriate to define what a wave is. The fourth definition given by the Official Royal Institution for the Spanish Language is the one that we require:

The propagation of periodic motion in a physical medium or in vacuum.

[1] $c = 3{\cdot}10^8$ m/s.

 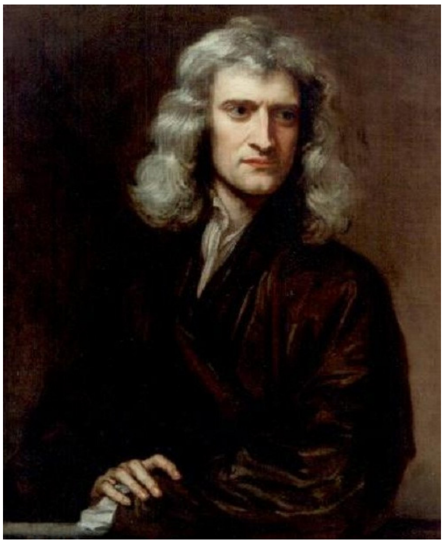

Figure 24. Portraits of Christian Huygens (left) and Isaac Newton (right). Source: Wikipedia. License: Public Domain.

In Physics, a wave is precisely the propagation of a disturbance through a certain medium. For example, when we speak, our voice is transmitted in the form of sound waves, which are simply disturbances of the density of the air propagated through the air from one speaker to another.

Another classic example is that of the waves formed in water when impacted by an object (Figure 25), or the very movement of the waves of the sea.

Figure 25. Example of the propagation of waves in water. Source: Pixabay. License: Creative Commons CCO.

Figure 26 shows a classic representation of a wave in science, where the horizontal x axis represents time and the y axis represents the intensity or amplitude of the wave.

Therefore light, according to Huygens and his followers, would be the propagation of a wave

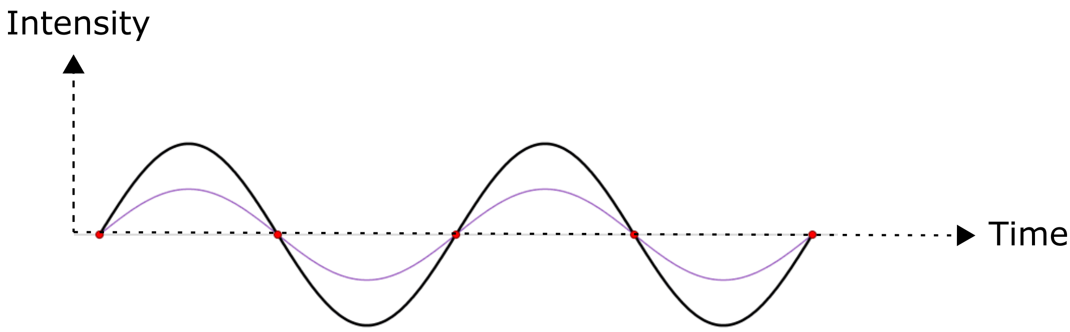

Figure 26. Physical representation of a wave. Source: Wikimedia Commons. License: Public Domain.

through different media: vacuum, air, water, glass, etc. However, another group of scientists, led by **Newton** himself, understood that light was in fact formed by **small particles** or "corpuscles" called **photons** (from the Greek word *phos/photos*: **light**).

Who was right? At the time, the majority of the scientific community supported Newton's theory, pushing aside the wavelike theory. However, which theory is considered to be valid today, four centuries later? We will explore this matter further in the following topic of this course: **Chapter 2: What is light? Waves and Particles**.

1.14. Thomas Young and the functioning of the Human Eye

Figure 27. Portrait of Thomas Young. Source: Wikimedia Commons. License: Public Domain. https://bit.ly/2ODL3kH

We have already seen how earlier scientists like Alhazen or da Vinci tried to explain how vision works, presenting different theories with varying degrees of accuracy. **Thomas Young** (1773-829) was an English doctor who devoted his time to studying the **functioning of the human eye**, establishing that the retina has three types of **photoreceptors** associated with the colors **red, green**

and blue (RGB). Each one of these cells reacts to each one of those colors, converting the light received into nerve impulses that are transmitted to the brain, where they are interpreted. In fact, as we will see in Chapter 6, there are two types of photoreceptors in the human eye: cones and rods, the former ones being those associated with red, green and blue.

Young is also famous for his well-known double-slit experiment, with which he attempted to obtain proof regarding the behavior of light as a wave or particle. We will see this experiment in class, but Figure 28 gives us a foretaste of what we will see when we do it. Why can we observe several "bands" on the lower image? This appears to prove light's behavior as a wave, but ...

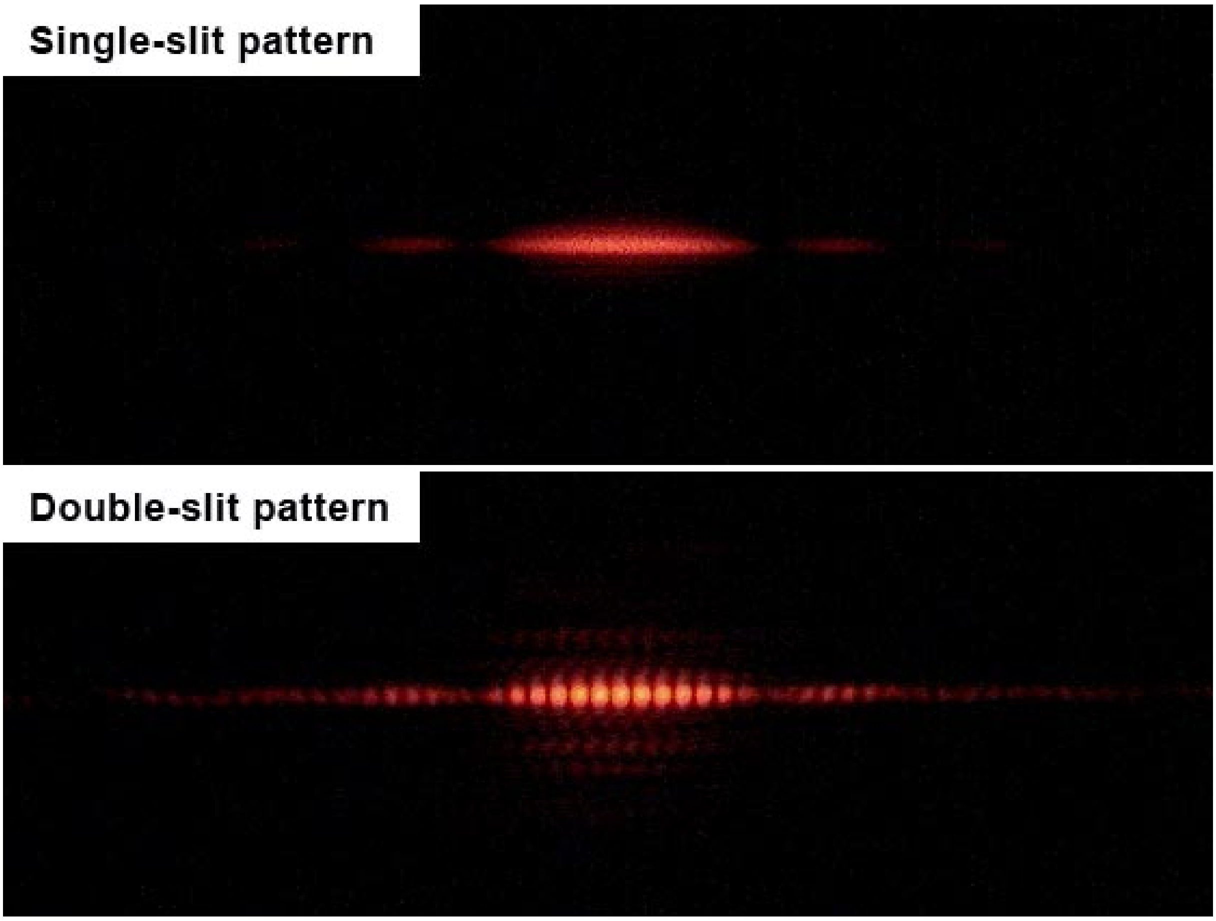

Figure 28. Example of the result of the slit experiment with one (top) and two (bottom) slits. Source: Wikimwand. License: CC-by-SA 3.0. `https://bit.ly/2zRfUog`

Important 14.1: Double-slit experiment

If you are interested in finding out more, there are lots of videos about this on YouTube, although you have to be careful because some of them explore the "quantum" phenomenon and may be a bit complicated. We will talk about this matter later on in the course.

In fact, if you have a laser pointer at home, you can easily try to replicate the experiment with the help of one of these videos.

1.15. Wollaston and the composition of the Sun

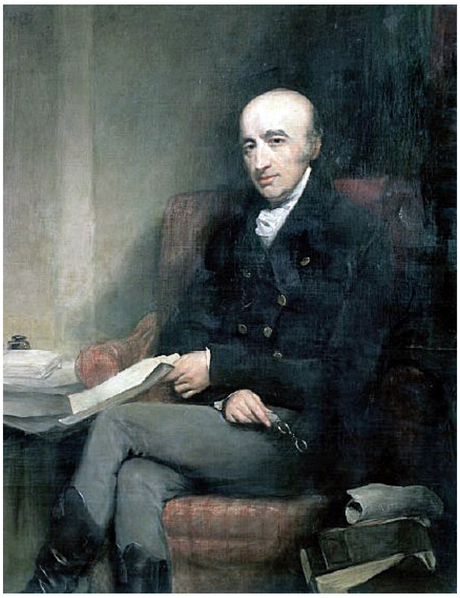

Figure 29. Portrait of William Hyde Wollaston. Source: Wikipedia. License: Public Domain. https://bit.ly/2QDWcng

William Hyde Wollaston (1776-1828) was renowned for his work in physics and chemistry although, interestingly, he had actually studied medicine. Wollaston made a number of contributions to the world of optics, such as his studies on the refraction of light, inventing a device which enabled him to measure the refractive "power" of solids.

Wollaston, who developed a method for processing platinum which made him rich, and also discovered various elements like palladium and rhodium, and even carried out several experiments which would lead to the development of the electric motor, made a particularly noteworthy contribution to the world of optics: he discovered dark lines in the Sun's **spectrum**.

Important 15.1: What is a spectrum?

When we talk about a **spectrum** in optics, we refer to the representation of light split up into its different **colors or wavelengths**. Let's take a look at the solar light spectrum. If we make a ray of sunlight shine through a prism, then we can split this light up into its different colors[a] (see Figure 30). If we then measure each color's contribution, using a device similar to a photographic camera, we obtain a representation like that shown in Figure 31.

As the light is split up into its different colors, we are capable of observing the contribution of ultraviolet (UV) (below 400nm) and infrared (IR) (above approximately 700nm), the greatest contribution being in the visible region of the spectrum (that which the human eye is capable of seeing), between violet (400 nm) and red (700 nm). The concept of **wavelength** will be explained in the following chapter of the course.

[a] As occurs with a rainbow.

Having explained the spectrum concept, we can now go back to Wollaston's key discovery. As already mentioned, in his observations of the solar spectrum, he noticed some "dark lines" that

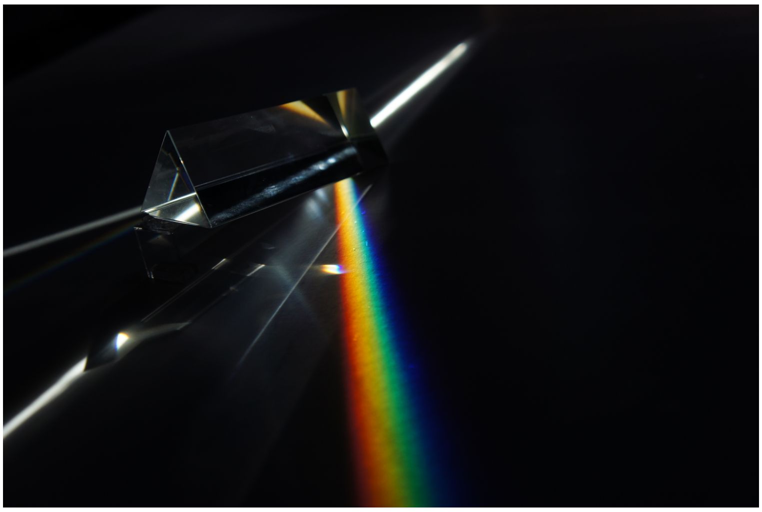

Figure 30. Light split up (dispersed) into its different colors when going through a prism. Source: Wikipedia. License: CCO 1.0. `https://bit.ly/2z5RgRt`

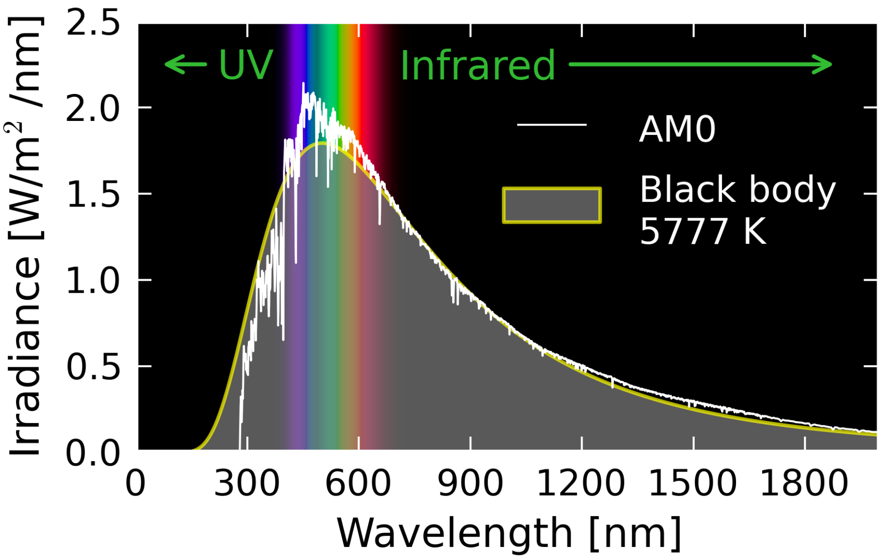

Figure 31. Solar spectrum. Source: Wikimedia Commons. License: Public Domain. `https://bit.ly/2RU4yHL`

seemed to separate the different colors, as can be appreciated in Figure 32. Half a century later, and following the observations of the Bavarian glassmaker **Joseph Fraunhofer**, **Kirchhoff and Bunsen** demonstrated that Fraunhofer lines were the **fingerprints of the elements present in the Sun's atmosphere**. **Spectral analysis** invented by Fraunhofer could serve, therefore, to make an astronomer's dream come true: to determine the chemical composition of both the Sun and other stars. This is how Astrophysics came about. Spectral analysis will be explained in greater detail in Chapter 5, for example by means of the technique known as LIBS (*Laser-Induced Breakdown Spectroscopy*), which enables analyzing the composition of materials using a laser, like the one used by Curiosity, the robot currently exploring Mars[1].

[1] You can find out more information at the following link: `https://bit.ly/2RLD190`

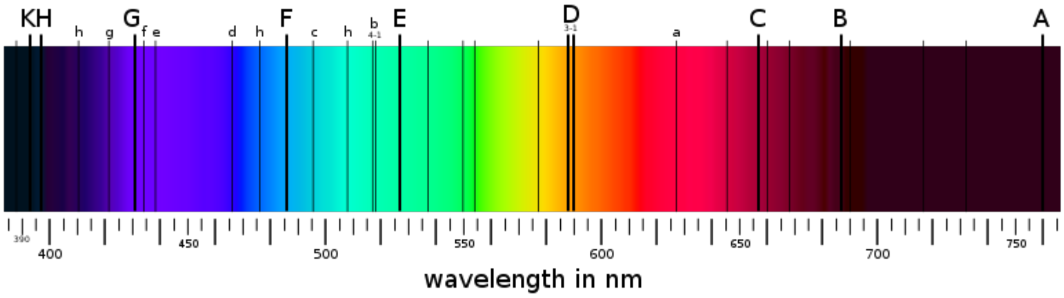

Figure 32. Fraunhofer's spectrum. Source: Wikipedia. License: Public Domain. `https://bit.ly/2DAV80A`

1.16. William Herschel and the discovery of invisible light

Nearing the end of this fascinating journey through the history of optics, we are now about to discover an exceptional figure, a musician in fact, who had a passion for astronomy and made great contributions to the science, like the discovery of the planet Uranus and many other celestial objects using telescopes which he had built himself. In the world of optics, he tried to develop the wavelike theory, maintaining that light propagates in a similar way to sound.

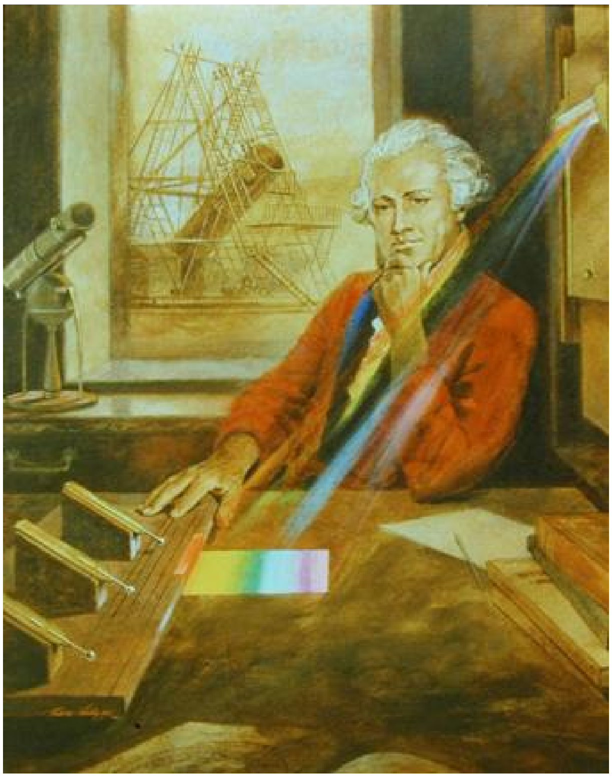

Figure 33. Portrait of William Herschel and his experiment. License: Public Domain.

Figure 33 depicts Herschel when discovering infrared light, which as we know is invisible to the human eye. Herschel split the light up into its different colors using a prism and thermometers to measure the energy associated with each color. Whilst carrying out the experiment, he realized something apparently inexplicable. In an area where light could not be seen, one of the thermometers showed a temperature higher than room temperature: How could that be? As Herschel correctly conjectured, the only reasonable explanation was the presence of radiation invisible to the eye: infrared radiation.

1.17. Maxwell and the Electromagnetic Theory

Figure 34. James Clerk Maxwell. Source: Wikipedia. License: Public Domain. `https://bit.ly/1OEhgSC`

James Clerk Maxwell (1831-1879) is, for many, the most important physicist of the 19th century, and had a great influence on 20th century Physics.

Maxwell developed the **classic electromagnetic theory**, synthesizing all previous work on electricity, magnetism and light. Maxwell's famous equations show that **electricity, magnetism and light are all manifestations of the same phenomenon, the electromagnetic field**.

1.18. 1.18. Becquerel and Hertz: the photoelectric effect

Towards the end of the 19th century, various experiments were developed that are the cornerstone of present-day **solar photovoltaic energy**.

Edmund Becquerel (1820-1891) was a French physicist who studied the solar spectrum, carried out work on luminescence and phosphorescence and discovered the **photoelectric effect** whilst experimenting with metallic electrodes in a conductive solution.

Important 18.1: Photoelectric effect

The **photoelectric effect** is based on the fact that certain materials are capable of generating electricity when light shines on them, as occurs with a solar photovoltaic panel.

For his part, Hertz, who had a real passion for physics, focused his studies on **electromagnetic waves**, for example demonstrating the existence of VHF and UHF waves. In fact he noticed the photoelectric effect whilst carrying out experiments with electromagnetic waves, although

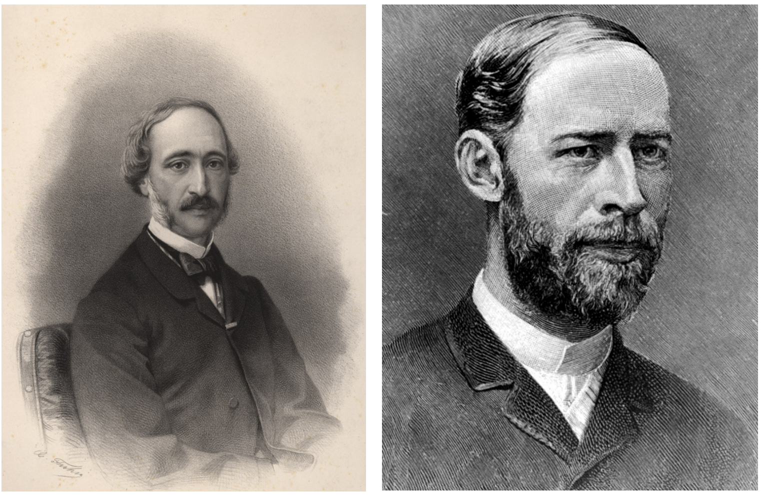

Figure 35. Edmond Becquerel (left) and Heinrich Hertz (right). Source: Wikipedia. License: Public Domain.

without attaching much importance to it. This was the general tone of his scientific career, as through his work he made it easier for other scientists to achieve important contributions, such as in the case of Marconi and the **radio**.

1.19. Conclusions

We have not really come to the end of the history of optics yet, but as our next figure, the very Albert Einstein, serves as a link to the birth of Photonics, we will wait until Chapter 4 to cover the final part of this great adventure: the short (but very important) history of Photonics.

This chapter has provided a brief historical overview of the evolution of optics, from the use of lenses and mirrors by the Egyptians and Greeks to Maxwell's electromagnetic theory or the photoelectric effect observed by Becquerel and Hertz (and soon we will see by Einstein too). A series of studies and key discoveries have been presented by reviewing the work of the scientists who made them. Furthermore, this chapter has also served as an introduction to some key concepts, like the phenomena or refraction and reflection, which we will study in greater detail further on in the course.

Now let's continue with this fascinating history: in Chapter 2 we will try to answer the difficult question: **What is light?**

List of Figures