

The Importance of Light in our Lives¹

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

Lecture Notes

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



Figure 0. Photograph of Stephen Hawking and Barack Obama. Source: Wikimedia. License: Public Domain
<http://bit.ly/2gQK2Hv>

The Importance of Light in our Lives

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THE IMPORTANCE OF LIGHT IN OUR LIVES

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 3

Sun, Light and Life: how the sun and photosynthesis work

3.1. From the *Dark Ages* to millions of stars

As we all know, the Sun is our planet's **main source of energy** and therefore of life on Earth. The Sun is just one of the millions of stars in our galaxy: the Milky Way. In fact, it is estimated that there are between **200 and 400 thousand million stars**: impressive, right? To get a clearer idea of the dimensions of our galaxy, it is enough to say that **it is estimated to have a width of approximately 100,000 light years**. This means that, riding on a hypothetical ship capable of travelling at the speed of light in vacuum¹, it would take an astonishing 100,000 years to go from one side of our galaxy to the other: so it is definitely not small!

The next question that you might ask yourself is: **how many galaxies are there in the universe?** Astronomers settle on saying that there are hundreds of thousands of millions. Conclusion: there is an unimaginable amount of stars in the universe that generate energy and light and, with that, the possibility of facilitating the existence of life in millions of worlds.

Faced with this reality, interestingly current astrophysical theories uphold that our universe lived through a period called the "*Dark Ages*" in which there was no light! During this time (we are talking about a long time ago, about 380,000 years after the Big Bang) the stars still hadn't formed and as a result, logically, there was no light.

¹As we already know, the speed of light in vacuum is $v = 300,000 \text{ m/s}$



Figure 1. Image of spiral galaxy NGC 6744, very similar to our Milky Way. Source: Wikimedia <http://bit.ly/2zUeRm1>

Important 1.1: On the hunt for exoplanets

Today great research efforts are being expended in **finding planets similar to the Earth**, where human beings could live and where extraterrestrial life may even have developed. Apart from the techniques used to detect the existence of those planets^a, it is considered that for life to have been able to develop on a planet, it must be situated within the so-called **Habitable Zone Distance (HZD)**, which depends on the temperature and luminosity of its associated star.

In this sense, it is interesting to remember that Stephen Hawking, one of the greatest scientists of our time, has warned us about the need to find other habitable planets for humanity to survive^b.

^aVarious dozens of exoplanets have been detected that are potentially habitable. For more information: <https://bit.ly/1GR60Nf>

^bNews article about Stephen Hawking and his opinion on the necessity of discovering potentially habitable exoplanets: <https://bit.ly/2pMQ1CD>

3.2. The Sun as a source of energy

‘ There is no doubt that without our star, the Sun, there would be no life on Earth and neither would there be (practically) any energy that we could use. Either directly (solar photovoltaic/thermal/thermoelectric energy) or indirectly (wind, hydraulic, ocean, biomass energy etc.), the Sun is responsible for almost all the energy that human beings can generate/convert/use, with only a few exceptions, like geothermal energy, that can be considered not to rely on the Sun.



Figure 2. Picture of Stephen Hawking and Barack Obama. Source: Wikimedia. License: Public Domain <http://bit.ly/2gQK2Hv>

Question 2.1: The Sun as a source of energy

Isn't that going too far? Or has the Sun got something to do with **fossil fuels**? Look for information about this and answer the question **in your own words**.

Figure 3 shows a more exact representation of the forms of renewable energy available on Earth. As can be observed, there is fundamental dependence on the Sun, that contributes 5.4 million EJ (1 exajoule = 10¹⁸ joules). We can see how other mechanisms not directly associated with the Sun's radiation, like tides (upon which the Sun has a certain influence) or convection in volcanoes, contribute much smaller amounts in comparison.

3.2.1. The fusion process: energy from the stars

We do not need to resort to physics to know that the Sun generates a tremendous amount of energy, which reaches us in the form of luminous radiation¹. However, understanding the process involved, in this case **nuclear fusion**, could be a first step towards trying to replicate it, in order to obtain a powerful source of renewable energy.

The Sun can be defined as a great ball of fiery gas (a plasma), which is approximately one million times the size of the Earth². The Sun is 4600 million years old (see Figure ??), which means that it is approximately halfway through its expected lifecycle.

¹We are talking about light in the broad sense of the word, not just light in the visible spectrum, but also optical radiation in ultraviolet (UV) and infrared (IR).

²The distance from the center of the Sun to its surface is equivalent to a return trip from the Earth to the Moon.

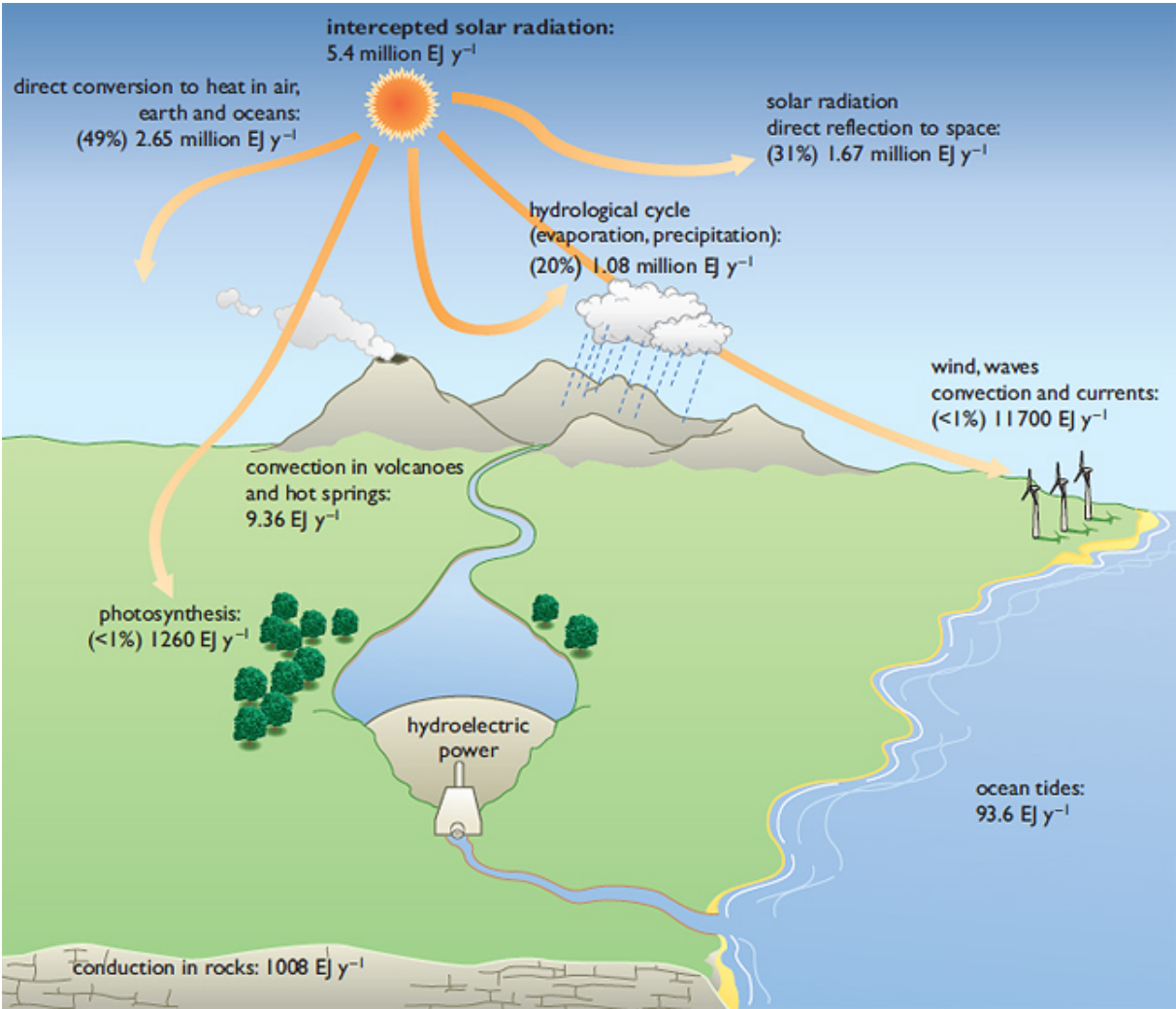


Figure 3. Diagram illustrating the Sun’s participation in generating the resource associated with different sources of energy. Source: open.edu <https://bit.ly/2BHKnFT>

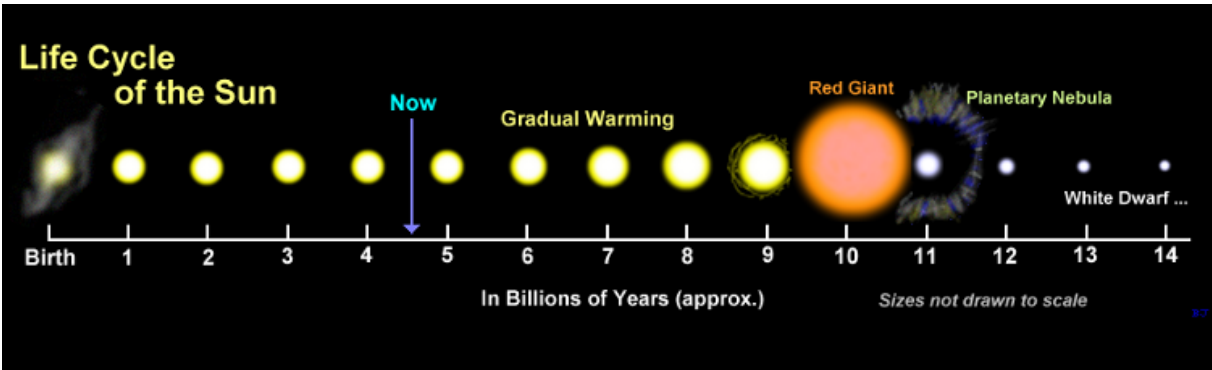


Figure 4. Evolution in the life of a star and the Sun’s current age. Source: Wikipedia. License: GNU Free Documentation License <https://bit.ly/1I1j4jN>

The Sun is basically composed of **Hydrogen** (H, 73%) and **Helium** (He, 25%), with an estimated temperature of 5600°C at its surface and 15 million °C at its core.

How is **energy** generated in the Sun? At a star's core, the temperature and pressure are so high that the particles (in this case, hydrogen and helium atoms) are accelerated at such high speeds that, when they bump into each other, nuclear reactions occur.

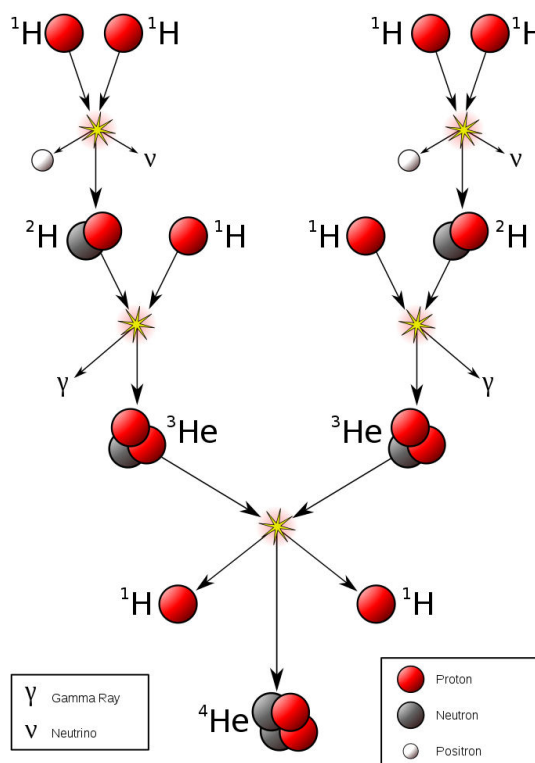


Figure 5. Schematic representation of the nuclear fusion process in stars. Source: Borb (CC BY-SA 3.0) <https://bit.ly/2BKwdnC>

Figure 5 shows how the **nuclear fusion** process takes place. Nuclear fusion can be understood as simply the process whereby several atomic nuclei come together to form a heavier nucleus releasing, at the same time, a huge amount of energy.

Question 2.2: Nuclear Fission and Fusion

Sometimes people get the terms **nuclear fission and fusion** mixed up. We already know that fusion refers to the process whereby energy is produced in the stars, but **what about fission?**

Look for information about this process and, **in your own words**, briefly explain what it entails and in what kind of energy-generating technology it is used.

In the fusion process in the Sun, two hydrogen protons come close enough together for the intense nuclear interaction to overcome the mutual electrical repulsion. In this process, Deuterium 2H is formed which, subsequently, when interacting with another proton from a hydrogen atom, forms 3He releasing radiation in the form of gamma rays. The fusion process ends with the formation of 4He .

Hang on a minute! Are we talking about **gamma ray radiation** here? Doesn't that sound ominous?

Question 2.3: Gamma rays

What is the energy and wavelength of **gamma rays** like in comparison with “visible” radiation? What events of the universe do gamma rays participate in? Are gamma rays used on the Earth?

Fortunately for us, the radiation that reaches the Earth comes in the form of other radiations: as we well know, in the visible range, ultraviolet, infrared, etc. Why is this?

Thousands of years go by from when a gamma ray photon is formed at the center of the Sun to when it manages to escape (some models estimate this figure to be 170,000 years!!!¹). This is because the original photon, in its attempt to escape from the Sun, bumps into obstacles (other particles) that change its direction. During this process, the photons gradually lose energy, eventually reaching levels associated with the aforementioned spectral regions.

How much energy is generated in the Sun? Referring to **Einstein’s famous equation** relating matter and energy, we can obtain a quick answer to this question:

$$E = mc^2 \quad (3.1)$$

In the above equation, E is energy, m is matter (mass) and c is the speed of light in vacuum.

In order to use this equation, it must be taken into account that in the Sun’s fusion process, **600 million tons of hydrogen** are used (**per second**) to generate **596 million tons of He**. **What happens to the remaining 4 million tons?** During the process, they have been converted into energy, thus by substituting this value into the above equation and using the constant c (speed of light), we obtain the following result:

100.000.000.000.000.000.000 KWh de energía

This figure implies that the amount of energy generated in the Sun per second is greater than the world energy consumption in a year. Whether or not it is possible to efficiently capture and use that energy is, however, an entirely different matter.

Important 2.1: Dyson Sphere

An interesting concept in this respect is the **Dyson sphere**, which refers to a hypothetical megastructure, proposed in 1960 by the physicist Freeman Dyson, that would serve to encompass a star and capture a large percentage of the energy it generates.

This structure, which would supposedly serve to detect advanced extraterrestrial civilizations, has appeared in the news in recent months due to the detection of a star (and since then another one) whose behavior (in its luminosity patterns) has given rise to different theories. More information at: <https://bit.ly/2p6iNj1>

¹Not to be confused with the amount of time it takes a photon to travel from the surface of the Sun to the Earth: about 8 minutes.

3.3. Using the Sun's energy: the legend of Archimedes

Renewable energy is currently experiencing a major boom, driven by several situations, like the future depletion of fossil fuels, the climate change or the increase in global energy consumption.

En la actualidad, la energías renovables están experimentando un gran auge propulsado por diferentes situaciones, como el futuro agotamiento de los combustibles fósiles, el cambio climático o el incremento en el consumo energético a nivel global.



Figure 6. Solar thermoelectric power plants PS10 and PS20 in Seville. Source: Wikimedia. License: CC BY-SA 3.0 <http://bit.ly/2xNP8ei>

In recent years, there has been a considerable boom in renewable energies that depend directly on the Sun. Today, photovoltaic energy is one of the main renewable energies, enabling the conversion of light into electrical energy by means of photovoltaic cells or panels. Likewise, solar thermal energy which uses the Sun's energy to heat liquids like water, or solar thermoelectric energy or **CSP (Concentrating Solar Power)** have steadily increased in importance. Spain is the leading country by installed capacity in CSP technology, with large power plants consisting of numerous mirrors that direct the Sun's radiation to a tower where a liquid is heated and then used to generate electrical energy by means of a turbine. Figure 6 shows CSP (thermoelectric) plants PS10 and PS20 in Seville.

Man's use of the Sun's energy dates back to ancient times, one of the most interesting examples very closely related to the concept of solar thermoelectric energy being the legend concerning **Archimedes' Defense of Syracuse**.

Although the use of mirrors to cauterize wounds and for other purposes dates back to earlier



Figure 7. Depiction of the supposed defense of Syracuse by means of a mirror system designed by Archimedes. License: Public Domain. Source: irrdeuctible.naukas.com <https://bit.ly/2zfyBzT>.

times, Archimedes can be considered one of the “fathers” of solar thermal/thermoelectric power. Archimedes is regarded as one of the most important scientists of ancient times, with important contributions to integral calculus, calculation of the value of π , explanation of the compound pulley or the law of hydrostatics, to name just a few.

According to legend, Archimedes tried to defend his city Syracuse from being attacked by the Romans using a **system of large mirrors capable of focusing the Sun’s energy** and setting the Roman ships on fire, however the veracity of this story has never been very clear. Several attempts have been made to replicate this supposed system (which, if it existed, was not very successful as Syracuse was forced to surrender and Archimedes was killed by a Roman soldier): from the “Myth Buster”¹ program to the very MIT (Massachusetts Institute of Technology)², with varying results.

Question 3.1: Archimedes and the “Death Ray”

Do you think that Archimedes’ “Death Ray” was real?

Investigate (using whatever bibliographical resources you consider to be necessary) the supposed veracity of this historical event and explain (**in your own words**) whether or not you think that it was technically possible to use mirrors for setting Roman ships on fire.

¹<https://bit.ly/2AaifL8>

²<https://bit.ly/1md1Ndl>

Important 3.1: Heliodysee

Heliodysee is a public information center, located in France, more precisely in the Eastern Pyrenees region. It is at the site of the great Odeillo solar furnace, consisting of a set of mirrors that reflect the Sun's radiation onto a second surface of mirrors that, finally, concentrate the radiation towards a target measuring 40 cm in diameter (with a concentration equivalent to approximately 10,000 suns). The origins of this center are interesting and go back to the use of mirrors for anti-aircraft purposes (imitating Archimedes' famous (and supposed) defense of Syracuse). The great furnace was built at a later date, between 1962 and 1968, and has served as a key research center for present-day thermosolar plants.



Figure 8. Photograph of Odeillo Solar Furnace in France. License: CCO Creative Commons. Source: <https://bit.ly/2Fwaf3D>.

3.4. Fusion Generators: emulating the energy of the stars

One of the most noteworthy projects aimed at discovering new technologies for generating sustainable energy, beyond fossil fuels, is the project concerning the development of **nuclear fusion generators**. This system would emulate the process whereby energy is generated within the stars of our planet, with the creation of small plants with an immense potential for clean energy, simply using hydrogen as a source of energy.

Creating this kind of plant, exemplified by the **ITER** project, is extremely complicated from a technical point of view and it is a veritable scientific challenge. Materials are required, for example, that are capable of confining the plasma (ionized gas) that is generated at **extremely high temperatures (150 million ° C)**.

The ITER project took shape on the 24th May 2006 with its seven original partners: the European Union, Japan, the United States, South Korea, India, Russia and China. The headquarters were eventually established in France (Cadarache), the EU contributing 40% of the project's cost and France and the rest of the partners contributing 10% each. Despite the huge investment (estimated to be about 14000 million euros), the project's progression is slow and it is expected to take 20 or 30 years before any major milestones are reached.

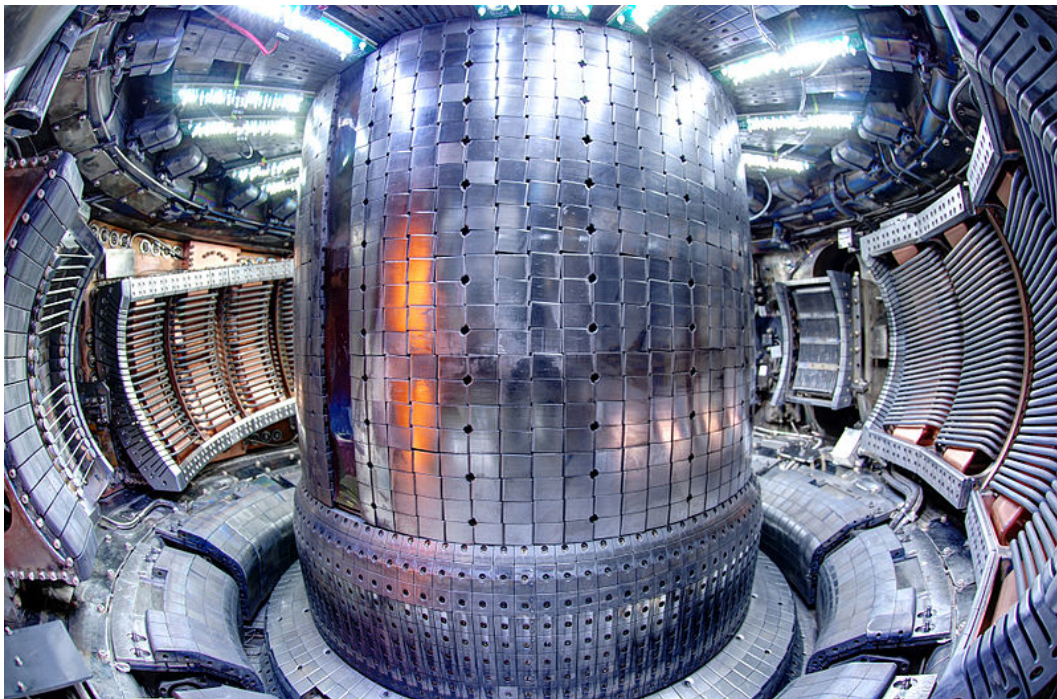


Figure 9. Picture of the inside of a fusion generator prototype, the Alcator C-Mod (project by the MIT Plasma Science and Fusion Center). License: CC-BY-SA 3.0. Source: <http://bit.ly/2hx6t1s>.

3.5. Photosynthesis: converting the Sun's energy

As already mentioned, the existence of a nearby star (more precisely, in a specific range of distances depending on its energy and other factors) is absolutely essential for the existence of life as we know it. In our case, the Sun is fundamental for the existence of life on Earth. However, other phenomena like **photosynthesis** are also key factors in this sense.

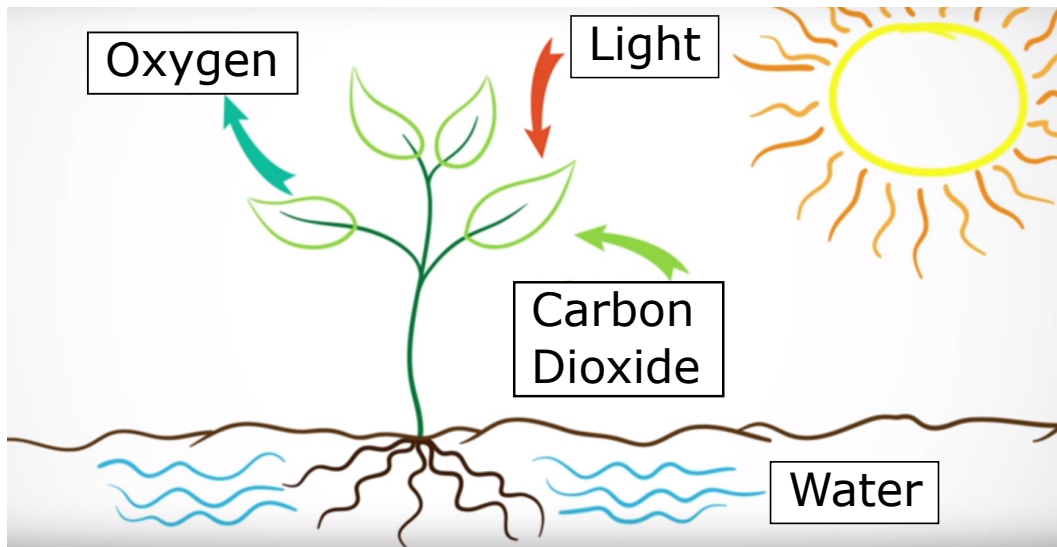


Figure 10. Illustration of the phenomenon of photosynthesis. License: Standard YouTube. Source: <https://bit.ly/2FMk5DX>.

The word **photosynthesis** comes from the Greek terms: *photos* (light) and *syn-thesis* (formation of compounds). Basically it is a process by which plants, using the Sun's energy, generate their own food in the form of sugars. In order to do this, in addition to sunlight, plants also need water, minerals and CO₂.

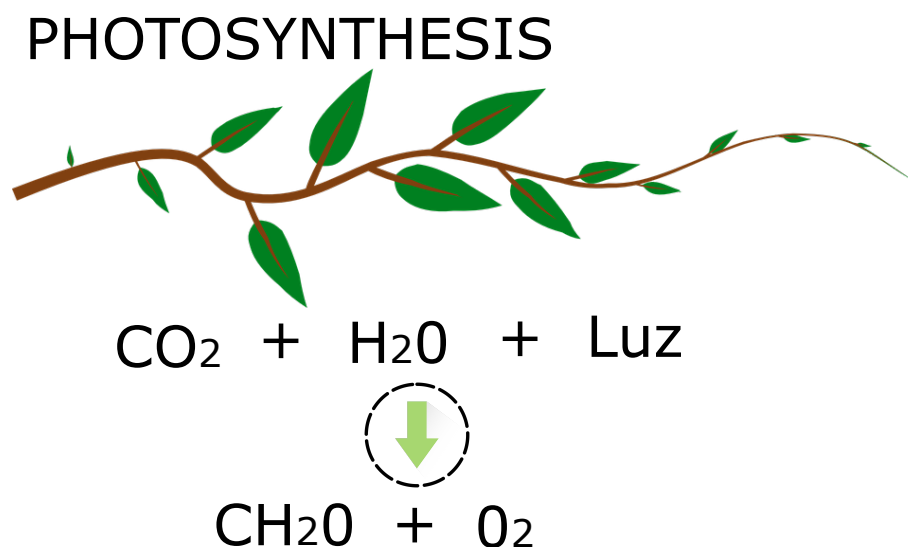


Figure 11. Diagram illustrating the process of photosynthesis. License: Author's own work.

3.5.1. Factors participating in photosynthesis

As already mentioned, **light** is a key component in the process. However, **what light is really involved in the process?** We know that Sunlight (white light) can be split up into its different components or colors, as occurs with a rainbow. So, are all the colors used equally in the process? The answer lies in the color of plants themselves.

Sure enough, plants are green, so is green light the key factor in this process? The answer is no, as when we observe an object which is a certain color, what that surface, material etc. is doing is precisely reflecting that color (those wavelengths), therefore green is not used in plants for photosynthesis, but is reflected by them and, logically, not used.

Besides light, other elements which are essential for photosynthesis are **water and carbon dioxide (CO₂)**, from which carbohydrates (CH₂O) are synthesized. Ambient **temperature** also plays an important role in the process, which is considered to be viable between 0 and 50°C. Furthermore, the **concentration of CO₂** may also play an important role, as the greater the concentration of this gas, the greater the output of the process.

3.5.2. The phases of photosynthesis

Photosynthesis is usually broken down into two phases: the photochemical phase (also known as the “light” phase) and the CO₂ fixation phase.

In the photochemical phase, the key element is the energy provided by light, which is captured by means of pigments, fundamentally chlorophyll¹. The photons absorbed excite the chlorophyll electrons, generating a certain electric current which is fundamental in the process.

In the CO₂ fixation phase, the energy obtained in the previous phase is used to generate organic matter from inorganic matter. The source of carbon in the process is CO₂.

Generally speaking, photosynthesis is carried out in plants’ leaves, notably in the **chloroplasts**: the characteristic green-colored structures (due to chlorophyll) of plant cells.

3.5.3. The importance of photosynthesis

It is obvious that photosynthesis has been a key process for the development of life (as we know it today) on our planet. Our atmosphere was initially very rich in CO₂, water vapor and nitrogen, but not so rich in oxygen. Interestingly, the first living organisms on our planet did not need oxygen in order to survive. This changed when the photosynthesis process began on our planet by means of certain bacteria, thus gradually increasing the level of oxygen.

It is also important to take into account the fundamental role of plants and photosynthesis in the fixation of atmospheric CO₂. That is why events like fires, that destroy large forested areas, are so worrying from a climate change point of view.

¹Certain types of marine algae function on the basis of other pigments and are capable of using green light.

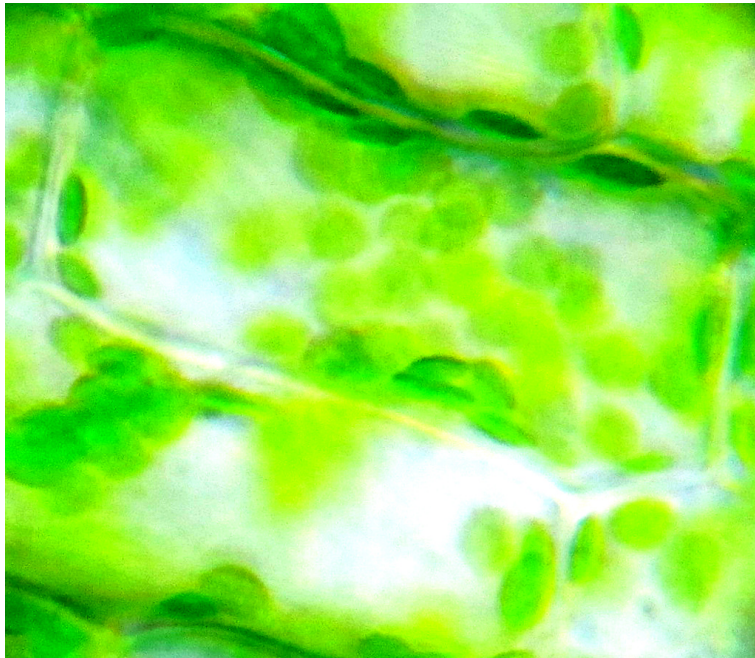


Figure 12. Image at magnification x400 showing the chloroplasts of Elodea (aquatic plant). Source: Flickr. License: CC-BY-SA 2.0.

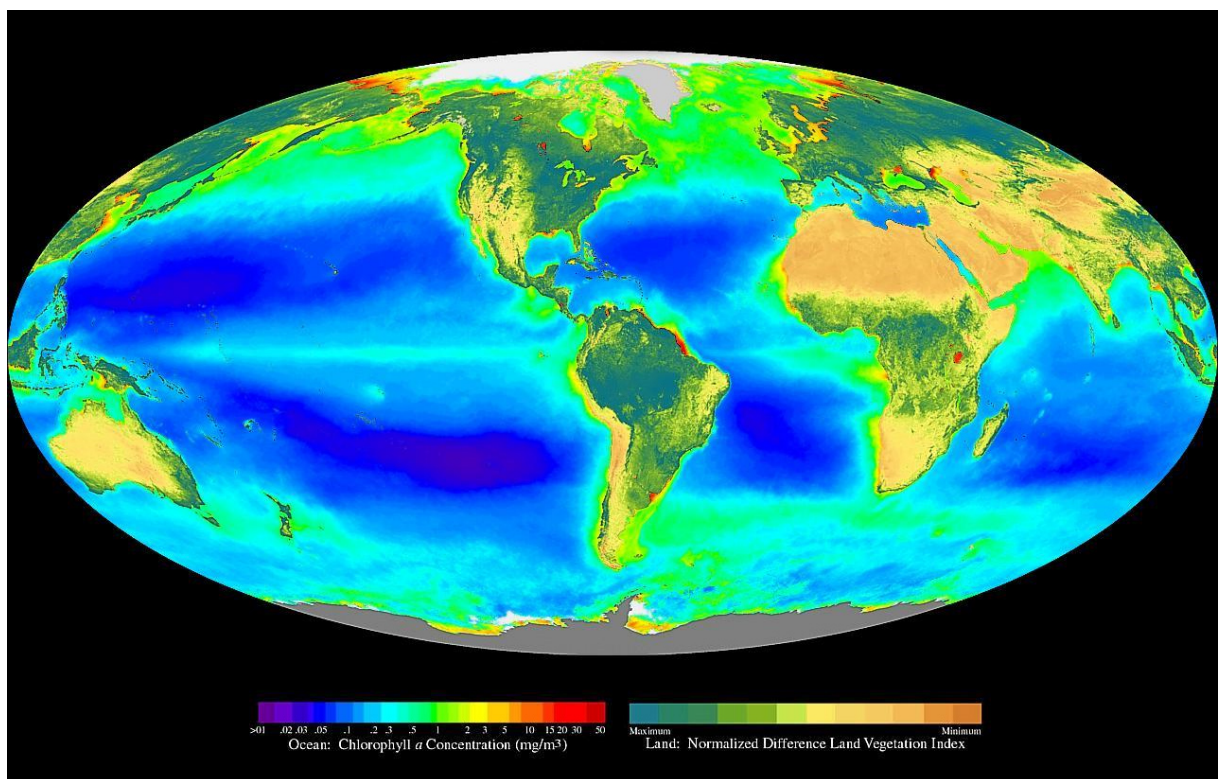


Figure 13. Distribution of photosynthesis on the Earth (including that carried out by phytoplankton in oceans). Source: Wikimedia. License: Public Domain. <http://bit.ly/2z6x6b8>

3.6. Artificial photosynthesis

In the same way that man is trying to replicate the nuclear fusion process in the stars with projects like ITER, today a great deal of research is taking place aimed at creating devices capable of carrying out **artificial photosynthesis**.

Just like photovoltaic cells can convert sunlight into electric current, artificial photosynthesis is based on solar cells capable of replicating the photosynthesis process, in other words, converting water, CO₂ and light into energy, for example **hydrogen**.

There are currently a number of research projects underway that are attempting to make this concept a reality, like A-LEAF financed by the European Union and led by a Spanish research institution¹.

Question 6.1: Artificial Photosynthesis

Look for information about projects underway that are focused on artificial photosynthesis.

What are their levels of maturity?

Do you think that this technology has a good chance of success in the near future?

¹<http://bit.ly/2iW6mUd>

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