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. Frame of the movie Goldfinger, from the James Bond saga. Source: Tor.com https://bit.ly/2OSZH7K

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.

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Chapter 5

Measuring the world using light: from biomedicine to civil work

As we all know, humans need to interact with their environment and do this through the senses: sight, touch, taste, smell and hearing. On the other hand, with the evolution of science and technology, the use of sensors has been extended to many fields of application: from medicine to the aerospace industry, a great number of industrial settings and many more besides. We have used the word **sensor**, but do we really know what that means? Below is a simple definition:

A sensor is a device which converts a physical or chemical magnitude into another magnitude, normally electric, and measures the phenomenon.

For example, a car's thermometer: the sensor measures a physical magnitude (temperature), in order to convert it into an electric signal which, after being processed by the car's electronics, is shown on the control panel. In fact, we can see that there is a clear interconnection between our senses and these sensors. After all, our senses also measure physicochemical magnitudes to transform them into electric signals that will eventually be processed in our brains.

The **evolution of Optics and Photonics** has made it possible to develop many different sensors, either using optical fiber or other diverse technologies. Below is a brief overview of some of the most interesting and curious sensor technologies based on the use of light.

Figure 1 shows a mobile telephone being used to take a photograph: Why do you think that we have chosen this picture? Correct! **The camera is just a sensor** which, imitating our sight, transforms the light into an electric signal and, once this has been processed, it is capable of representing the image captured.

Figure 1. Picture of a mobile telephone whose photographic camera is being used. Source: pixabay. License: CC0 Creative Commons.

Question 0.1: Sensors in a mobile telephone

However, a mobile telephone has a lot more sensors. Look for information about this (or think about the features of your device) and name **at least 5 sensors that a present-day mobile telephone has**, besides a camera.

5.1. A simple example of a laser sensor

A **simple example of a sensor** based on light is the now commonly-used **laser meter**. A laser meter is a relatively simple way of estimating the distance between two points: it measures the time it takes for the light to go to and from the device to the point being measured (a wall, for example). As we know the speed of light in air, if we also know how long it takes the laser light to go there and back, it is easy to determine the distance using the following equation[1]:

$$s = v \cdot t \tag{5.1}$$

5.2. Infrared thermography

All hot objects emit infrared radiation. That is the principle upon which, for example, the greenhouse effect is based, where a balance is established between the Sun's incoming radiation

[1] In this equation **s** is space, **v** velocity and **t** time.

Figure 2. Laser distance meter. Source: Wikimedia (original picture modified). License: CC-BY-SA 2.0. http://bit.ly/2zrnRjq

and the Earth's outgoing radiation[1]. The Earth, when it heats up, releases part of that heat in the form of infrared radiation and part of that radiation "rebounds" in the greenhouse effect gases, like carbon dioxide, methane, etc.

The fact that infrared radiation is associated with the heat of an object means that the temperature of that object can be estimated if the aforementioned radiation is captured. Just like the camera seen in Figure 1 captures the radiation in the visible spectrum, there are cameras capable of capturing infrared radiation: these are the so-called infrared (IR) or thermal cameras. Figure 3 shows two examples of thermograms: one of a hand (left) and one of a steam train (right).

The first example takes us to the field of **medicine**, where a typical use of infrared thermography is based on detecting alterations in the circulatory system, for example in limbs. The picture on the right is an example of applications in transport or even in industry and shows us the distribution of temperatures in a steam train. By analyzing this picture we could detect possible faults in the train's systems. Another typical example in this case is the use of this technology to detect faults or malfunctioning in junction boxes or power lines, as these problems show up as hot spots.

Infrared thermography does not directly reveal the temperature at every point of the image, but instead reveals the distribution of temperatures according to a map of associated colors. In order to find out the exact temperature, it is necessary to know a certain parameter of the material being analyzed, called ***emissivity***.

[1] Due to the so-called **climate change**, the **greenhouse effect** has taken on a negative connotation. However, without the greenhouse effect there would be no life on our planet, or at least not life as we know it, as the temperature of our planet would be much lower.

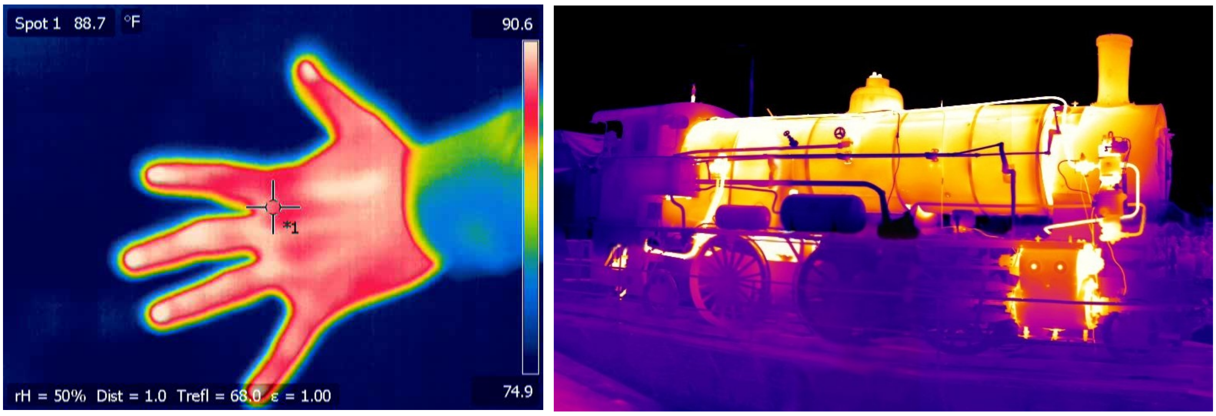

Figure 3. Thermal image (thermogram) of a hand (left) and a steam train (right). Source: Wikicommons (left) and pixabay (right). License: CC-BY-SA-3.0 / CC0 Creative Commons.

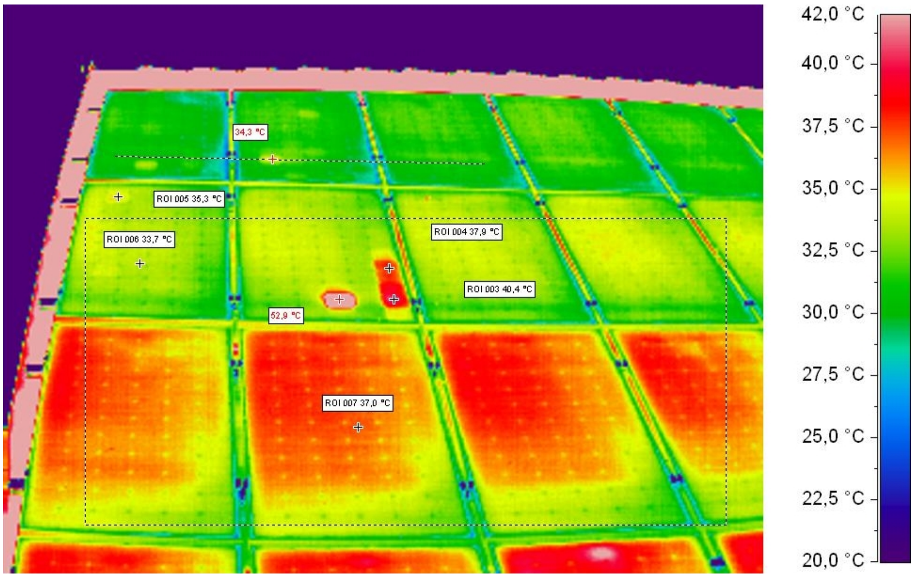

Figure 4. Thermal image (thermogram) of a photovoltaic solar generator. Source: Wikicommons. License: CC-BY-SA-3.0.

Important 2.1: Infrared thermography and photovoltaics

An interesting example of the application of infrared thermography is the inspection of **photovoltaic solar plants**. Here, one of the typical problems that can occur with photovoltaic panels or modules is that **hot spots** occur when a section of the panel is covered by dirt, leaves from trees, etc. This may lead to degradation of the panel so that it becomes useless. This problem can be detected by locating abnormally hot regions in the panel, as can be observed in Figure 4, in particular at the top, where a panel with a homogenous temperature (in green) shows two hotter spots (in red).

Question 2.1: Infrared thermography

Look for information about an application that uses infrared thermography different from those mentioned here and briefly explain it **in your own words**.

5.3. Spectroscopy

Spectroscopy is defined as the science that studies the **interaction between light and matter**. When such an interaction occurs, light is able to record the “fingerprint” of the materials with which it interacts, thus enabling applications for identifying materials, quantifying their composition, etc.

There is a wide variety of different spectroscopic techniques: **emission, absorption, laser-induced breakdown spectroscopy, etc.** Below are some examples.

5.3.1. Emission spectroscopy

Emission spectroscopy is based on **capturing light emitted by a source** naturally (the Sun) or light which is stimulated (as we will see in the case of laser-induced spectroscopy) **and analyzing its spectrum**. As already discussed in Chapter 1, in Section 1.15 to be precise, a spectrum can be defined as the representation of light split up into its different colors or wavelengths. We mentioned the example of the spectrum of sunlight: if we make a ray of sunlight shine through a prism, then we can split this light up into its different colors (see Figure 5).

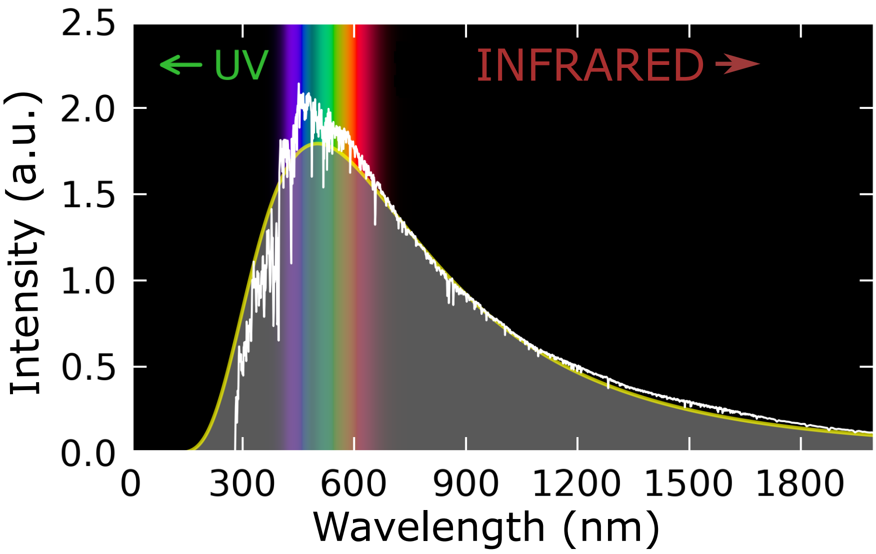

Figure 5. Solar spectrum. Source: Wikimedia Commons (original image modified). License: Public Domain. `https://bit.ly/2RU4yHL`

In emission spectroscopy it is necessary to analyze the spectrum of the light captured, which is done by means of an instrument called a **spectrometer**, consisting of **a prism or similar device for splitting the light up into its different wavelengths**. Figure 6 shows the basic parts of a spectrometer, with a source emitting light, mirrors which guide the light through the inside of the spectrometer, a prism or diffraction grating which splits the light up into its different spectral components (colors or wavelengths) and a detector, which is a sensor similar to those used in photographic cameras.

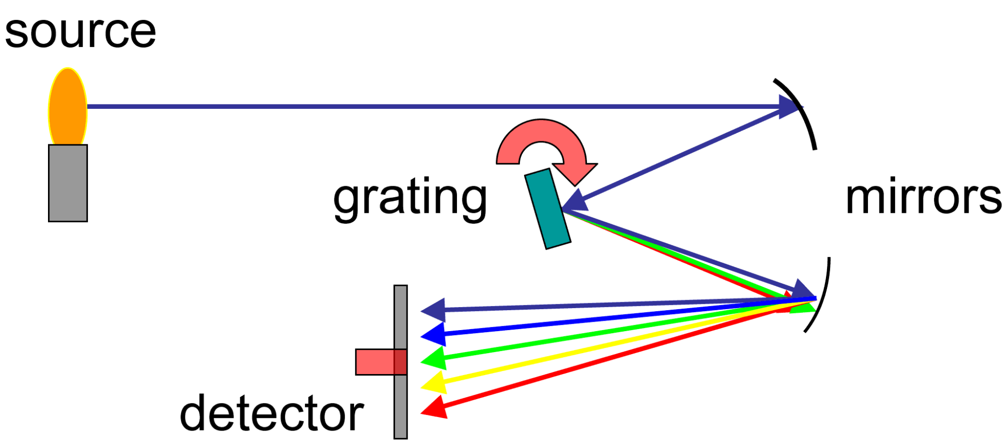

Figure 6. Diagram of a spectrometer. Source: Wikimedia Commons. License: CC-BY-SA 3.0. `http://bit.ly/2yhWqr9`

An example of the application of emission spectroscopy is the analysis or monitoring[1] of welding processes. As we know, intense luminous radiation occurs naturally in these processes, which is why welders have to protect their eyes with special protective goggles or face shields. If that light is captured, for example using an optical fiber, and guided to a spectrometer, it is possible to analyze the evolution of the spectra of the welding process. Figure 7 shows an example of a spectrum captured during a welding process. As can be observed, the spectrum is made up of several **emission lines**. **Each one of these lines is associated with an atomic element participating in the process**, such as iron (**Fe** on the graph) as in this case stainless steel sheets are being welded. Analysis of the evolution of those emission lines and their variations may indicate the existence of defects in the process, like porosity, cracks, etc.

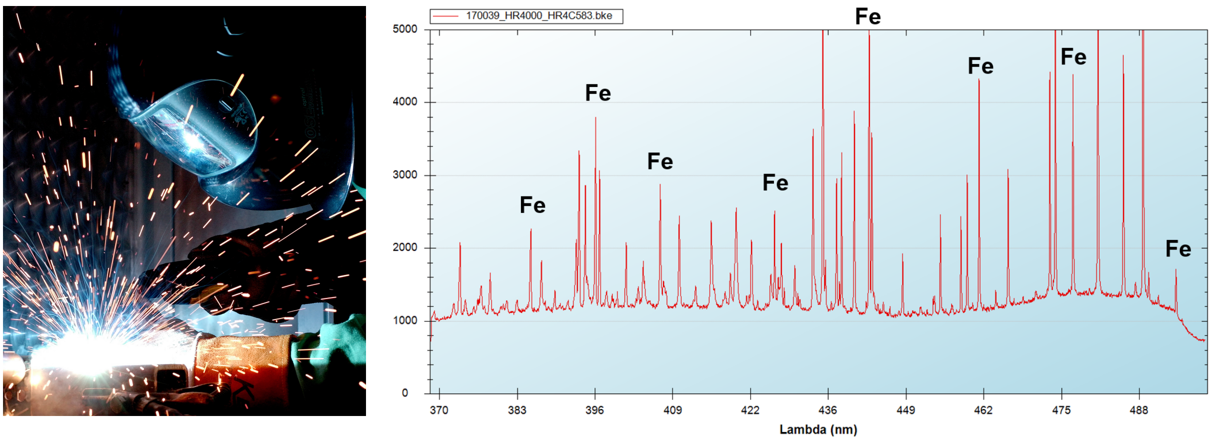

Figure 7. Picture of a welding process and the light generated (left) and a welding spectrum (right). Source: Wikimedia Commons (left). License: CC-BY-SA 3.0. Image on the right: Author's own work.

[1] Monitoring in this field is synonym of supervision, in other words, capturing different parameters of a process in order to check that it is being carried out correctly.

Important 3.1: Emission lines

The fact that each emission line is associated with a single atomic element is explained by the emission phenomenon that we have seen in previous chapters. The emission of a photon occurs when an electron "goes down" from a higher energy level to a lower one. It is precisely that difference in energy that determines the wavelength of the photon (or emission line) emitted, which is unique for each element in the periodic table.

Figure 8 shows an example of this technique being applied to an orbital welding process (where tubes are welded) for the nuclear power sector (welding of steam generators for nuclear power plants). The close-up picture on the right shows that a pore has formed during welding. By analyzing the signal resulting from taking into account various emission lines of the spectrum, is it easy to see the viability of detecting a defect in real time (whilst the welding is being carried out).

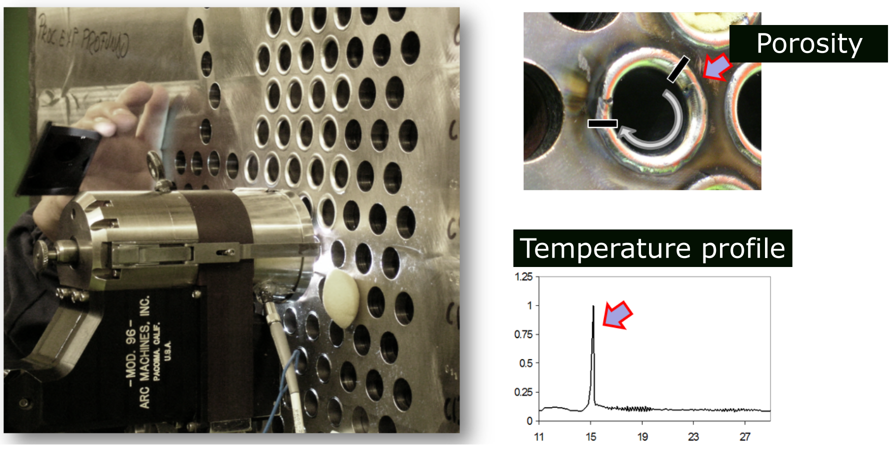

Figure 8. Example of emission spectroscopy being applied to monitoring a welding process. Source: Author's own work.

5.3.2. Laser-induced spectroscopy

Whereas in the welding process there is natural emission of light, in many other cases it is not possible to simply apply emission spectroscopy: it is necessary to intentionally generate light in order to analyze the process or material desired. In this case, it is typical to employ the variant called **laser-induced (breakdown) spectroscopy or LIBS**. LIBS uses a laser with sufficient power to volatilize part of the surface it strikes, emitting light in the process.

A very good example of LIBS is the system integrated into the **Curiosity robot** which has been exploring Mars for some years now[1]. The LIBS system is used to analyze the composition of Martian rocks, something that would otherwise be quite difficult to implement. Figure 9 illustrates Curiosity using the LIBS system laser to analyze the composition of a rock on Mars.

[1] More information at the following link: https://bit.ly/1Rc5LS7

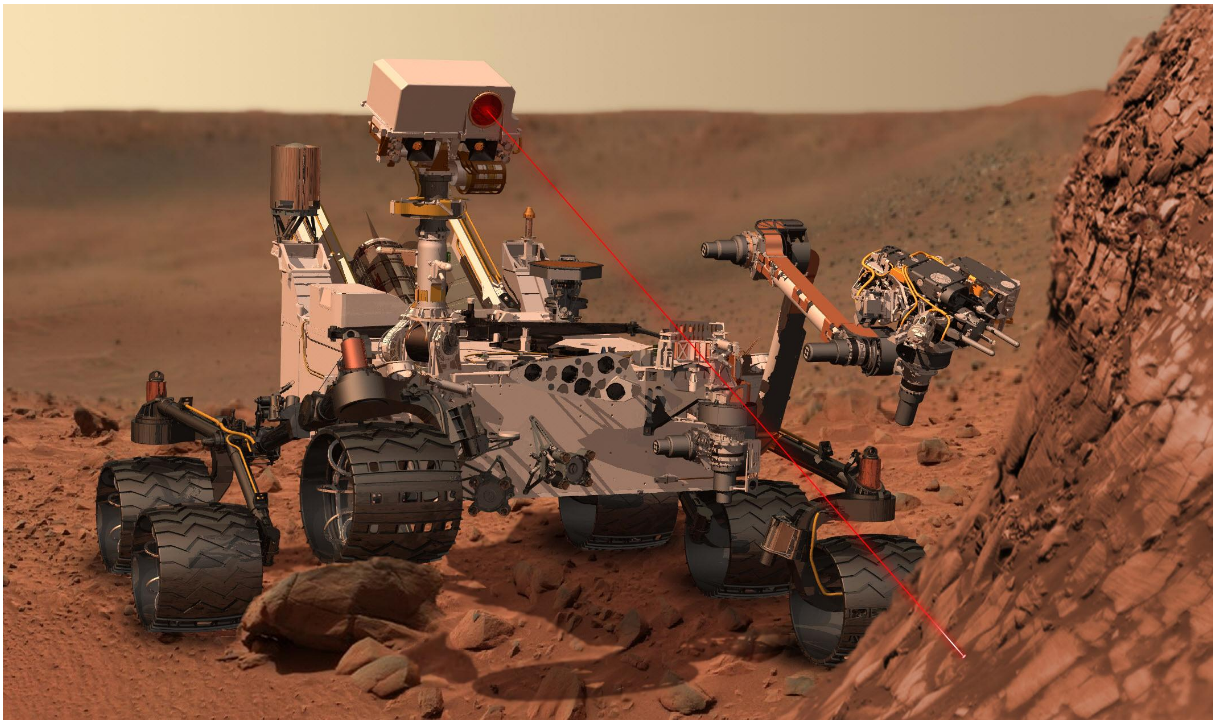

Figure 9. Illustration of the robot Curiosity analyzing the composition of a rock on Mars using a LIBS system. Source: Wikimedia Commons. License: Public Domain. `http://bit.ly/2zGvgP5`

Important 3.2: LIBS

This video shows a LIBS system (you can hear the sound made by the laser on the samples) used to determine the level of copper in rocks which are moving along a conveyor belt: `https://youtu.be/5hnfNcBkXAk`

A LIBS system is capable of determining the **composition** of a material by analyzing the spectrum and the relationship between its emission lines, as explained above. LIBS is, therefore, useful in a great number of industrial applications, as well as in archeological studies: let's take a look at two interesting examples of this.

LIBS for paleo-nutritional analysis. In a study to find out if the plague affected nobles and lower classes equally, LIBS was used to determine whether the bones found in a mass grave in Italy (dating back to the 15th century) belonged to people from noble classes or "plebeians". A person's diet affects the composition of their bones, such that a diet rich in protein leads to higher levels of zinc. On the other hand, high levels of barium, strontium or magnesium in bones indicate a fundamentally vegetarian diet. By using LIBS to analyze the bones found in the grave and determining the relationship between the levels of zinc and strontium, it is possible to find out how many noble people were buried in that grave. As can be observed in Figure 10, there are samples, like number 13, which clearly seem to be associated with a noble, whereas there are others, like number 6 or number 9, with lower levels of zinc, that could belong to people from lower social classes.

LIBS for dating coins from Roman times. Conventional dating methods (like carbon-14) cannot be used for all objects, such as old coins. LIBS dating is not, of course, direct but requires an

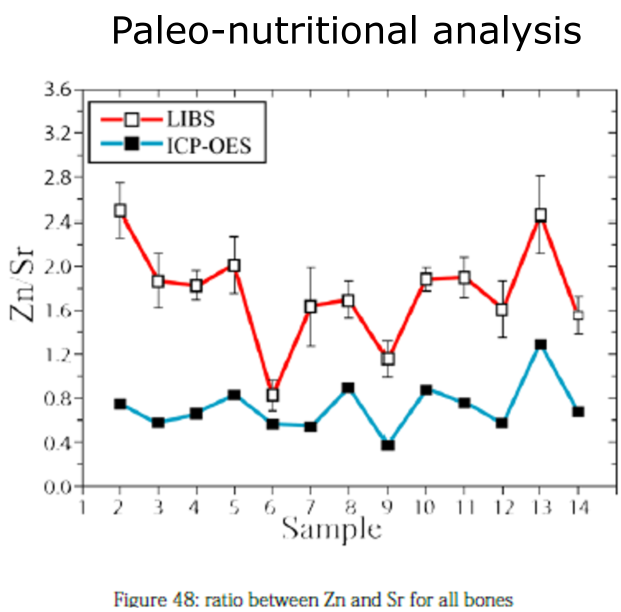

Figure 10. Paleonutritional analysis carried out using LIBS. Source: Author's own work.

intermediate step. First of all, it is necessary to determine the composition of the coins, in this case, Roman silver denarii like the one shown in Figure 11. The composition of Roman denarius coins changed over time, their content in cheaper metals, like copper, increasing when the Empire went through difficult times, coinciding with wars and revolts. Figure 12 shows an example of a spectrum of one of these coins, revealing lines corresponding to copper (Cu), silver (Ag) or lead (Pb). The graph on the right shows a correlation between the level of copper in coins and certain key historical events like the uprising in Spain or the war against Pompey.

Figure 11. A Roman silver denarius. Source: X-Ray Fluorescence and Laser-Induced Breakdown Spectroscopy analysis of Roman silver denarii (Pardini et al.).

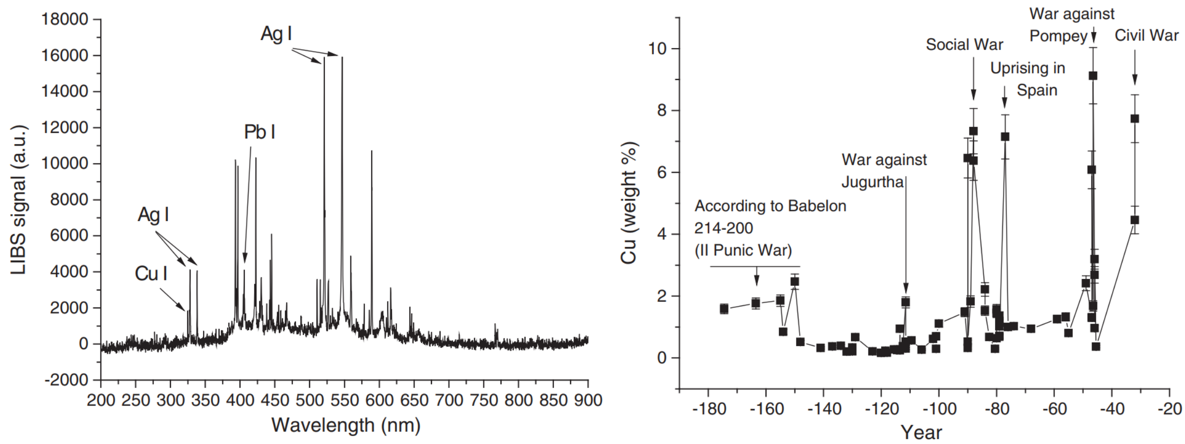

Figure 12. LIBS spectrum of a silver denarius (left) and the historical evolution of the copper content in silver denarii (right). Source: X-Ray Fluorescence and Laser-Induced Breakdown Spectroscopy analysis of Roman silver denarii (Pardini et al.).

Question 3.1: LIBS

Look for information about another LIBS application that you find interesting and briefly explain it **in your own words**.

5.4. LIDAR: the optical radar

One of the most interesting present-day applications of the laser is the so-called **optical radar or LIDAR**[1]. These systems are an extension of the concept of the laser as a distance measuring device seen earlier, as they are based on measuring distance by estimating the time it takes for a pulse of light to go there and back. LIDAR systems are not static, but instead having a sweeping operation to capture information about surfaces, buildings, surroundings, etc. Although it has other applications, the most normal use of LIDAR is **on an aircraft**. In this sense, in order to reproduce field maps through analysis, besides the emitter and laser sensor, a GPS sensor and an inertial navigation sensor are also required in order to know the LIDAR system's position at all times.

With LIDAR systems, it is possible to create maps with a high degree of resolution or detail, thanks to the laser's special characteristics, like coherence. Figure 13 shows an example of a topographic image of Mars created with the MOLA laser system (Mars Orbiter Laser Altimeter).

[1] IDAR: Laser Imaging Detection and Ranging

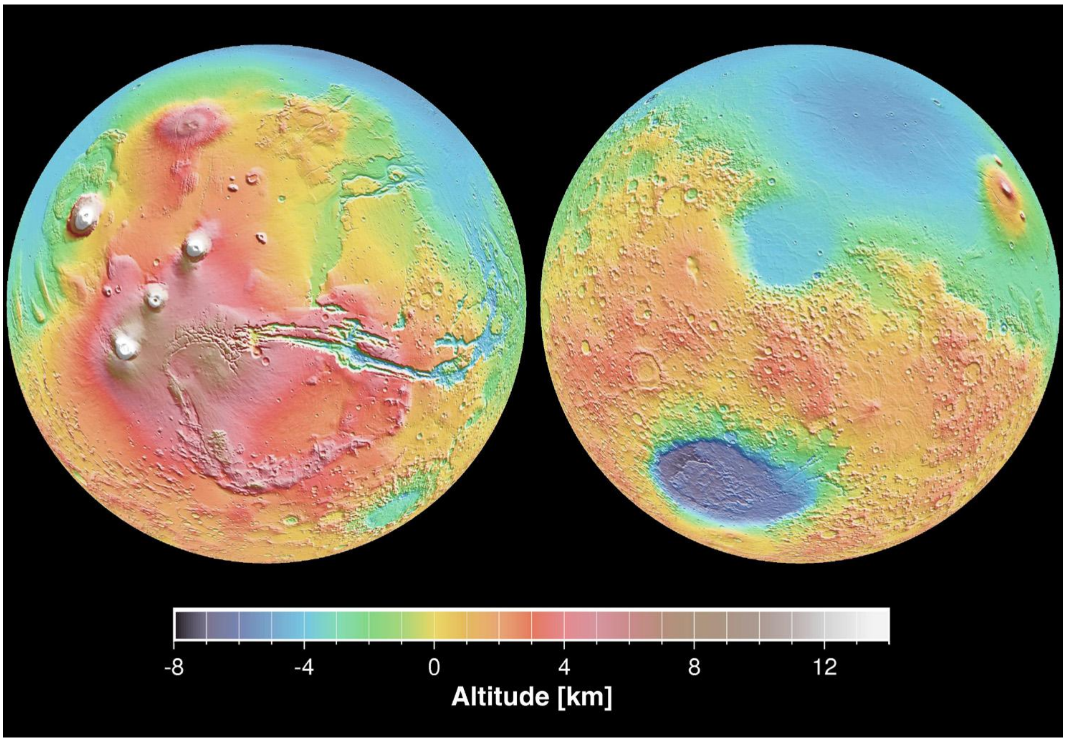

Figure 13. Topographic image of Mars created in 2001 by the MOLA laser system. Source: NASA (Jet Propulsion Laboratory). License: Public Domain. `https://go.nasa.gov/2iTd0Hn`

Question 4.1: Autonomous cars and LIDAR

You have most likely heard of the concept **autonomous car**: a car that drives itself without the need for a driver, thanks to a multitude of sensors and "intelligent" systems. Look for information about this and explain **in your own word**s if there is a **relationship between LIDAR technology and the autonomous car**.

5.5. Optical fiber as a sensor

In previous examples, we have seen systems where sensors are being used by cameras (like in infrared thermography) or spectrometers, as in spectroscopy. However, the **optical fiber itself can be used as a sensor element**, not just as a guide for communication systems.

5.6. Point sensors

On the one hand, in optical fiber, sensors called **diffraction gratings or Bragg gratings**[1] can be inscribed. These elements can be inscribed by pointing the radiation from an ultraviolet laser at the section of fiber desired. This way, a periodical pattern is inscribed in the core of the optical fiber whose refractive index is different from that of the fiber's core. The result is that part of the

[1]These terms are synonyms and will be used interchangeably throughout the rest of the course.

light that reaches that point of the fiber will be reflected, allowing the rest to go through. The wavelength of the reflected light will depend on the temperature and strain of the fiber, so there is a sensor for temperature and strain.

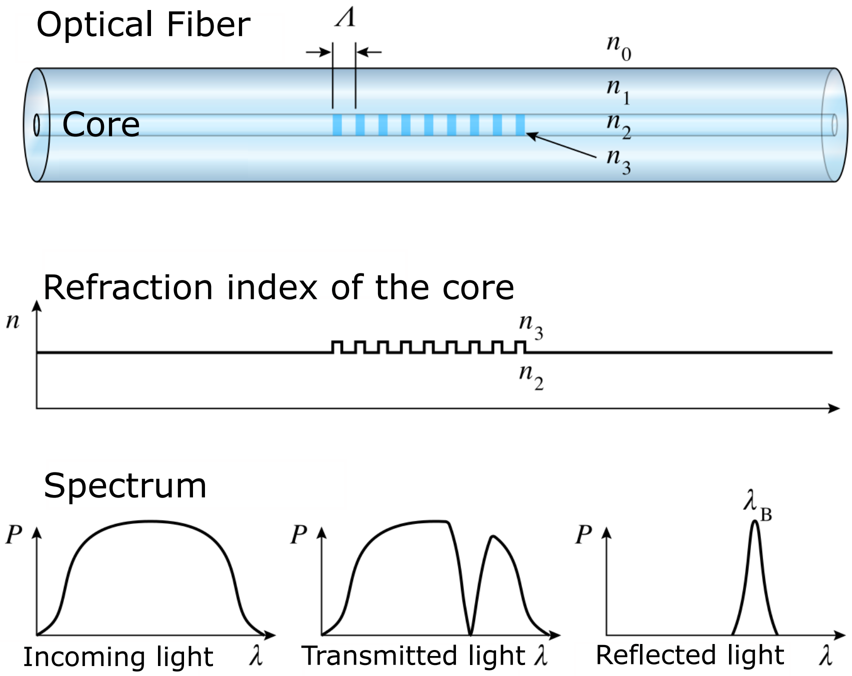

Figure 14. Bragg grating inscribed in an optical fiber. Close-ups of the change in refractive index and the spectrums of incident and reflected light. Source: Wikimedia. License: CC BY-SA 3.0. `http://bit.ly/2ztBRJr`

Figure 14 represents the concept of **Bragg grating**. The image shows the pattern recorded in the core of the fiber with a different refractive index (n_3). At the bottom, we can see how the light that reaches the diffraction grating experiences a reflection of one single "peak" at a certain wavelength, that λ being dependent on the **temperature and strain** to which the grating is subjected.

Logically in this case we are referring to a **point sensor**, in other words, a sensor capable of giving the measurement of the parameter we require at the point where the sensor is installed. Gratings as sensors have numerous fields of application, owing to the fact that this is a mature technology which has been tested over many years. A typical example of the application of this kind of sensor is in civil work. In Figure 15 you can see photographs showing the **installation and testing of a sensor system based on multiple diffraction gratings**[1] on Las Navas viaduct, which is part of the Northern motorway that connects Santander with Asturias, near Cabezón de la Sal. As you can see, the sensors have been placed inside methacrylate structures for their protection and, above all, to efficiently follow the movements of the structure. We can also see the concreting of part of the bridge and the load test.

Gratings, also often called **FBGs** (Fiber Bragg gratings), have applications in a multitude of sectors. In the **renewable energy** sector, there is high demand for applications involving **monitoring and sensing**. One example is wind turbines, which generate dozens of control signals for their correct functioning. A very important factor that needs to be controlled in this field is the structural integrity of the wind turbine's blades which, in the latest models, can be as long as

[1] Various gratings can be installed in the same optical fiber, as long as their wavelengths are different.

Figure 15. Installation of optical fiber sensors based on diffraction gratings on Las Navas viaduct (year 2000). Source: Author's own work.

a football pitch. These blades are manufactured using composite materials like carbon fiber and they are not rigid, but allow for a certain amount of bending. It is therefore vitally important to be aware of the behavior of the blades in real time in order to prevent potential problems that could end up destroying the entire wind turbine, for example at times of abnormally strong winds or turbulence[1].

Figure 16 is a photograph showing the installation of an optical fiber grating sensor on the **blade of a wind turbine**.

[1] The following video shows an example of what might happen: `https://youtu.be/CqEccgR0q-o`.

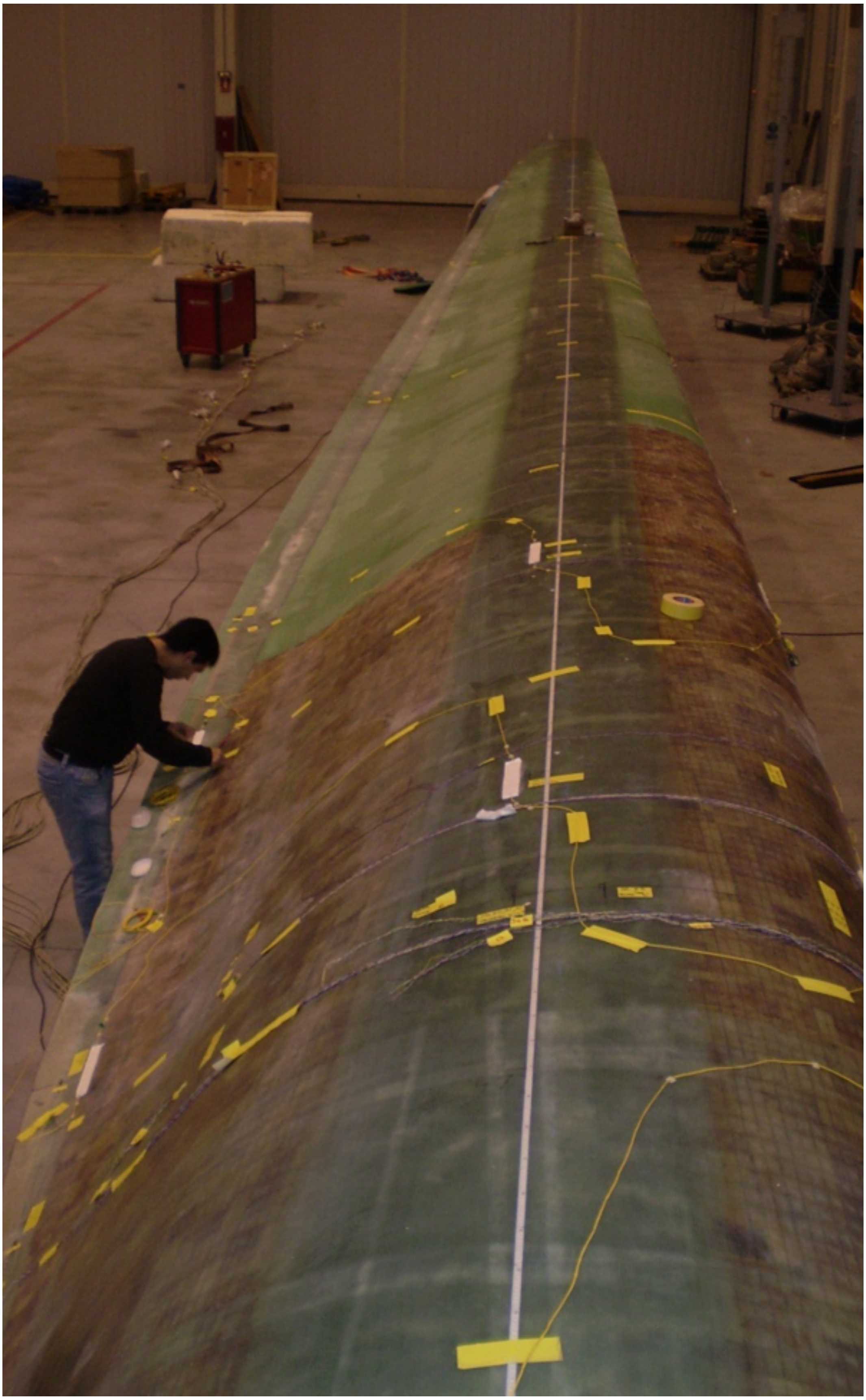

Figure 16. Installation of optical fiber sensors based on diffraction gratings on the blade of a wind turbine. Source: Photonics Engineering Group at the University of Cantabria.

Important 6.1: Testing the blades of a wind turbine

The following video shows how the correct mechanical functioning a wind turbine's blades is put to test. As you can see, they are indeed flexible: `https://youtu.be/5m-jwwM3qRs`

Important 6.2: Wind turbine test laboratory

In Spain, there is a Wind Turbine Test Laboratory in Sangu¨esa, where the various components of a modern wind turbine can be tested and validated: `https://youtu.be/ouxPbOuTKcE`

5.7. Distributed sensors

An interesting concept that we must introduce is that of **distributed sensors**. When we talk about a sensor, we normally think about taking a measurement at a specific point, for example a wind gauge to measure the speed of the wind, a thermometer to measure the temperature of a person or a diffraction grating to find out the temperature at a certain position on a bridge.

When we talk about **distributed sensors or sensing**, we are talking about taking measurements of a certain physical magnitude over a certain distance, in this case using optical fiber. This means that **the entire fiber optic cable acts as a sensor!** Obviously this implies significant advantages when it comes to monitoring infrastructures which require taking measurements of several points and/or extend over long distances. Typical examples of this include oil or gas pipelines, power lines, dams, bridges, etc. Let's imagine the first example: an oil pipeline that covers dozens of kilometers in which we want to detect a possible leakage: what sensor technology could we use for that? It is difficult to imagine an efficient and economically viable solution using conventional sensors. However, fiber optic distributed sensors would enable implementing a satisfactory solution.

These sensors are based on the **scattering** phenomenon. To put it simply, scattering means that the light being transmitted in a certain direction is scattered in all directions, for example by particles that it bumps into along the way. A very illustrative example of this is the Sun and the color of the sky: have you ever wondered why the sky is blue? Shouldn't the sky really be dark and star-laden at all times?

Indeed, as we can see in Figure 17, the Sun observed from beyond the Earth's atmosphere is white and the sky is black: what happens on Earth? The reason why the sky looks blue and the Sun looks yellow is due to a scattering phenomenon called **Rayleigh scattering**. This scattering occurs when the light encounters very small particles, measuring even less than its wavelength. In the sky, these are molecules of certain gases and particles in suspension. The interaction between the light and those particles makes part of the light "scatter", so that those photons are emitted in all directions. But, what photons undergo that phenomenon most intensely? The answer is: the shorter the wavelength, the greater the intensity of the resulting scattering. Below is a simple formula for this:

$$I_{RAYLEIGH} = \frac{Constant}{\lambda^4} \tag{5.2}$$

Figure 17. View of the Sun and the Earth from the International Space Station. Source: Wikimedia (NASA). License: Public Domain. `http://bit.ly/2zSJEUc`

In other words, Rayleigh scattering intensity is inversely proportional to the fourth power of wavelength. If we now look at Figure 5.18 and remember than the shorter wavelengths within the visible spectrum correspond to violet and blue, then we can understand why the sky looks blue: of all the photons emitted by the Sun, the blue ones are scattered in the sky by molecules and particles.

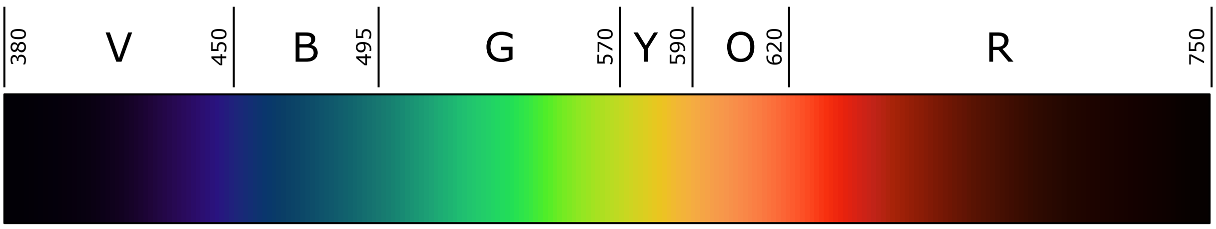

Figure 18. Visible spectrum (V: Violet, B: Blue, G: Green, Y: Yellow, O: Orange, R: Red). Source: Wikimedia. License: Public Domain. `http://bit.ly/2zBGbIV`

And now, **what happens with the Sun?** Why does it look yellow when it should be white? The answer is simple, yellow is the complementary color of blue; in other words, if we take blue out of the color white, the resulting color is yellow.

Important 7.1: The Sun, white?

Is it really true that the Sun should look white? The answer is simple is we think that white is, by definition, the mixture or sum of all the colors.

Now that we have explained what Rayleigh scattering is, it is easy to understand **how scattering works in an optical fiber**. When light enters one end of the fiber, a small part of that light is reflected back as the light travels through it. If we place a sensor (a photo-receptor) at the entry point of the fiber, we can find out what happens at every point along the fiber. Rayleigh scattering is what is used in a device called an **OTDR**[1] to verify optical fiber links. If a link is broken, for example by a digger, we can find out exactly where it has been broken if we use one of these instruments. It is easy to deduce where the fiber is broken, as it works by measuring the time it takes the light to reach this breakage point and go back again, the speed of light being a known factor.

Figure 19 shows an OTDR in operation. The yellow signal that appears on the screen, normally called a "trace", gives us information about events occurring in the fiber channel. For example, in the first section (first 5 and a half squares) there is just a slope indicating the attenuation of the fiber analyzed. The peak that follows indicates a mechanical connection in the fiber (by means of a transition). Finally, when the signal becomes noisy, it means that the fiber channel has come to an end.

There are other types of scattering besides Rayleigh scattering, such as **Brillouin scattering and Raman scattering**, which enable the distributed measurement of temperature and strain in optical fiber. These systems normally use standard and consequently very cheap optical fiber. The devices required for taking measurements in that fiber (injection and detection of light) are usually sophisticated and expensive.

Important 7.2: Raman: Nobel Prize in 1930

These effects are considered to be so important that in fact one of their discoverers, Sir Chandrasekhara Venkata **Raman** (Madra´s, 7th November 1888-Bangalore, 21st November 1970), the Hindu physicist who discovered the scattering that carries his name, **received the Nobel Prize in Physics in 1930**.

[1] *Optical Time Domain Reflectrometry*

Figure 19. Picture of an OTDR device. Source: Wikimedia. License: CC-BY-SA 3.0. `http://bit.ly/2yxFPj8`

Figure 20. Photograph of Raman. Source: Wikimedia. License: Public Domain. `http://bit.ly/2hyfiis8`

5.8. Biomedical applications of light

Just as we explained in the section on spectroscopy that it is possible analyze the composition and characteristics of different objects by means of light-matter interaction, studying the interaction between light and human body tissues and organs can give rise to a wide range of applications in the **biomedicine sector**.

Phenomena related to light like **refraction, absorption and scattering** (all of which have already been mentioned in previous sections) allow us to **gather highly valuable information about the light that has travelled through our tissues**.

Question 8.1: Blue blood

Try to find an "optical" explanation for **royal blue blood**.

5.8.1. Absorption

One of the main mechanisms in the **interaction between light and tissues** (and other elements, like gases) is **absorption**. When light passes through a material, part of the energy associated with that radiation may be absorbed by the material, so that the intensity of the light exiting I1, is lower than the intensity of the light entering $I_1 I_1$, as represented in Figure 21[1].

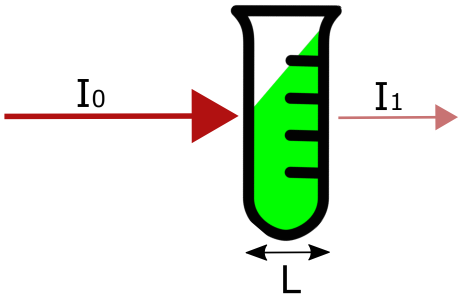

Figure 21. The absorption of light phenomenon. Source: Author's own work.

In order to understand this absorption mechanism, we can think about how some materials, when absorbing Sunlight, reemit part of the energy absorbed in the form of heat (as occurs with the Earth and the well-known greenhouse effect). The scientific formula for the phenomenon represented in Figure 21 uses the so-called **Beer-Lambert Law**:

$$\frac{I_1}{I_0} = 10^{\alpha \cdot L} \tag{5.3}$$

In the above equation, α is a parameter indicating the concentration of the material (liquid, gas) in the test tube that the light will pass through. The greater the concentration and the longer the path of interaction L, then the greater the absorption.

[1] In this diagram, L indicates the length of the path of interaction between the light and the material.

Question 8.2: Absorption of light and energy

At this point in the course, we know that **light is associated with energy** (think about a powerful laser, for example, capable of cutting a metal sheet). On the other hand, we know that energy can neither be created nor destroyed, only transformed.

Based on these assumptions, try to answer the following question: **what happens when light is absorbed by a material? What happens with the associated energy?**

As regards biomedical applications: how can we define this absorption process? It can be described as the process involving the extraction of energy from light by means of molecular *species*, in other words, molecules within the body's tissues and compounds.

This effect, from a biomedical perspective, will be of use both in **diagnosis and therapeutic processes**. How can absorption serve as a tool for diagnosis? The answer is simple if we remember what we saw in the section on emission spectroscopy. In the same way that each atomic element emits a unique light (thanks to its wavelength) due to the energy levels of its electrons, this phenomenon also occurs the other way round: light is absorbed by atoms or molecules, and consequently they will leave their fingerprints on the light, more precisely on its spectrum.

Figure 22 shows the absorption spectrum of hemoglobin[1], to be specific the spectrum for different concentrations (from 10 to 150 mg/mL).

What can this information be used for? For example, for **developing a portable and simple system for monitoring the brain of a newborn child**. Its development can be jeopardized if there is insufficient blood flow to the brain, which can be easily determined using a system that sends light and detects whether or not this light is absorbed at wavelengths where hemoglobin has absorption peaks, in other words, around 410 (violet) and 590 (red) nanometers.

Obviously the example given for hemoglobin can be applied to many other compounds found in the human body, like proteins, melanin, water, collagen, etc., the absorption spectra of which are known (see Figure 23)

Obviously the example given for hemoglobin can be applied to many other compounds found in the human body, like **proteins, melanin, water, collagen,** etc., the absorption spectra of which are known (see Figure 24).

5.8.2. *Scattering*

Scattering processes have already been mentioned in the course, in particular **Rayleigh, Brillouin and Raman** scattering processes. As we already know, scattering occurs when light bumps into tiny obstacles and spreads out in all directions.

To understand this better, we can remember the example that we saw about why the sky looks blue. The example given in Figure 25 is also useful, which shows an experiment in which laser light is projected onto a glass in which some kind of substance has been diluted (sugar in water, for example). In the picture we can see that if a detector is placed almost in front of the source, the system will register part of the light given out, which is scattered by the particles in the substance. Furthermore, if the detector is moved away from the axis parallel to the laser, it continues to

[1] Hemoglobin is a protein inside red blood cells and is responsible for transporting oxygen.

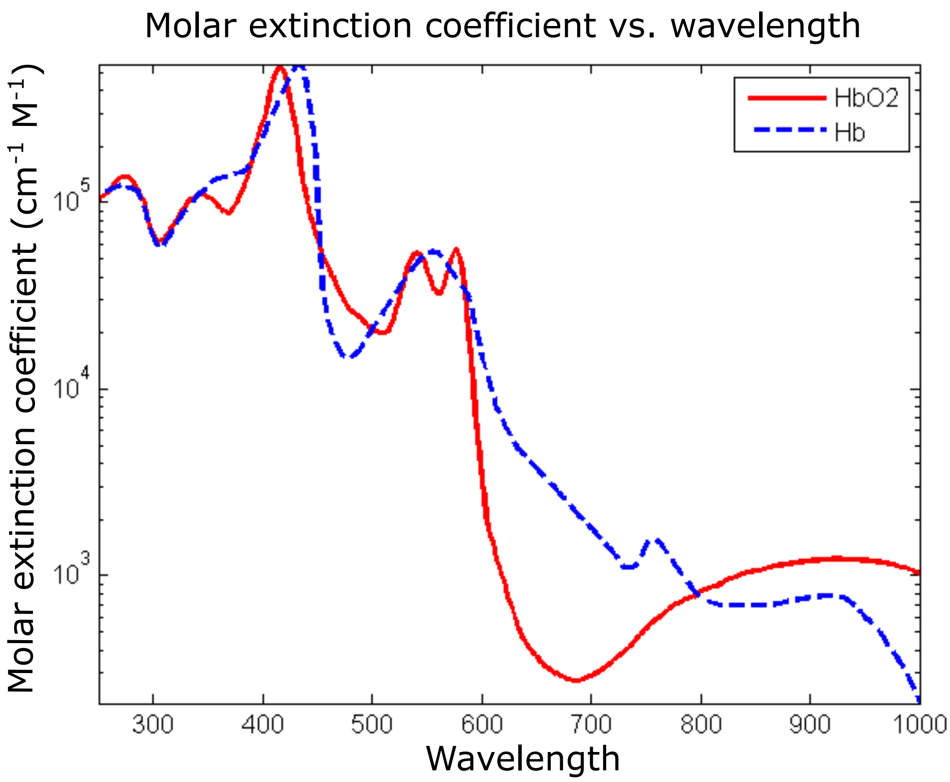

Figure 22. Absorption spectrum for hemoglobin. Source: Wikimedia. License: CC-BY-SA 3.0. `http://bit.ly/2zLhyJ0`

Figure 23. Picture of a newborn baby with a hat incorporating a device for real-time monitoring of the level of hemoglobin in blood. Source: Bozkurt et al. "A portable near infrared spectroscopy system for bed-side monitoring of newborn brain", Biomedical Engineering Online (2005). `https://doi.org/10.1186/1475-925X-4-29`.

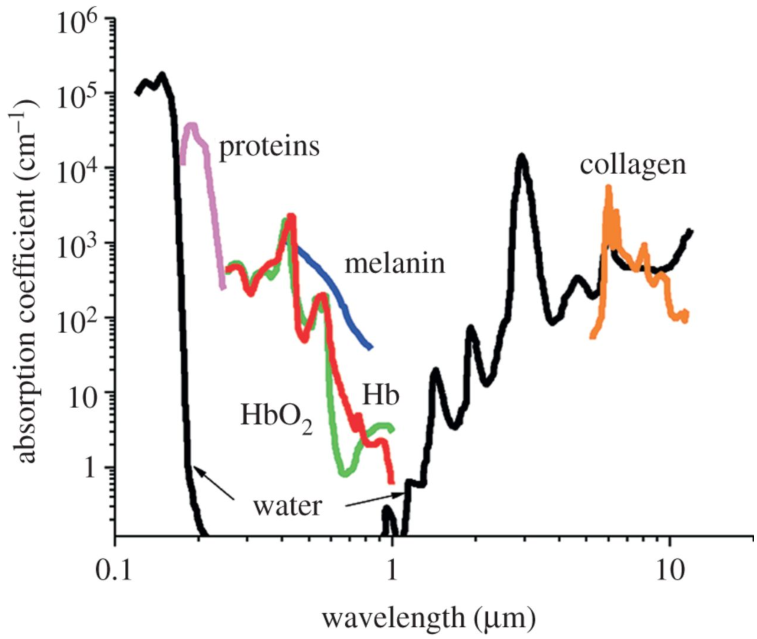

Figure 24. Absorption spectra for different compounds in the human body. Source: Lacroix et al. "New generation of magnetic and luminescent nanoparticles for in vivo real-time imaging", Interface Focus.

receive light thanks to the scattering phenomenon, which would not happen in a vacuum, as there would not be any particles to scatter the light.

What kind of tiny obstacles are we referring to when we talk about using the scattering phenomenon in biomedical applications? We are talking, for example, about different elements that we can find within a cell. Like the absorption phenomenon, scattering can be useful in diagnostic and therapeutic applications.

It is useful in diagnosis, because the **characteristics of the light after undergoing the scattering process will depend on the size, morphology and structure of the components in the tissues**. This means that all these parameters may be detected by means of changes caused to the light with which we are carrying out the analysis. A very interesting example of this involves using these techniques to detect and delimit cancer tissue. It is a well-known fact that it is often necessary to perform operations or treatments which require a clear delimitation of the tissues affected by this disease. However, this is not an easy task for the pathologist. Imaging techniques based on analyzing light scattering enable identifying the affected tissue as this tissue has particular characteristics which make the light scattering different to that of normal tissue.

Figure 26 shows an example of the detection and automated identification of regions with tumor tissue in its different variants (from 1 to 6). Therefore, the idea is that with a suitable source of light and a suitable detector, an automated identification of tissues affected by cancer can be performed.

5.9. Fluorescence to indicate cancer

Amongst the great variety of biomedical techniques deriving from the "intelligent" use of light, there is one particularly remarkable technique which involves the phenomenon of **fluorescence**. **Luminescence** is the emission of light not based on temperature, in other words, not based

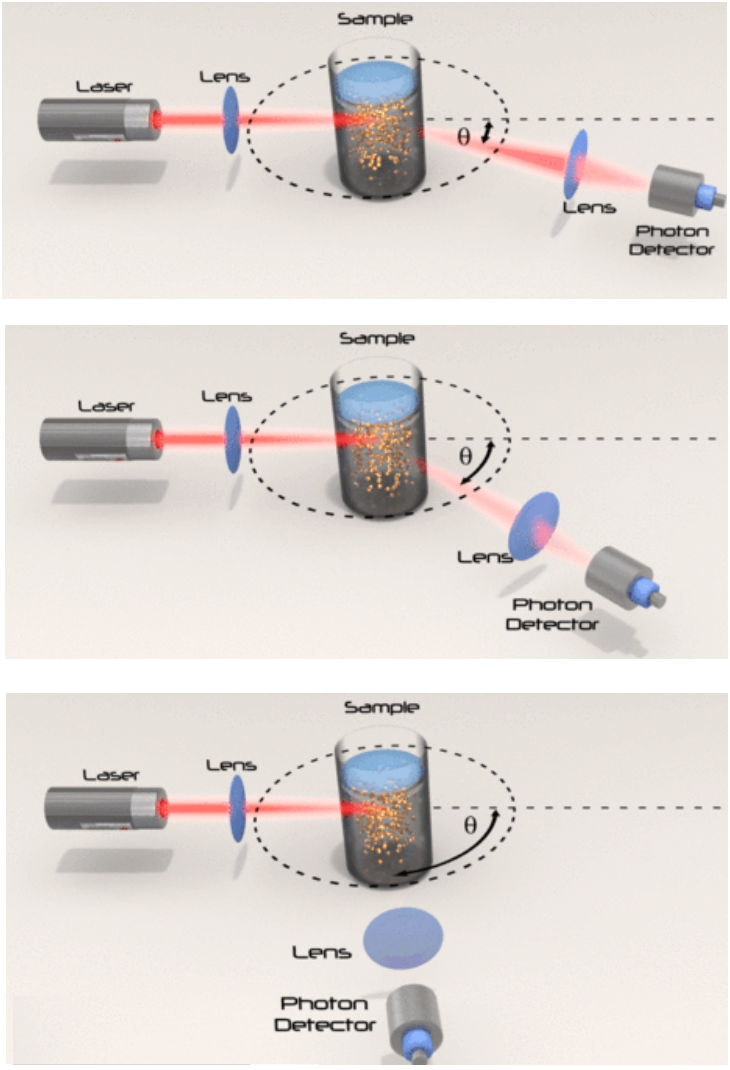

Figure 25. Schematic representation of an experiment involving light scattering. Source: Wikimedia. License: CC-BY-SA 4.0. `http://bit.ly/2hGAItS`

on the working principle of old filament bulbs[1]. Instead, luminescence is understood to be the property of certain bodies to emit ***cold* light**, which is caused by another kind of electromagnetic radiation. Fluorescence, for example, is generated by ultraviolet radiation; in other words, a body receives ultraviolet radiation (not visible to the human eye) and emits light in another part of the spectrum, for example visible light.

Question 9.1: Florescent tube

Briefly explain **in your own words how light is generated in a conventional fluorescent tube.** You do not have to explain the electrical part of the process.

[1] In this course, we have already covered the basic concepts related to this phenomenon.

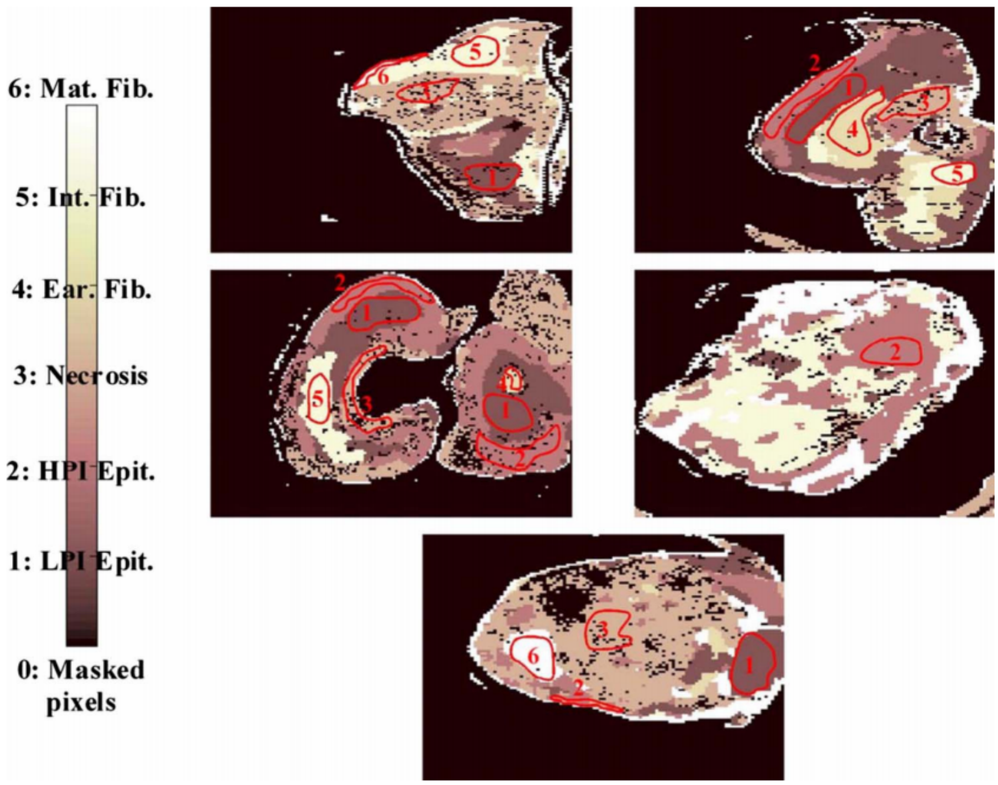

Figure 26. Example of the application of optical techniques in the automated identification of regions affected by cancer in different samples. Source: Garcia-Allende et al. "Automated identification of tumor microscopic morphology based on macroscopically measured scatter signatures', Journal of Biomedical Optics (2009).

As regards its application as a ***marker*** of cancer cells, the process could be as follows. First of all, it is necessary to identify a compound whose presence varies in cancer cells with regard to "healthy" cells. In the example that we are going to see, folic acid will play this role. Secondly, an agent must be developed that, when injected into the affected area, only attaches to the cancer cells. If this agent is also fluorescent, if it is precisely illuminated with UV light, the effect created will be that shown in Figure 27. If we look at the image on the left, it is impossible to identify the cancer cells with the naked eye (in this case the patient has ovarian cancer). However, in the image on the right, after carrying out the process described above, the cancer cells emit light by means of the fluorescence phenomenon, and are consequently easily identifiable.

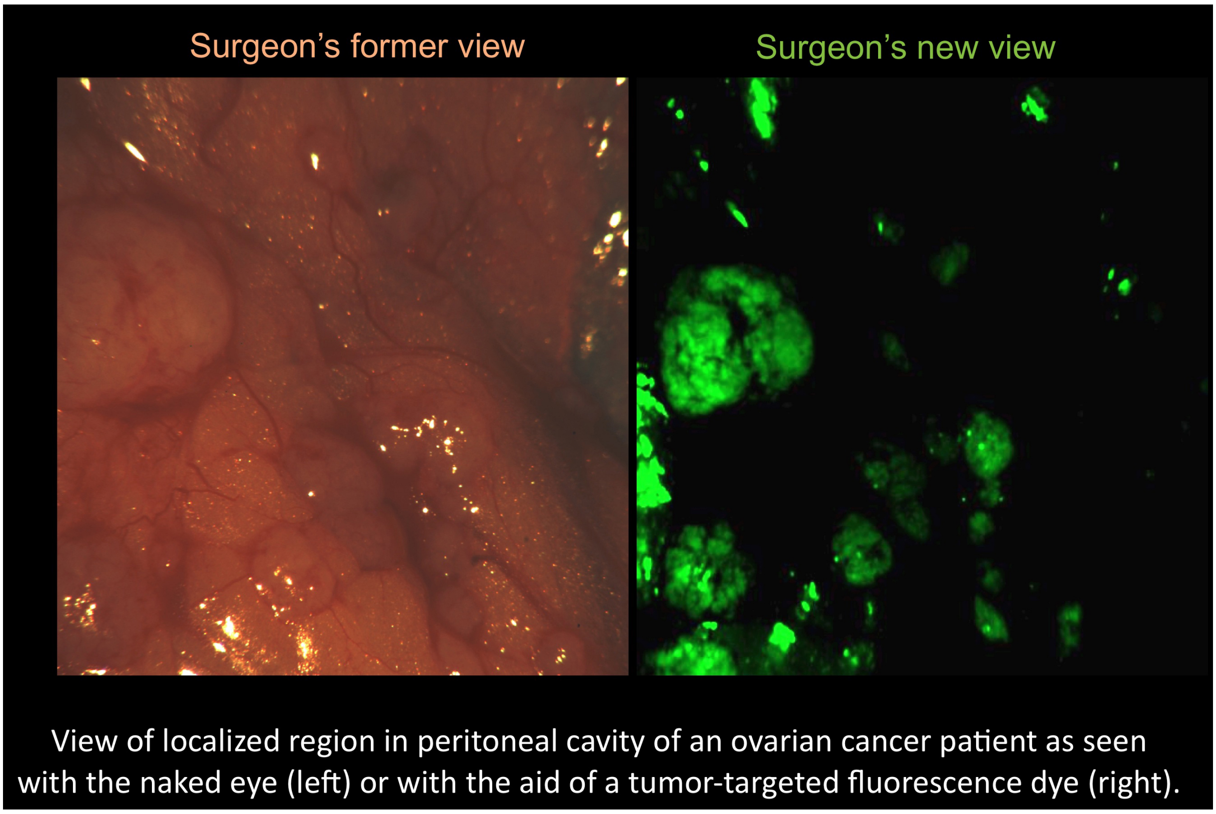

Figure 27. Example of the application of fluorescence to marking cancer cells. Source: Image courtesy of Gooitzen van Dam (Medical News Today). `http://bit.ly/2zL1A57`

5.10. Conclusions

This chapter has provided a quick review of some of the applications which make it possible for us to interact with the world around us by means of the **"intelligent" use of light**. In particular, we have presented applications in which the use of light has enabled the development of sensor systems for measuring different parameters in a variety of applications. The following examples have been given:

Applications in the field of industry such as monitoring welding processes by means of spectroscopic techniques.

Applications in the field of renewable energy , for example photovoltaic solar energy (infrared thermography) and wind power, with real time monitoring of wind turbine blades using optical fiber sensors.

Applications in the field of history/archaeology with the use of LIBS for dating Roman coins or the paleo-nutritional analysis of bones found in graves from the middle ages.

Applications in the field of medicine , such as delimiting cancer tissue using imaging and scattering techniques or monitoring brain development in the newborn by means of systems involving the absorption of light by different compounds.

The applications described in this chapter are just "the tip of the iceberg", however there are many other techniques which, owing to space restrictions, have not been covered in this summary.

Avid readers are encouraged to seek further information in order to broaden their knowledge of this matter by looking at other examples. Please feel free to consult the Professor[1] whenever you wish.

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List of Figures