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. Group of “short-sighted heisenberians” (in fact it’s really a group of Englishmen doing “Morris dancing”). Source: http://inciclopedia.wikia.com. License: CC-BY-SA 3.0.

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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.

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CHAPTER 2

What is Light? Waves and Particles

2.1. Where shall we start?

By remembering Newton and Huygens! In the previous Chapter, providing a short overview of the history of optics in recent centuries, we saw that there had been a long-standing dispute between scientists about the nature of light. If we were to put ourselves in the shoes of Newton and Huygens, back at the end of the 18th century, obviously it would not have been easy to determine the true nature of light. These scientists (and later ones) would rely on their intuition and, above all, on diverse experiments in order to try to validate their hypotheses. First of all, let us attempt to clarify the concepts of particle and wave.

2.1.1. Particles

What is a particle? If we refer to the dictionary of the Official Royal Institution for the Spanish Language, the meaning of **particle** that we are looking for is:

A tiny portion of matter.

When we talk about particles in physics, we are talking about the **elementary constituents of matter**. For example, we know that matter is made up of **atoms** and that these, in turn, are formed by a nucleus composed of **protons/neutrons and electrons**, that "orbit" around the nucleus (autoreffig:0). An electron is an example of an elementary particle: Figure 2 shows a graphic example of this. This figure depicts Young's double-slit experiment which we already referred to in Chapter 1. Originally, this experiment seemed to validate the theory that light was a wave. However, a team of researchers decided to give the experiment "a new twist" and perform it by firing "elementary" particles one by one. In the image, what we can see are electrons fired individually and detected on a screen: each dot is an electron, a particle. Out of interest, the number of electrons in each image is 11 (a), 200 (b), 6000 (c), 40000 (d) and 140000 (e).

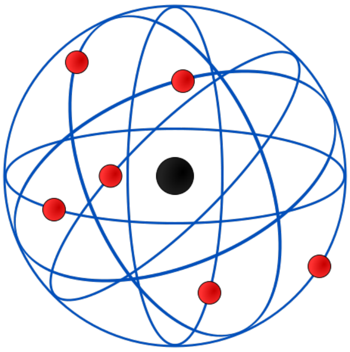

Figure 1. Representation of an atom according to Rutherford's atomic model (nucleus shown in black and electrons in red). Source: Wikimedia Commons (CC BY-SA 3.0). `https://bit.ly/1Vr4tGX`

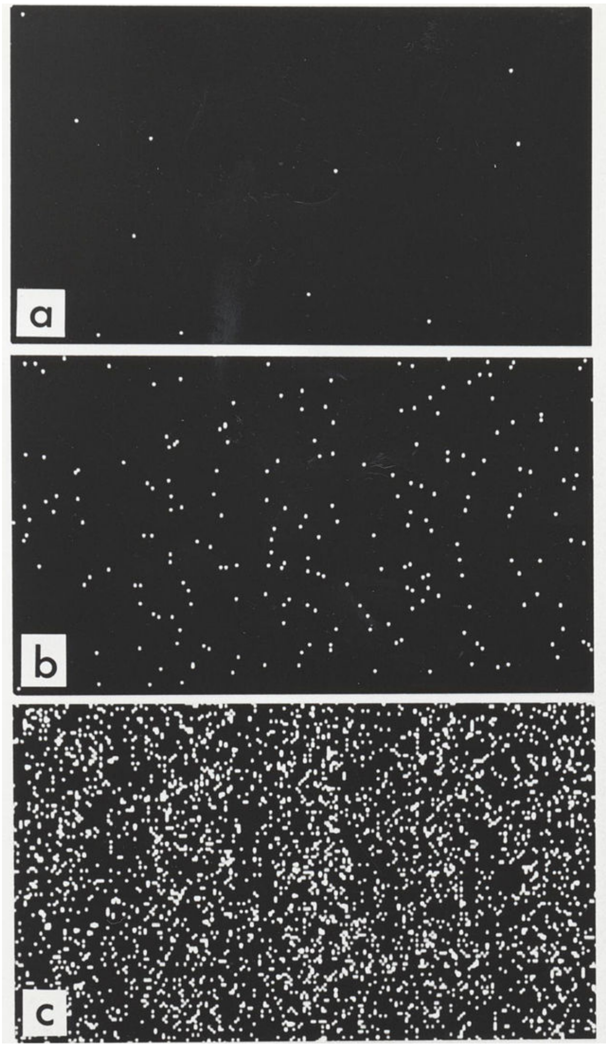

Figure 2. . Double-slit experiment performed by the team of Dr. Tonomura. Source: Wikipedia (CC BY-SA 3.0). `https://bit.ly/1gxo2zt`

If you have understood the concept of particle from the previous explanation, then you will immediately understand that the **corpuscular theory of light** implies that light is made up of tiny particles called **photons**. In other words, when we see a beam of light, we can imagine that it is composed of a multitude of tiny photons, as occurs with the electrons in Figure 2.

Question 1.1: Fundamental particles?

We have talked about neutrons and protons, but: are they considered today to be fundamental particles? Are smaller and "more fundamental" particles known today?

If you are interested in this matter, do some research of your own and try to answer this question.

2.1.2. Waves

As commented in the previous chapter, a wave can be defined as:

Periodic movement propagating through a physical medium or the vacuum.

We also commented that a wave is a disturbance that propagates through a certain medium, as occurs with sound through the air, for example. To take it one step further, we could say that a wave is a disturbance that propagates through a medium and transports energy. This clarification is important and easy to comprehend. Think, for example, of waves[1] on the beach: we know that they transport energy as we have all experienced being knocked over by a wave[2].

Important 1.1: Waves and Energy

There are a number of renewable energies associated with the seas and oceans, like those based on marine currents, tidal height difference or temperature difference at varying ocean depths. One of the most well-known energies is wave power, which utilizes the energy transported by waves by means of "buoy" type devices (Figure 3, left) or the so-called *Pelamis* or sea snake (Figure 3, right).

Question 1.2: Wave Power

Look for information about the operating principle of at least one wave power generating device and briefly explain it **in your own words**, providing an example of a real wave farm.

In your opinion: **will wave power be a key renewable technology in the near future?**

Maxwell, the great physicist we referred to in Chapter 1, demonstrated the close relationship between **electricity and magnetism** and suggested that **light is an electromagnetic wave**. What does that mean? Basically that light would be the combination of an electric field and a magnetic field that would propagate like a wave, as shown in Figure 4. In this figure, we can see a wave, in yellow, whose value varies as it goes across the screen (we can also see a green signal, but we are going to ignore that for now). The aforementioned wave could very well be the **electricity that reaches our homes**, which in Spain has a voltage of 230V and a frequency of 50Hz.

[1] Interestingly, in English the same word **wave** is used for a wave in the sea or an electromagnetic wave.

[2] In fact there is a renewable energy, called **wave power**, which uses the energy of ocean waves to generate electric power.

Figure 3. Devices for utilizing wave power (left: PB40 PowerBuoy by Ocean Power Technologies (License: Public Domain); right: Pelamis machine (License: Public Domain)).

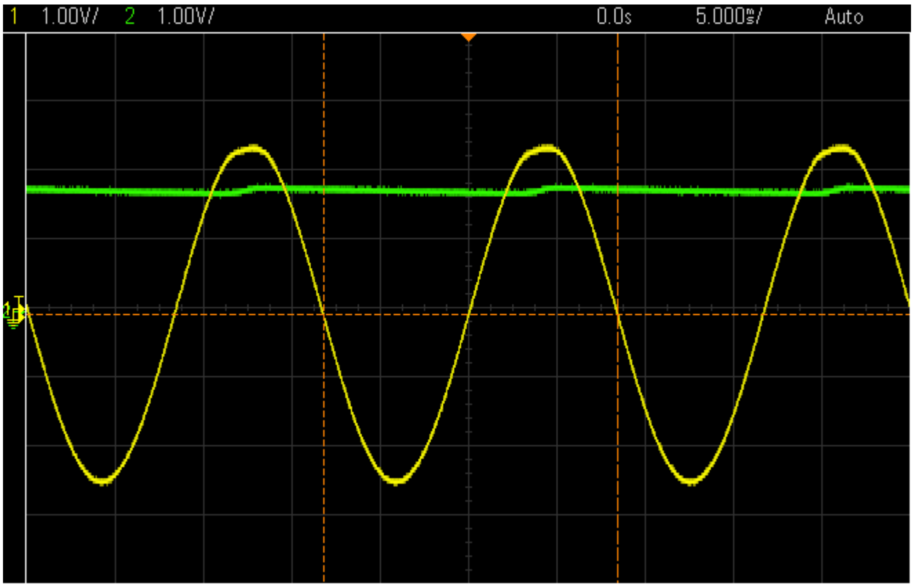

Figure 4. Wave measured and represented on the screen of an oscilloscope. Source: Wikipedia (CCO 1.0). `https://bit.ly/2zR5LrL`

Now the time has come to briefly explain the main parameters that define a wave:

The amplitude A (also known as intensity) of a wave gives us an idea of its intensity or the energy associated with it. If we look at Figure 4, the amplitude is the distance (on the vertical axis) between the wave's minimum and maximum points. For electricity, this amplitude is 230V. For an ocean wave, the amplitude is the height of the wave.

The period T of a wave gives us an idea of how fast "it moves" or varies with time. In other words, looking at the horizontal axis, if the valleys and peaks of the wave are very close together, then the period is shorter (**expressed in seconds**) and if they are further apart, then the period is longer.

The frequency f of a wave is just another way of expressing how fast or slow it varies. In fact, the frequency is the contrary of the period, in other words: $f = \frac{1}{T}$. Frequency is expressed in hertz, which are equivalent to $\frac{1}{seconds(s)}$.

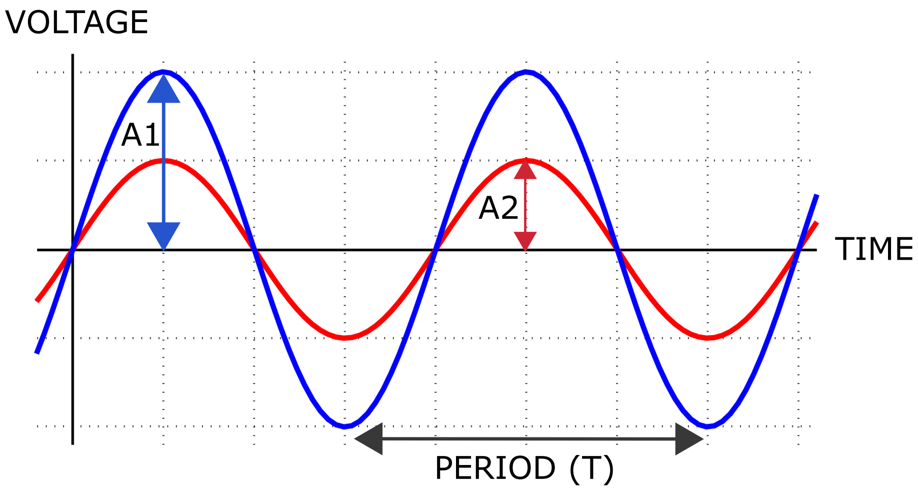

Figure 5. Amplitude (voltage) and frequency of a wave. Source: Wikimedia Commons (CC-BY-SA 4.0) (Original image modified). `https://bit.ly/2DmKXvt`

These fundamental parameters of a wave have been represented in Figure 5. As can be observed, waves 1 (blue) and 2 (red) have the same **period**, but the **amplitude** of the first one is double that of the second one.

A final important and very interesting concept is the **wavelength** λ. The λ of a wave refers to its physical size, or to the spatial dimensions of the wave. If in Figure 5 we have "distance" on the horizontal axis instead of time, then what before was the wave's period (how long it takes to get back to the same point) is now the wavelength (the wave's size).

Important 1.2: Electro-magnetic waves and ocean waves

Ocean waves behave like electromagnetic waves as they move. In fact, parameters like wavelength are used to describe them. Figure 6 shows how the λ of the ocean waves varies, the shallower the water becomes, in other words, as they approach the coast.

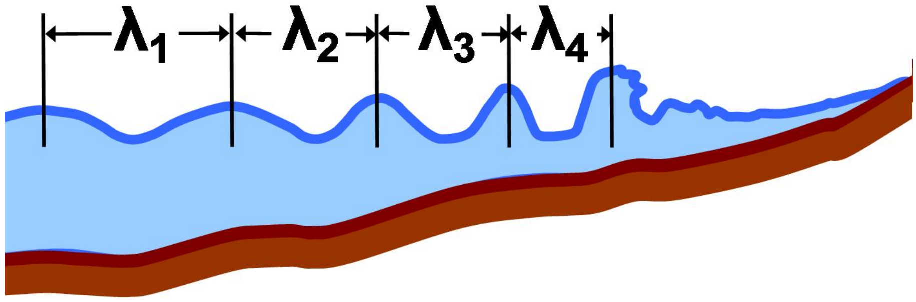

Figure 6. Representation of the evolution of the wavelength of ocean waves as they approach the coast. Source: Wikimedia Commons. License: CC-BY-SA 3.0. `https://bit.ly/2OHVvYr`

Figure 8 shows waves associated with different wavelengths all along the electromagnetic spectrum. As can be observed, the waves associated with **X-rays or ultraviolet radiation** have a very small λ (they are very small, the size of atoms); whereas **radio waves**, for example, are a lot bigger (comparable to the size of a building).

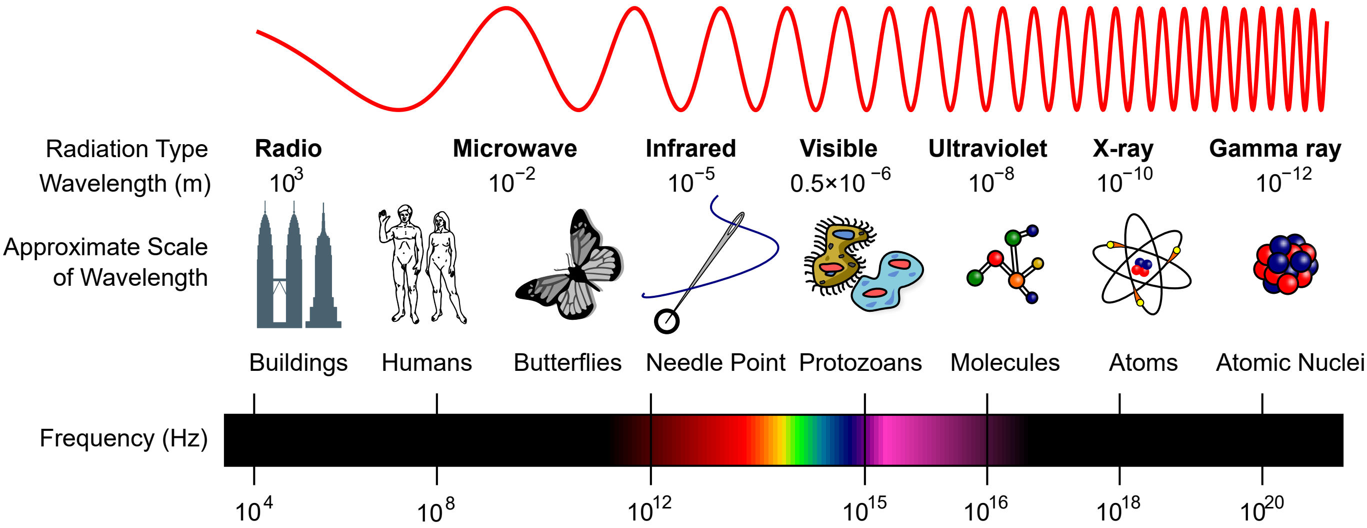

Figure 7. Electromagnetic spectrum. Source: Wikimedia Commons. License: Public Domain. `https://bit.ly/2DE7MMj`

Important 1.3: Radio transmitters and their frequency

Today, you probably use a digital radio, but for a long time radios had a dial for tuning into radio stations manually. When you moved the dial, you tuned the radio into a certain frequency and could look for different stations transmitting at different frequencies.

2.1.3. The energy of a photon

Looking at Figure 8, we can easily locate the wavelengths corresponding to **visible light, ultraviolet light and X-rays**: what happens with their wavelengths? As we move from visible light to X-rays, the wavelength gets shorter. Does that give us any additional information of interest? Of course it does:

The **energy associated with light** or radiation is directly related to its wavelength, in fact it is inversely proportional to its λ. The expression indicating this is as follows:

$$E = h \cdot f \tag{2.1}$$

$$E = h \cdot \frac{c}{\lambda} \tag{2.2}$$

In the above equations, **E** is the light's energy, **h** is a constant (Planck's constant), **c** is the speed of light in vacuum, **f** is the frequency and λ is the light's wavelength[1].

Using these equations, we can find out which light has more energy and, therefore, can be (potentially) more dangerous to humans. For example, visible light generally does not cause any

[1] It is easy to deduce that frequency and wavelength are related, such that $f = \frac{c}{\lambda}$.

problems, whereas we know that repeated exposure to ultraviolet light or X-rays (which are more energetic) can lead to health problems.

Question 1.3: Radio stations and their energy

In order to consolidate the concepts that we have just seen, I propose the following exercise: choose two radio stations at random and look for their frequencies. Note down their corresponding frequencies and calculate their energies using the simple equation that we have just seen[a]: which station transmits waves with more energy?

[a]Bear in mind that $h = 6{,}63 \cdot 10^{-34} J \cdot s$

2.2. Wave-Particle duality

So far in this chapter we have covered some basic notions concerning waves and particles. However, we still haven't answered the fundamental question: **What is light: a wave or a particle?** We already know the postulates of scientists like Huygens and Newton in the 17th century in support of one or other approach, but we had to wait almost another two centuries before any advancements were made concerning the matter, and not precisely to validate any of these two "arguments".

Important 2.1: Waves and Particles beyond Huygens and Newton

After Huygens and Newton, other scientists continued with their investigations. For example, Young and Fresnel seemed to ratify the wavelike theory with their slit experiments. On the other hand, Planck and Einstein suggested the existence of light "quanta" or particles: photons. Einstein's theory was based on his observations and explanation of the photoelectric effect, for which he received the Nobel Prize in Physics in 1921. De Broglie made use of all this previous work in the development of his own theory.

Louis-Victor de Broglie (1892-1987) was a French theoretical physicist who focused his research on the quantum theory2 and, as a result of his studies and investigations, proposed the so-called wave-particle duality, which we will go on to explain. Before doing so, it is worth mentioning that even though his scientific colleagues initially ignored this theory, thanks to Einstein's support, it became widely recognized and de Broglie even received the **Nobel Prize in Physics in 1929**.

What did "the Prince"[2] de Broglie suggest in his duality theory? Very simple: that light is neither a wave nor a particle, but that it behaves like one or the other depending on how we observe it. We will try to explain this apparently complex concept using the superb example provided by **Pedro Gómez-Esteban in his Blog: "El Tamiz"**[3].

Imagine that there is a group of people, called the **short-sighted heisenberians** (shown in Figure 9) which, as it name very well indicates, is made up of **short-sighted** people who are only able to see things which are close up. Another strange characteristic is that, **when nobody can see them, they dance like mad**!!

[2]Louis de Broglie came from a French family of noble origin.
[3]http://eltamiz.com/2008/01/15/la-dualidad-onda-corpusculo/

Figure 8. Louis de Broglie. Source: Wikimedia Commons. License: Public Domain. https://bit.ly/2aUSosi

Figure 9. Group of "short-sighted heisenberians" (in fact it's really a group of Englishmen doing "Morris dancing"). Source: http://inciclopedia.wikia.com. License: CC-BY-SA 3.0.

However, they are also **very shy** and if someone is looking at them, they stand completely still and stare at their observer, but as they are short-sighted, the observer has to be very near for them to realize this and, consequently, for them to stand still.

Now imagine that you go into a room with **20 of these people**. **8 of them are very "myopic"** and you can see them dancing and **the other 12 are more "perceptive"** and when you enter the room they are already standing still looking at you.

If you went into different rooms in the building, you would end up coming to the conclusion that there are two types of people: **dancers and starers**.

Now let's take a moment to think about this: are we really defining what they are (their illness: the short-sighted heisenberians)? Or are we defining how they behave when faced with certain situations?

What would happen if we installed hidden cameras in the rooms? **They would all be dancers.**

What would happen if we went and stood right in front of them, one by one? **They would all be starers.**

Why have we used this example? Because it can be directly extrapolated to the case of waves and particles: why do we call certain things **waves** or **particles**? Because when we interact with them to see what they are like, what we really see is how they react (as waves or particles) and that is why we call them that way, but we are not perceiving what they really are.

We could also express this idea in the following way:

The Universe is composed of ondicules. In certain circumstances, those ondicules behave in a certain way, what we have traditionally called "wave" and in other circumstances they behave differently, what has come to be called "particle" But things are neither waves nor particles: they are ondicules[1].

What happens is that when we try to study ondicules, some are very "wave-like" (as generally occurs with light, for example in Young's slit experiment) and we have to design very specific experiments to see them behave like a particle, as occurs with the photoelectric effect[2]. Other ondicules, like the electron, have very "particle-like" behavior and it is very difficult to design experiments that demonstrate their behavior as a wave.

2.3. Double-Slit experiment 2.0

In the previous chapter, we presented the famous double-slit experiment carried out by Young, which convinced him to support the wave-like theory of light. However, a version of this experiment has recently been carried out that we will call 2.0 that has provided very interesting data concerning the matter of wave-particle duality. Let's begin with the following idea: when the wave-particle duality of light was suggested, scientists thought that waves could be understood as a composition of multiple photons, which would interact with each other to give rise to interference phenomena, etc.

Let us take a moment to explain the **interference phenomenon** and the **slit experiment**. Figure 10 shows the result of this experiment in which light (in this case generated by a source of red light) goes through both slits and forms at pattern on the screen onto which it is projected. This pattern consists of areas with a great intensity of light and dark areas: why are these areas generated?

Let us begin by assuming that we have a **photon "gun"** (which generates particles, not waves), a sheet with 2 slits and a screen which the photons will eventually hit, as shown in Figure 11. We

[1] http://eltamiz.com/2008/01/15/la-dualidad-onda-corpusculo/
[2] We will discuss this effect in Chapter 4

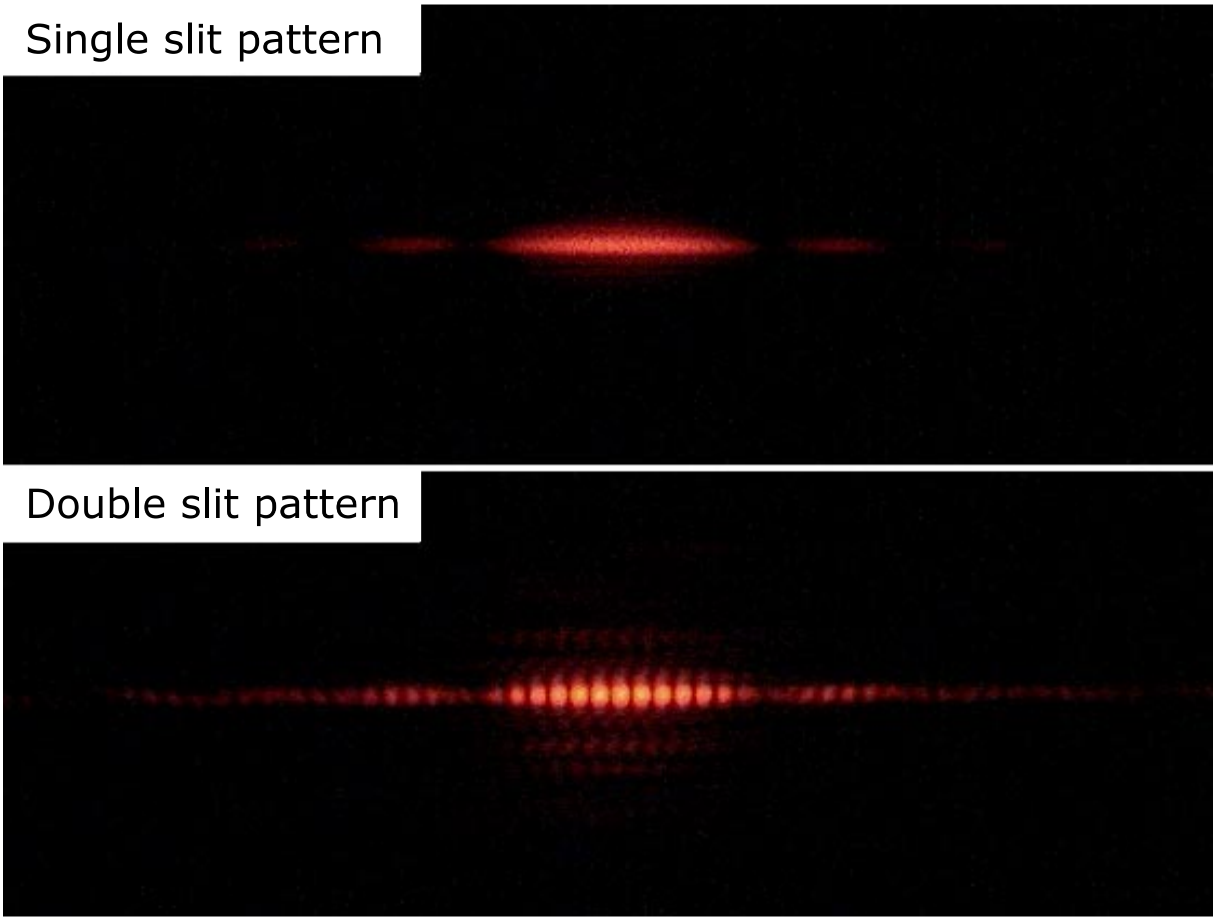

Figure 10. Example of the result of the slit experiment with one (above) and two (below) slits. Source: Wikimwand. License: CC-by-SA 3.0. `https://bit.ly/2PuLAKK`.

can think of the particles as "marbles" the size of the slit which, given the experiment, will hit the screen right behind the slits, as indicated in the diagram.

However, we already know that what really happens is the famous interference pattern. This phenomenon can only be explained if we understand light to be a series of waves that propagates. In this case, a new "front of waves" is generated at each slit. For each spot on the screen, the waves will interact by adding together or subtracting from each other, depending on how they coincide, giving rise to the interference phenomenon. Figure 12 shows the slit experiment again, this time understanding that light propagates as waves.

The pattern generated on the screen, with several bright fringes and other dark ones, is due to **interferences** between the waves. To understand this better, Figure 13 shows an example of wave interference. In the first example, when the waves come together, they are "in phase" so that the result is constructive interference giving rise to a bright fringe. On the other hand, in the second example, the waves are "out of phase", resulting in destructive interference and a black fringe (absence of light) on the screen.

In this way, at each spot of the space (in this case on the screen onto which the light is projected) the waves interact one way or another, constructively or negatively, giving rise to bright fringes of light or no light, explaining the aforementioned stripy pattern shown in Figure 10. This experiment seems to confirm that light is a wave, but we can still take this study one step further.

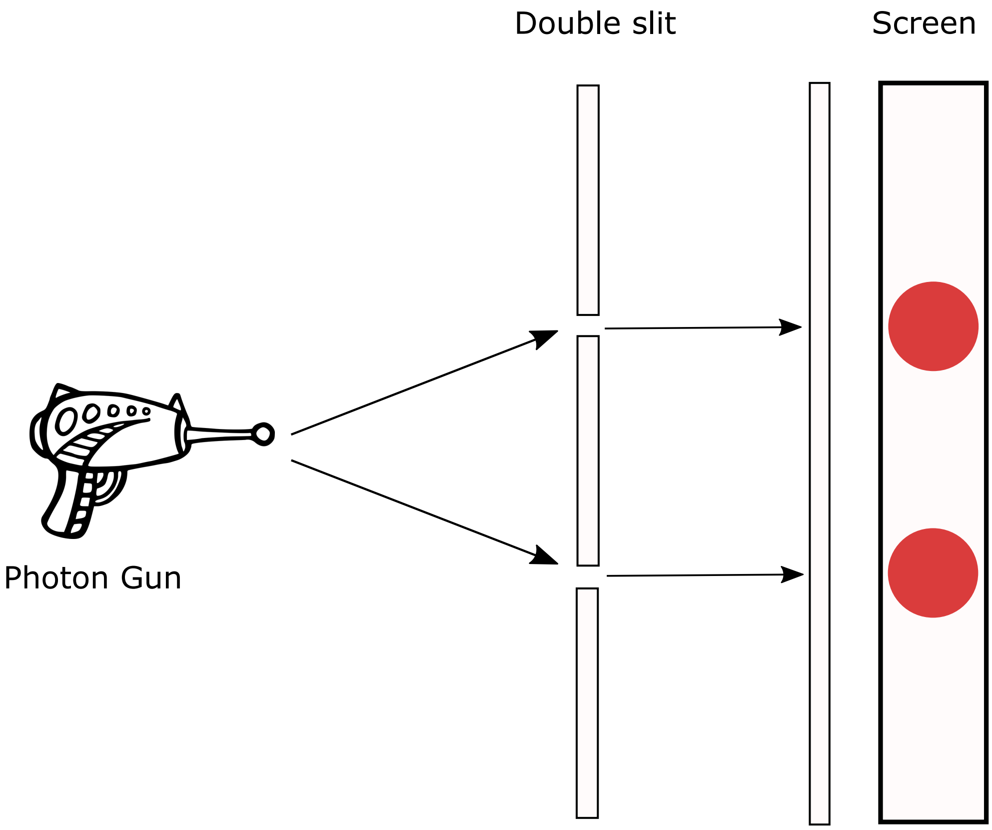

Figure 11. Schematic representation of the slit experiment (particles). Author's own work.

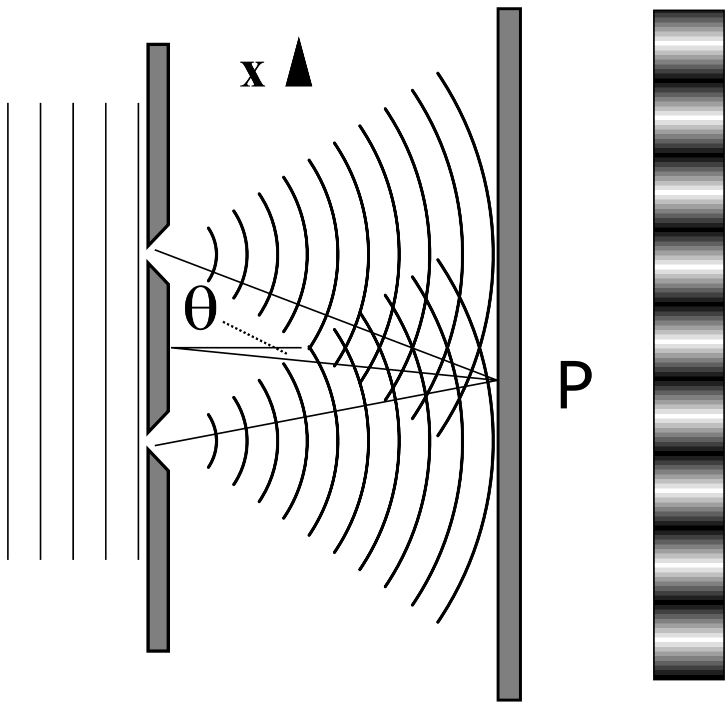

Figure 12. Schematic representation of the slit experiment (waves). Source: Wikipedia. License: CC-BY-SA 3.0. https://en.wikipedia.org/wiki/Double-slit_experiment

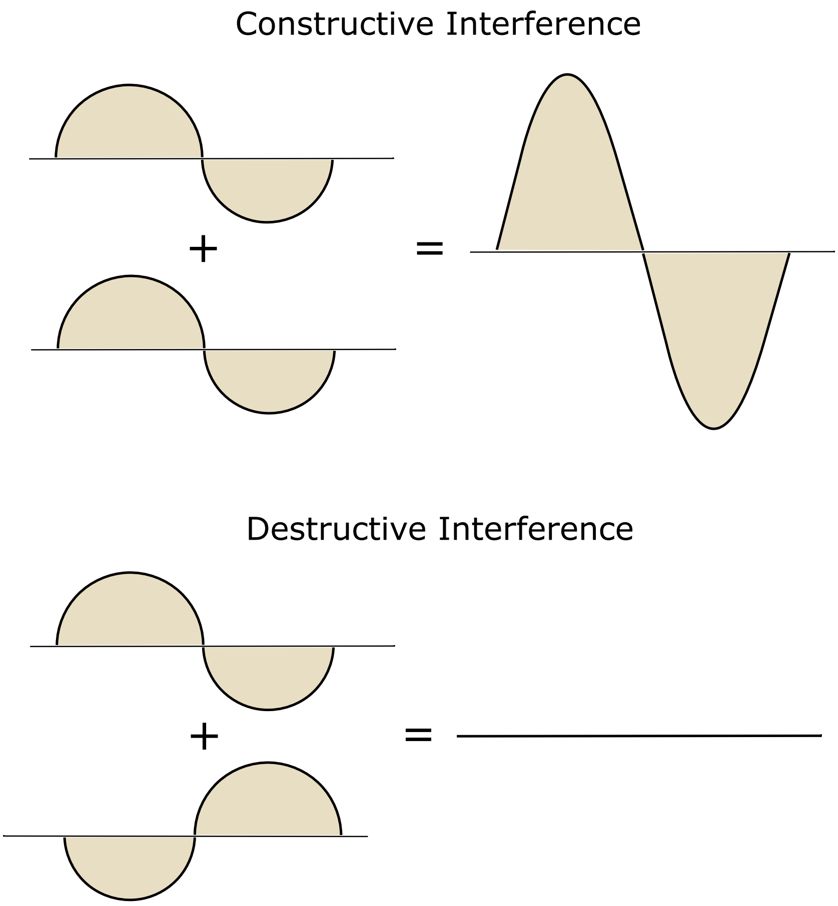

Figure 13. Schematic representation of the interference phenomenon. Source: Author's own work.

Now let us imagine that we have a situation like the one shown in Figure 11, where we have a particle gun that will fire particles individually (one by one) onto the slits. What we expect to see is those particles hitting the screen, as shown in the top image of Figure 14. As the number of particles being fired increases, logically we see more hits on the screen. However, from image **c** onwards, and especially in images **d** and **e**, we observe an effect that we don't expect to see:

Electrons also behave like a wave, even when fired one by one!

This is something quite unexpected, as **an electron is a very particle-like ondicule**. However, this result indicates that the electron itself acts like a wave and that, in fact, it interferes with itself to generate the stripy pattern already seen.

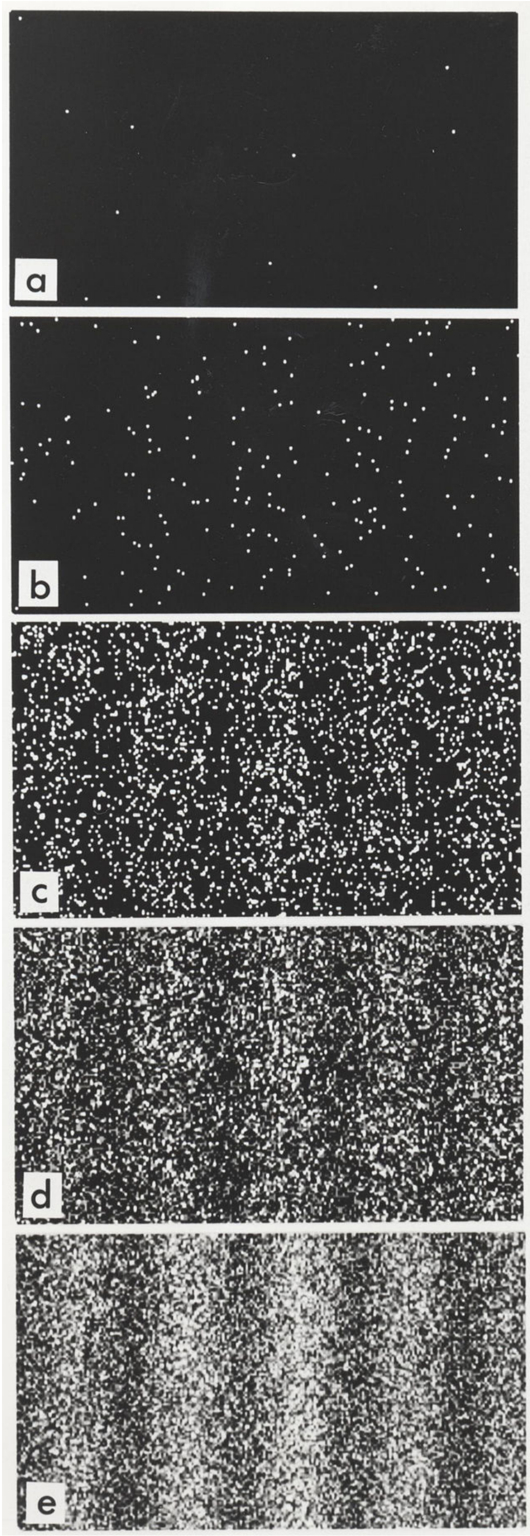

Figure 14. Double-slit experiment carried out by Dr. Tonomura's team. Source: Wikipedia (CC BY-SA 3.0). https://en.wikipedia.org/wiki/Double-slit_experiment

2.4. Conclusions

In this chapter, we have tried to provide some answers to the apparently simple (but in fact very profound) question: **what is light?**

We have introduced the concepts of particle and wave and their main characteristics to conclude that light is in fact neither a wave nor a particle, but that it behaves like one or the other, depending on how we observe it. For our purposes and for the rest of this course, we may use the concept of particle or wave indistinctly to explain the behavior of light.

In the following chapter, we will briefly explain **how the Sun works**, which is the star that provides energy and makes it possible for life on our planet. Moreover, we will provide a brief description of the process of photosynthesis, which is also fundamentally responsible for the existence of life on Earth.

Important 4.1: Quantum physics and its paradoxes

This course does not intend to further explore waves and particles. The objective here is for students to become familiar with and understand wave-particle duality, having understood first of all what waves and particles basically are.

However, students who wish to delve a little deeper into the matter will be interested to know that, in order to explain the result of the previous experiment, it must be supposed that the electron, as a wave, goes through both slits at the same time and therefore interferes with itself. The next "natural" step consisted in placing 2 detectors, one at each slit, in order to observe the electron simultaneously passing through them, but: surprise, surprise! With the detectors in place, the electron only goes through one slit and the interference pattern does not appear on the screen.

What is happening? When we place the detectors, we are interacting with the electrons (for example, firing photons to "see them") and therefore modifying them in some way[a].

[a]For more information, consult the **Blog "El Tamiz"** (https://eltamiz.com/2008/01/15/ la-dualidad-onda-corpusculo/) and also this video explaining what we have said about the double-slit experiment (https://youtu.be/KYX4ki7y-xI)

List of Figures