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THE PHOTOELECTRIC EFFECT: AN EXAMPLE OF THE MEDIATION OF TEACHING LEARNING PROCESSES WITH GOOGLE COLLABORATORY

O EFEITO FOTOELÉTRICO: UM EXEMPLO DA MEDIAÇÃO DOS PROCESSOS DE ENSINO-APRENDIZAGEM COM O GOOGLE COLABORATÓRIO

EL EFECTO FOTOELÉCTRICO: UM EJEMPLO DE LA MEDIACIÓN EN PROCESOS DE ENSEÑANZA Y APRENDIZAJE MEDIANTE EL GOOGLE COLLABORATORY

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Resumen

El efecto fotoeléctrico es un experimento legendario llevado a cabo magistralmente por Robert Andrews Millikan, un experimentador de renombre, quien a pesar de sus opiniones y conclusiones contradictorias sobre los fenómenos cuánticos observados, fue históricamente un protagonista esencial en la construcción de la física cuántica. En este experimento se confirmó la explicación teórica de Albert Einstein sobre el efecto fotoeléctrico, se obtuvo una determinación precisa de la constante de Planck y, además, se inició la caracterización de los materiales fotoeléctricos. En este trabajo, el experimento del efecto fotoeléctrico se utiliza para implementar un ejemplo de mediación de los procesos de enseñanza-aprendizaje con Google Collaboratory. Esta propuesta forma parte del flujo de eventos en el contexto de la nueva tendencia que surge en el escenario del desarrollo científico, tecnológico y técnico, y marca el comienzo de una forma nueva y radical de desarrollar la ciencia, la educación y la cultura para seguir construyendo el discurso científico de nuestro tiempo.

Palabras clave: Técnica de enseñanza. Historia. Ciencias de la computación.

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Física

Abstract

The photoelectric effect, is a legendary experiment carried out masterfully by Robert Andrews Millikan, a renowned experimentalist, who despite his continuous contradictory opinions and conclusions about the observed quantum phenomena, historically was an essential protagonist in theconstruction of quantum physics. In this experiment, Albert Einstein's theoretical explanation of the photoelectric effect was confirmed, a precise determination of Planck's constant was obtained, and furthermore, it induced the beginning of the characterization of photoelectric materials. In this work, the photoelectric effect experiment, is used to implement an example of the mediation of teaching-learning processes with Google Collaboratory. This proposal, is part of the flow of events in the context of the new trend that emerges in the scenario of scientific, technological and technical development, is the beginning of a new and radical way to develop science, education and culture to continue constructing the scientific discourse of our time.

Keywords: Teaching technique, history, computer science, physics

Resumo

O efeito fotoelétrico é um experimento lendário realizado com maestria por Robert Andrews Millikan, um renomado experimentalista, que, apesar de suas opiniões e conclusões contraditórias contínuas sobre os fenômenos quânticos observados, historicamente foi um protagonista essencial na construção da física quântica. Neste experimento, a explicação teórica de Albert Einstein sobre o efeito fotoelétrico foi confirmada, obteve-se uma determinação precisa da constante de Planck e, além disso, induziu-se o início da caracterização de materiais fotoelétricos. Neste trabalho, o experimento do efeito fotoelétrico é utilizado para implementar um exemplo de mediação dos processos de ensino-aprendizagem com o Google Collaboratory. Essa proposta faz parte do fluxo de eventos no contexto da nova tendência que emerge no cenário do desenvolvimento científico, tecnológico e técnico, sendo o início de uma forma nova e radical de desenvolver ciência, educação e cultura para continuar construindo o discurso científico de nosso tempo.

Palavras-chave: Técnica de ensino, história, ciência da computação, física

1. Introduction

The beginning of this new millennium brought with it the creation and growing development of tools and communication, education and collaborative work applications usable on the network of internet and for which an increasing number of resources have been implemented that translate into benefits and number of participants. The new panorama created by the pandemic accelerated the improvement and ostensibly massified the use of the various tools. The scientific, academic and educational communities were the communities that were least alien to this revolution and most closely linked to its development and application. Currently the most developed and massively used tools are: Google Meet, Zoom, Jitsi Meet, Blackboard collaborate, Skype among others. Specialized tools and applications scientific, academic and collaborative work that have caused the greatest impact are: Jupyter Notebook,JupiterLab, JupiterHub, Google Colaboratory, Codeanywhere, AWS Cloud9, Atom. (Sanz, 2019), (Deaza, 2021).

Consequently, there is currently a wide range of collaborative tools and applications in the different areas of knowledge to work at different levels and obviously each one of them at their corresponding level can be used to mediate teaching-learning processes. This new trend, emerging in the natural context of scientific, technological and technical development, is the beginning of a new and radical way of developing science, education and culture. to continue building the scientific discourse of our time. The educational model to mediate teaching-learning processes using Google Collaboratory is based on the fact that Google Collaboratory is a free environment based on Jupyter notebook that runs on Google's cloud servers. It allows to install contained and non-contained libraries and repositories by default and also those native and non-native to python, to write and execute code in python, to document the topic using Latex and HTML, to create and share notebooks using different tools, applications, platforms and mechanisms on top of internet, import, export and publish notebooks, data, archives, files from and/or to Google Drive, GitHub, local drives and other cloud spaces, access and use of CPU, GPU and TPU. (Baume, 2021), (Deaza, 2016).

2. Theoretical Model

It can be affirmed without fear of mistakes that given the vertiginous scientific and technological development of our days; an educational praxis detached from a scientific praxis is unthinkable. Classroom activity, teacher-student interactivity and technological resources cannot continue to be limited to navigating the arid discourse of the scope of science. The classroom must be transformed philosophically, politically, pedagogically, didactically and technologically. The path towards a scientific, interactive and technological classroom that simultaneously allows student and teacher learning must be initiated.

The fusion of the previous ideas must lead to the materialization of a changing and revolutionary dynamic classroom. We must always take a first step to build a reality based on the utopia we long for. This should be the hope that accompanies new educators. The purpose of using Google Collaboratory as a mediator of teaching-learning processes is to closely link scientific praxis with educational praxis in a practical context in the teaching-learning process inside the classroom, outside of it, and even insert this link into everyday life, making use of consumer technologies. (Deaza, 2021).

3. Methodology

A logical conceptual process must dominate the tangible implementation of a methodology. completely practical, closely linked to the science of the subject that constitutes the axis of a session in the teaching-learning process. A methodological sequence is proposed below.

- Masterful presentation of the topic.
- Motivation for numerical analysis, graphics, creation of databases, simulation and animation.
- Presentation and introduction of Google Collaboratory.
- Training in the use of HTML and LaTeX to document the topic.
- Development of the code for scientific analysis of the topic
- Dynamization of the process to induce the student to adopt the work methodology.
- Conceptual, numerical and graphic evaluation of learning outcomes.

The model should qualitatively evaluate the degree of appropriation of concepts, definitions, laws and mathematical formalism and the student's ability to interpret, analyze and apply what has been learned. The result of the qualitative evaluation is, in reality, what is called conceptual evaluation and should be translated into a numerical scale that allows averaging with the numerical evaluation, the latter comes from the qualification of tasks, workshops and individual and collective exams. The numerical results of the evaluation must be delivered to the student who must graphically analyze their learning results monitored by the teacher. (Deaza, 2016).

To implement the model using Google Collaboratory, we will use the photoelectric effect, a legendary experiment done by R. Millikan, in which he tried for ten years to prove that Einstein's theory was not correct, to finally conclude that it was. Einstein and Millikan were awarded Nobel Prizes in 1921 and 1923, respectively. (Einstein,1905), (Millikan, 1916).

4. The Photoelectric Effect and Historic Context

4.1 The need for historical context in the conceptualization of the scientific ideas that frame the theories of light

Although in this project we seek to emphasize the learning of the photoelectric effect from the use of modern technological tools due to their boom in the times, it is also essential that the student has an articulated view of the knowledge that frames development and evolution of scientific theories. In this sense, the work of the history of science is relevant, which allows the student to understand the development of science as a company created by humans, which is changing their conceptions of reality according to their historical context (Niaz et al., 2010), (Galili, 2008). For these reasons, for its connection with the photoelectric effect and by the nature of this document we have decided to make a synthetic historical summary of the theories of the nature of light from its origins to the present day.

4.2 The nature of light

Since ancient times man has worried about the nature of things, of course the essence and behavior of light have been one of the greatest mysteries for man to this day. Throughout history, the nature of light has been debated as to whether light is a wave or a corpuscle. Since according to classical physics, a wave is a disturbance without mass that travels extended in space, while a particle has a defined position in space and has a precise mass, these differences make these physical entities of a completely opposite nature. However, currently within quantum physics it has been concluded that light has dual behavior. The light is wave and particle at the same time, which is called corpuscle duality. (Llandres et al., 1996), (Eisberg et al. 1978)

4.3 The Greeks: The quantification of light and matter

For anyone, is no secret that in ancient times the Hellenic civilization stood out from others for its approach to reality through what was called philosophy. In this context and due to the different questions that Greek philosophers asked themselves, the concern arose about the nature of human vision and with it the nature of light. In order to answer these questions, two theories were created: the "Extramission" and the "Intromission" of rays or particles called "Effluvium". In the extramission proposed by Empedocles (495/490 - 435/430 BC), the observer emits effluvia from his eyes in order to detect objects, while in the intromission formulated by Leucippus (460 - 370 BC), it is the object that emits the effluvia that enters the observer's eyes (Gallardo, 2010).

At the heart of the theories of quantization of matter and light is the figure of the Greek Democritus philosopher (460 - 370 BC), this philosopher is recognized for being the creator of the idea that the subject is formed by “atoms”, Which are established as the fundamental unit of matter. However, the contribution of Helleno to the granular conception of light is not very mentioned. For Democritus the effluvia were the constituent particles of light, with dissimilar forms, and dispositions, moreover, product of their interactions the different colors were generated. Even Plato (427 - 347 BC) adhered to the idea of effluviums as particles, but in this case its geometric shape was tetrahedral and the varied colors of light would be defined by their different speeds. (Llandres et al., 1996). This historical information is evidenced that the models of quantization of matter and energy in their most primitive form had origin in Greek philosophical thinking. (Gallardo, 2010).

4.4 Wave theory of light in the seventeenth century

By the 17th century the phenomena of light propagation such as reflection and refraction were already recognized and even treated quite prudently by Arab philosophers and scientists such as Alhacen (965 - 1060) and Al-farisi (1267 - 1319). In this century the wave theory of light was strongly developed by scientists such as Rene Descartes (1596 - 1650), Francesco Maria Grimaldi (1618 - 1663), Robert Hooke (1635 - 1703) and Cristian Huygens (1629 - 1695). It was these scientists who, with their wave theory, were able to explain phenomena such as reflection, refraction, diffraction and even the double refraction of light.

The synthesis of these ideas was presented by Huygens in his book entitled "Treaty on Light" which was published in 1690. In this Document Huygens presented the light as a wave or disturbance that traveled through a material medium (ether), analogically as sound waves do. From this perspective, disturbance and wave move in parallel. Unfortunately, this model did not explain the polarization of light. As for the instant propagation of light, the Dutch scientist stated that, as the waves in a pond require time to spread, in the same way light waves need time to extend at constant speed. (Eisenstaedt, 2015).

4.5 Corpuscular theory of light in the 18th century

In 1704 Isaac Newton (1642 - 1727) published his book "Optics", in this Treaty Newton explained some phenomena of light such as; Reflection, refraction and colors. Here the experimental works of him were revealed regarding the colors and composition of white light. Using these evidences Newton raised his explanation of the nature of the light, for him, light was composed of materials or material corpuscles of different sizes that were emitted by the bodies and arrived in a straight line in the eyes.

These ideas allowed him to explain in a simple way the reflection and refraction of light, however, to explain the refraction of light, unlike undulatory theory, light would increase its speed within the refractor environment, this justified by the forces of mechanical attraction in the neighborhoods of the medium. With his postulates Newton was able to explain the rainbow, in addition, by his great influence, Newton's ideas regarding the behavior of light were the predominant during almost the entire 18th century. (Granés S., 1988), (Eisenstaedt, 2015) & (Gallardo, 2010).

4.6 The new wave of light

At the beginning of the 19th century the vision of nature and the behavior of light would change forever. In the hands of scientists Thomas Young (1773 - 1829), François Arago (1786 - 1853) and Augustin Fresnel (1788 - 1823) the final theory would be developed to crush the corpuscular vision of the light raised by Newton at the beginning of the 18th century.

In the first instance Thomas Young carried out the double slit experiment, in this work the British scientist proved the wave nature of light, which allowed him to explain the phenomena of interference and diffraction (Eisenstaedt, 2015). Some time later, in 1819, the mathematical theory of the undulatory nature of light was presented by Fresnel at the Academy of Sciences in Paris, with which the various observations regarding the behavior of light were correctly justified. However, Simeon Poisson (1781 - 1840) showed that these ideas predicted the existence of a point of light behind an object that blocked the light. However, this point of light was put into evidence experimentally by Arago (Gallardo, 2010), (Eisenstaedt, 2015) & (Trabulse, 2007). Finally, to explain the polarization problem of light, discovered by Étienne-Louis Malus (1775 - 1812) in 1809, Young proposed that light behaved as a wave of transverse character, i.e., the direction of wave propagation and the direction of the perturbation are perpendicular to each other. Perhaps the only problem not solved by this model was that of the medium of propagation of light (ether).

These results resulted in the momentary decline of the corpuscular or granular theory of light in the nineteenth century. (Gallardo, 2010), (Llandres et al., 1996). Despite this story, Jean Eisenstaedt (1940) in his book entitled "Before Einstein: Relativity, Light and Gravitation," says the possibility of a parallel story in which the ideas of corpuscular theory could in this historical context, be Approaching the basic ideas of the relativity of Albert Einstein (1879

- 1955), the creators of these ideas would be mainly John Michell (1724 - 1793) and Robert Blair (1748 - 1828). (Eisenstaedt, 2015). Which unfortunately were overshadowed by the wave of the undulating nature of light.

4.7 Electromagnetism: the parallel paths of light

At the beginning of the 19th century and simultaneously to the development of undulatory theories of light, the fundamental ideas of electromagnetism were discovered. The definitive finding in the direction of electromagnetism was made by Hans Christian Ørsted (1777 - 1851) in 1820, who found experimentally that, the electric current flowing through a conductive thread could move the magnetized needle of a small compass. (Gamow, 1960), (Gallardo, 2010).

Enlightened by this experience, André-Marie Ampère (1775-1836) and Michael Faraday (1791-1867) experimentally discovered the laws of electromagnetism. However, it was the British scientist James Clerk Maxwell (1831-1879) who would develop a successful theoretical formulation of electromagnetic theory in his 1865 paper "A Dynamical Theory of the Electromagnetic Field". Perhaps the most disturbing result of Maxwell's theoretical expressions was his prediction of the possible existence of electromagnetic waves. With these equations it became possible to determine the speed of propagation of these waves, to Maxwell's surprise these waves propagated at a speed of about 300000 km/s, which turned out to be the speed of light.

With this evidence it became undoubted for the British scientist who, the light was an electromagnetic wave that spread through the ether. (Gamow, 1960), (Gallardo, 2010). While the developments of electromagnetism laid the conceptual basis of the undulating nature of light, the problem of the “ether” material by which these waves are propagated, it was not resolved, until the German physicist Albert Einstein raised the special relativity in 1905 (Gamow, 1960), (Gallardo, 2010) & (Eisenstaedt, 2015).

4.8 Color, temperature and radiation

On the other hand, by the middle of the 19th century the science of thermodynamics had already been developed by scholars such as William Thompson (1824 - 1907) "Lord Kelvin", Rudolf Clausius (1822 - 1888), James Prescott Joule (1818 - 1889), among others. However, in this context, thermodynamics needed to be explained by an underlying theory. To explain the microscopic basis of thermodynamics, scientists like Maxwell, Ludwig Boltzmann (1844-1906), and Josiah Willard Gibbs (1839-1903) developed what became known as the kinetic theory of heat. This theory assumed the existence of small constituent particles of matter, which were governed by Newton's laws, and that due to their molecular agitation the temperature of any physical system could be defined (Gamow, 1960).

Also, by this same time (1862) German physicist Gustav Kirchhoff (1824 - 1887) was doing the study of what he baptized as "black body." Theoretical body that could absorb all the energy it received in the form of radiation, which would generate thermal agitation in the body, and that would cause an emission of energy known as black body radiation. (Gallardo, 2010). By the end of the 19th century different scientists had carried out empirical studies of the radiation issued by black bodies at different temperatures, in these studies empirical laws were found for the problem by Wilhelm Wien (1864 -1928), Josef Stefan (1835 - 1893) and Ludwig Boltzmann. It is important to note that these laws were found using electromagnetism laws and emerging ideas of statistical mechanics. (Gamow, 1960).

Despite these developments, the underlying theory that would account for blackbody radiation curves remained elusive, even the scientists Lord Rayleigh (1842 - 1919) and James Jeans (1877 - 1946) developed a model that was called classical, since it was based on the laws of electromagnetism and the ideas of classical statistical mechanics, however, this ended up becoming the ultraviolet catastrophe, since it predicted that the energy emitted by the body diverges at these wavelengths, a result that was not compatible with the observations (Gamow, 1960). (Gamow, 1960).

Finally, to account for the theory that explained the black body problem, the German scientist Max Planck (1858 - 1947) developed a hypothesis in which the energy emitted by the black body was not emitted continuously, but was produced in a discrete manner, i.e. in the form of energy packets called "Quanta". This idea allowed Planck to propose in 1900 the law of black body radiation. This hypothesis was known as Planck's law and became one of the fundamental ideas of Quantum Mechanics that appeared time after the hand of Niels Bohr (1885 - 1962) and Albert Einstein (Gamow, 1960), (Gallardo, 2010).

4.9 The photoelectric effect: Revenge of the corpuscular theory of light

The photoelectric effect saw the light with the experiments performed by Heinrich Hertz (1857 - 1894) in 1887 to test the existence of electromagnetic waves predicted by Maxwell's theory. In this experience Hertz used an electromagnetic wave receiver coil that when he received a wave issued a spark. In this experience the scientist detected that, with an ultraviolet light incident in the spark, it intensified. This experience was also carried out by other scientists, such as Wilhelm Hallwachs (1859 –1922), but this phenomenon could not be explained by the undulating theory of light, dominant until that moment (Rodríguez & Cervantes, 2006).

In the 20th century one of the first to work on the photoelectric effect was a disciple of Hertz. The German scientist Philipp Lenard (1862 - 1947) studied the behavior of electrons within the photoelectric effect, in this research he found the relationship that existed between the kinetic energy of the particles and the frequency of the incident light. The kinetic energy gained by the particles after interaction with the radiation could be measured using an electric potential called the "braking potential". The discovery that the energy of the photoelectrons depended on the frequency of the radiation and not on the intensity of the radiation came as a surprise, since it was expected that the energy would depend on the intensity of the light and not on the frequency. On the other hand, when the light beam interacted with the photosensitive material, the electrons were released immediately, but from the classical point of view these results were an anomaly, since it was expected that the particles would take some time to leave the material (Rodriguez & Cervantes,2006), (Niaz et al.,2010).

Finally, Robert Andrews Millikan (1868 - 1953) proposed experiments that tried to show that Einstein's hypotheses were false, since he considered that the correct physical theory of light was the wave theory. With these experiences, Millikan was able to establish the value of Planck's constant. The conclusion that the physical theory of energy quanta or photons formulated by Einstein was correct was very important, especially because it came directly from a detractor. Millikan was later awarded the Nobel Prize in Physics in 1923 for this work. (Rodríguez & Cervantes, 2006), (Niaz et al., 2010). Thus, the photoelectric effect was the first evidence that under certain circumstances light behaves as a particle and in others acts as a wave, this would be known as wave-particle duality of light, a fundamental idea of current "Quantum Mechanics".

4.10 The importance of historical travel

Perhaps this trip is presented as something capricious in the process of understanding the photoelectric effect, however, this route shows this discovery, not as an isolated event in the history of science, but as the consequence of a thought that has been developing since antiquity to the present day. It is even very important to note that the ideas of particle or wave for light have been around since the origins of Greek thought, however, it stands out as the two ideas were mutually exclusive all the way, only at the end of this long road, with the discovery of the photoelectric effect, it was conclusively concluded that these two natures of light do not exclude each other, but rather combine to account for a dual reality.

In short: "The legitimate, safe, and fruitful method of preparing a student to receive a physical hypothesis is the historical method. To trace the transformations through which the empirical matter accumulated while the theoretical form was first sketched; to describe the long collaboration through which common sense and deductive logic analyzed this matter and modeled that form until one was exactly adapted to the other: that is the best way, surely even the only way, to give scholars of physics a correct understanding. and clear vision of the very complex and lively organization of this science" Galili, I. (2008).

5. The Photoelectric Effect

Thomson's experiments showed that metals contained electrons, but it was not known whether the electrons were free-roaming or bound to atoms. However, the mechanism of emission of the electrons due to the absorption of the incident electromagnetic radiation must include an interaction between the electromagnetic field of the electromagnetic wave and the electric charge of the electrons. In this model and in most basic models of the photoelectric effect, the interaction with the magnetic component of the electromagnetic field of the electromagnetic wave is omitted. The oscillating electric field of the electromagnetic wave acts on the electrically charged electrons, inducing an oscillation in the electrons with an amplitude proportional to the amplitude of the electric field, then (Eisberg, 2002).

$$\overline{AverageKineticEnergy} \propto OscillationAmplitude^2 \propto ElectricFieldAmplitude^2 \propto \sqrt{LuminousIntensity^2} \quad (1)$$

This conclusion, in the context of classical physics, was the biggest obstacle to accepting that the energy transferred to the electrons and transformed into the kinetic energy with which they are released from the surface of the material is independent of the light intensity of the incident electromagnetic radiation.

Using classical physics, a correct estimate of the time required for electrons to absorb energy is of the order of t = 6s. This delay in the photoelectric effect experiments, was not observed. (Eisberg, 2002). In the year 1905, A. Einstein based entirely on Max Planck's postulate, proposed that the energy of a quantum

$$E = h\nu \quad (2)$$

It is completely absorbed by some electron on the photocathode. h is Planck's constant and ν is the frequency of electromagnetic radiation. If this energy is greater than the sum of the energy used by the electron to reach the surface of the material and the energy needed to overcome the contact potential, the electron can escape from the surface. of the material (Einstein, 1905). In conclusion

$$E_{Max} = \frac{1}{2}mv^2 = h\nu - \phi_w \quad (3)$$

The kinetic energy with which the electrons escape from the surface is a linear function of the frequency of the electromagnetic radiation. Φ_W is the work function and is the work required to extract the electron from the material surface. (Portis, 1974). When the electrons are stopped at the photocathode surface, no electric current will be observed and consequently all the kinetic energy will have been transformed into electric potential energy and then

$$eV_b = h\nu - \phi_w \quad (4)$$

Then, a graph of the braked voltage as a function of the frequency of the electromagnetic radiation allows one to determine a slope of the linear function that must be approximately

$$Slope \simeq \frac{h}{e} \quad (5)$$

a cutoff point in the codomain, approximately equal to the work function, which is a characteristic of each material, a cutoff point in the frequency domain, which is the threshold frequency, below this frequency there will be no photoemission.

The most relevant conclusions of the article by A. Einstein and that can be confronted in the experiment are (Portis,1974)

1. The kinetic energy with which the photoelectrons are released from the surface of the material and which can be determined from the braked voltage necessary to completely interrupt the flow of photoelectrons from the cathode to the anode, is independent of the luminous intensity of the electromagnetic radiation, but it is a linear function of the frequency of electromagnetic radiation.

2. There is a threshold frequency of electromagnetic radiation below which photoemission of electrons does not occur. Equivalently, there is a wavelength associated with the threshold frequency above which electron photoemission does not occur. This frequency or wavelength is a characteristic of each material.

3. The saturation electronic photocurrent is directly proportional to the luminous intensity of the electromagnetic radiation.

6. The Experiment

The figure shows a basic scheme of a usual circuit to do an experiment similar to the one done by Robert Andrews Millikan to observe the Photoelectric Effect. The electromagnetic radiation coming from a lamp passes through a filter whose color is associated with a frequency specified by the manufacturer of the filter, incident on the surface of the photocathode. The electrons on the photocathode surface absorb quanta of electromagnetic radiation, if the energy of the quanta is greater than the energy associated with the contact potential that has them bound to the material, the electrons will be released and due to the electric field associated with the potential difference between the photocathode and the anode, the electrons go to the anode completing the circuit.

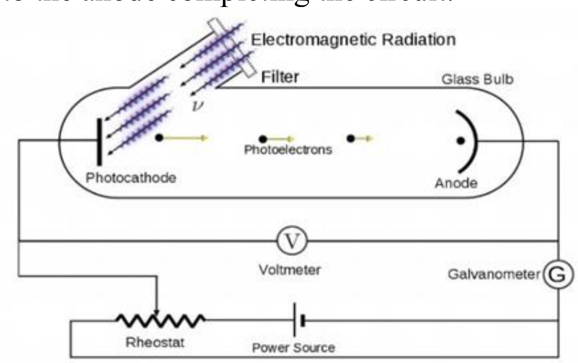

Figure 1. Scheme photoelectric effect experiment.
Credits: Julio Güémez, Manuel Fiolhais [10]

The center zero galvanometer will indicate the maximum conventionally positive electric current. The voltmeter will indicate the minimum voltage. Using the rheostat to increase the voltage, then the galvanometer will indicate a gradual decrease in electric current. When the electric current is zero, the voltage indicated by the voltmeter is a voltage that stops the electrons on the photocathode surface and is called the braked voltage. If you continue to vary the voltage, the current now flows in the opposite direction. The procedure was done using three filters whose frequencies are associated with the colors yellow, green and blue.

The frequency of the electromagnetic radiation associated with the yellow filter is **ν=5.19×1014Hz** and the data obtained is shown in the table that results from reading the file **YellowFilter.csv** (Portis, 1974), Julio (Güémez & Fiolhais, 2018), (Liu, 2007), (Ajzenber, 1967), (Garver, 2006).

```
In [ ]: print("frequency=5.19x10¹⁴ Hz wavelength=5780A V-I")
        import pandas as pd
        YellowFilter = pd.read_csv('YellowFilter.csv')
        YellowFilter.iloc[:16]

        frequency=5.19x10¹⁴ Hz wavelength=5780A V-I
```

Figure 2. Code

Table 1. Voltage and Electric Current (Yellow Filter)

Out[ ]:

	Yellow Filter Data V-I
Voltage	Electric Current
-0.0	0.3
-0.1	0.2
-0.15	0.0
-0.2	-0.2
-0.3	-0.4
-0.4	-0.5
-0.5	-0.7
-0.6	-0.8
-0.7	-1.0
-0.8	-1.2

The frequency of the electromagnetic radiation associated with the green filter is **$\nu=5.50\times10^{14}$Hz** and the data obtained is shown in the table that results from reading the file **GreenFilter.csv**

```
In [ ]: print("frequency=5.5x10¹⁴ Hz wavelength=5460A V-I")
        import pandas as pd
        GreenFilter = pd.read_csv('GreenFilter.csv')
        GreenFilter.iloc[:16]

        frequency=5.5x10¹⁴ Hz wavelength=5460A V-I
```

Figure 3. Code
Fuente: Own.

Table 2. Voltage and Electric Current (Green Filter)

Out[ ]:

	Green Filter Data V-I
Voltage	Electric Current
-0.05	0.6
-0.1	0.2
-0.18	0.0
-0.2	-0.2
-0.3	-0.5
-0.4	-0.8
-0.5	-1.1
-0.6	-1.3
-0.7	-1.5
-0.8	-1.7

The frequency of the electromagnetic radiation associated with the blue filter is **v=6.88×1014Hz** and the data obtained is shown in the table that results from reading the file **BlueFilter.csv**

```
In [ ]: print("frequency=6.88x10¹⁴ Hz wavelength=4360A V-I")
        import pandas as pd
        BlueFilter = pd.read_csv('BlueFilter.csv')
        BlueFilter.iloc[:16]

        frequency=6.88x10¹⁴ Hz wavelength=4360A V-I
```

Figure 4. Code

Table 2. Voltage and Electric Current (Blue Filter)

Out[ ]:

	Blue Filter Data V-I
Voltage	Electric Current
-0.1	3.1
-0.2	2.5
-0.3	1.8
-0.4	1.4
-0.5	0.8
-0.6	0.4
-0.7	0.2
-0.75	0.0
-0.8	-0.1
-0.9	-0.2

7. Analysis and Results.

It is necessary to construct the I−V characteristic curves for each filter. The data for the voltage V and the electric current I are contained in the row matrices x and y for each filter. Now we proceed to graph the data of the first table and to implement a polynomial fit of order 2 whose correlation factor is the closest to 1 and consequently is the best fit.

```
In [ ]: from numpy.ma.extras import corrcoef
        import numpy as np
        import matplotlib.pyplot as plt

        x=[0.0,-0.1,-0.15,-0.2,-0.3,-0.4,-0.5,-0.6,-0.7,-0.8]
        y=[0.3,0.2,0.0,-0.2,-0.4,-0.5,-0.7,-0.8,-1.0,-1.2]

        plt.scatter(x,y,color="red")
        plt.title("$I - V$ Characteristic - Yellow Filter - Photoelectric Effect")
        plt.xlabel("Voltage $V$")
        plt.ylabel("Electric Current Intensity $I$")

        linear_model=np.polyfit(x,y,2)
        linear_model_fn=np.poly1d(linear_model)
        x_s=np.arange(-1,0.1,0.001)
        plt.plot(x_s,linear_model_fn(x_s),color="blue")
        plt.grid()
        plt.show()
        uncertainty=np.var(linear_model)
        print("- The Uncertainty =",uncertainty)
        correlation=np.corrcoef(x,y)
        print("- The Correlation Coefficient =", correlation)
        print("- The Second Order Adjustment Coefficients are:")
        print(linear_model)
```

Figure 5. Code

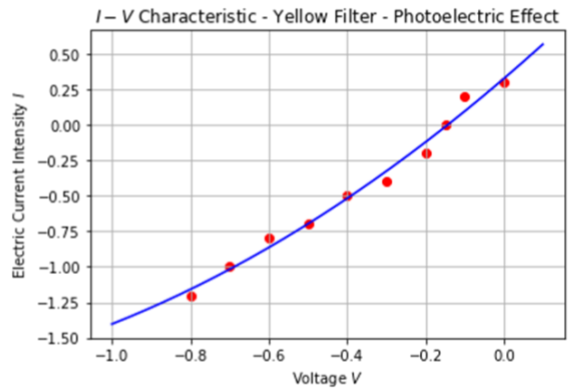

Figure 6. I - V Characteristic - Yellow Filter - Photoelectric Effect
Source: Own

The uncertainty of the polynomial fit model is also calculated. (Ayars E. [3]).

- The Uncertainty = 0.8050703013415932
- The Correlation Coefficient = [[1. 0.9907772]
 [0.9907772 1.]]
- The Second Order Adjustment Coefficients are:
[0.63653222 2.3653732 0.32573018]

The correlation coefficient or correlation factor is **Γ=0.9907772** then the data of voltage **V** and electric current **I** are highly correlated and consequently

$$0.63653222x^2 + 2.6353732x + 0.32573018 \quad (6)$$

now we compute the roots of the above

```
In [ ]: import cmath

        a=float(input("Enter the Value of (a):\n"))
        b=float(input("Enter the Value of (b):\n"))
        c=float(input("Enter the Value of (c):\n"))

        # calculate the discriminant
        d = (b**2) - (4*a*c)

        # find two solutions
        sol1 = (-b-cmath.sqrt(d))/(2*a)
        sol2 = (-b+cmath.sqrt(d))/(2*a)

        print('The solution are {0} and {1}'.format(sol1,sol2))
```

Figure 7. Code

Enter the Value of (a): 0.63653222

Enter the Value of (b): 2.3653732
Enter the Value of (c): 0.32573018

The solutions are (-3.5728023617266937+0j) and (-0.14322822663849524+0j)

The root located in the interval of the filter data whose frequency is **ν=5.19×10^14Hz** is the braked voltage **V_b** associated with this frequency, then

$$\nu=5.19\times10^{14}\text{Hz}$$

and

$$V_b=0.14322822663849524\text{V}$$

```
In [ ]: import numpy as np
        import matplotlib.pyplot as plt

        x=[-0.05,-0.1,-0.18,-0.2,-0.3,-0.4,-0.5,-0.6,-0.7,-0.8]
        y=[0.6,0.2,0.0,-0.2,-0.5,-0.8,-1.1,-1.3,-1.5,-1.7]

        plt.scatter(x,y,color="red")
        plt.title("$I - V$ Characteristic - Green Filter - Photoelectric Effect")
        plt.xlabel("Voltage $V$")
        plt.ylabel("Electric Current Intensity $I$")

        linear_model=np.polyfit(x,y,2)
        linear_model_fn=np.poly1d(linear_model)
        x_s=np.arange(-1,0.1,0.001)
        plt.plot(x_s,linear_model_fn(x_s),color="blue")
        plt.grid()
        plt.show()
        uncertainty=np.var(linear_model)
        print("- The Uncertainty =",uncertainty)
        correlation=np.corrcoef(x,y)
        print("- The Correlation Coefficient =", correlation)
        print("- The Second Order Adjustment Coefficients are:")
        print(linear_model)
```

Figure 8. Code

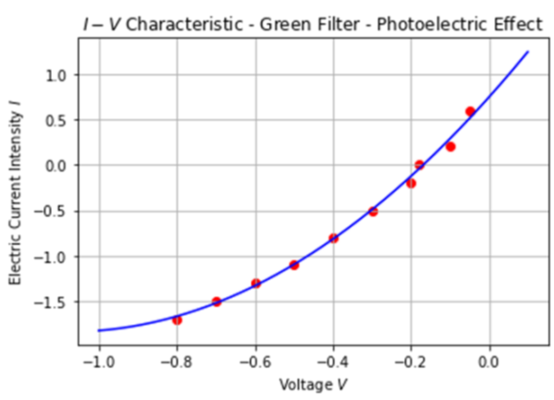

Figure 9. I - V Characteristic - Green Filter - Photoelectric Effect
Source: Own

- The Uncertainty = 2.8056056045602316
- The Correlation Coefficient = [[1. 0.98618049] [0.98618049 1.]]
- The Second Order Adjustment Coefficients are: [2.23091971 4.80054491 0.74571517]

The correlation coefficient or correlation factor is **Γ=0.98618049** then the data of voltage **V** and electric current I are highly correlated and consequently

$$2.23091971x^2 + 4.80054491x + 0.74571517 \quad (7)$$

now we compute the roots of the above

```
In [ ]: import cmath

        a=float(input("Enter the Value of (a):\n"))
        b=float(input("Enter the Value of (b):\n"))
        c=float(input("Enter the Value of (c):\n"))

        # calculate the discriminant
        d = (b**2) - (4*a*c)

        # find two solutions
        sol1 = (-b-cmath.sqrt(d))/(2*a)
        sol2 = (-b+cmath.sqrt(d))/(2*a)

        print('The solution are {0} and {1}'.format(sol1,sol2))
```

Figure 10. Code

Enter the Value of (a): 2.23091971
Enter the Value of (b): 4.80054491
Enter the Value of (c): 0.74571517
The solutions are (-1.9832827014603644+0j) and (-0.16854055263603726+0j)

The root located in the interval of the filter data whose frequency is **ν=5.50×10^14Hz** is the braked voltage **V_b** associated with this frequency, then

$$\nu=5.50\times10^{14}\text{Hz}$$

and

$$V_b=0.16854055263603726\text{V}$$

```
In [ ]: import numpy as np
        import matplotlib.pyplot as plt

        x=[-0.1,-0.2,-0.3,-0.4,-0.5,-0.6,-0.7,-0.75,-0.8,-0.9]
        y=[3.1,2.5,1.8,1.4,0.8,0.4,0.2,0.0,-0.1,-0.2]

        plt.scatter(x,y,color="red")
        plt.title("$I - V$ Characteristic - Blue Filter - Photoelectric Effect")
        plt.xlabel("Voltage $V$")
        plt.ylabel("Electric Current Intensity $I$")

        linear_model=np.polyfit(x,y,2)
        linear_model_fn=np.poly1d(linear_model)
        x_s=np.arange(-1,0.1,0.001)
        plt.plot(x_s,linear_model_fn(x_s),color="blue")
        plt.grid()
        plt.show()
        uncertainty=np.var(linear_model)
        print("- The Uncertainty =",uncertainty)
        correlation=np.corrcoef(x,y)
        print("- The Correlation Coefficient =", correlation)
        print("- The Second Order Adjustment Coefficients are:")
        print(linear_model)
```

Figure 11. Code

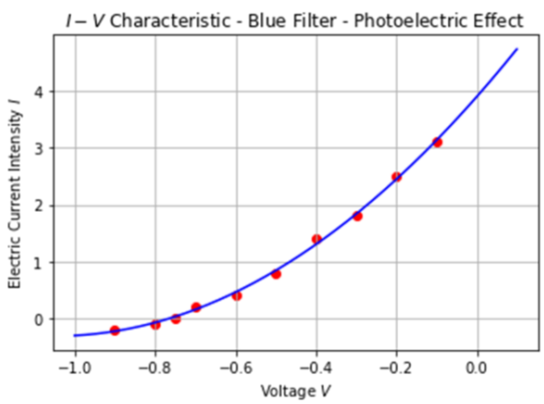

Figure 12. I - V Characteristic - Blue Filter - Photoelectric Effect
Source: Own

- The Uncertainty = 3.8766170196699092
- The Correlation Coefficient = [[1. 0.98012779] [0.98012779 1.]]
- The Second Order Adjustment Coefficients are: [3.83495596 8.04662031 3.90579694]

The correlation coefficient or correlation factor is

Γ=0.98012779

then the data of voltage V and electric current I are highly correlated and consequently

$$3.83495596x^2 + 8.04662031x + 3.90579694 \quad (8)$$

now we compute the roots of the above equation

```
In [ ]: import cmath

        a=float(input("Enter the Value of (a):\n"))
        b=float(input("Enter the Value of (b):\n"))
        c=float(input("Enter the Value of (c):\n"))

        # calculate the discriminant
        d = (b**2) - (4*a*c)

        # find two solutions
        sol1 = (-b-cmath.sqrt(d))/(2*a)
        sol2 = (-b+cmath.sqrt(d))/(2*a)

        print('The solution are {0} and {1}'.format(sol1,sol2))
```

Figure 13. Code

Enter the Value of (a): 3.83495596
Enter the Value of (b): 8.04662031
Enter the Value of (c): 3.90579694
The solutions are (-1.3357682379668165+0j) and (-0.7624619357116316+0j)

The root located in the interval of the filter data whose frequency is ν=6.88×1014Hz is the braked voltage Vb associated with this frequency, then

$$\nu=6.88\times10^{14}\text{Hz}$$

and

$$V_b=0.7624619357116316\text{V}$$

The instrument box to carry out the photoelectric effect experiment, only contained three filters, so we have a minimum of data necessary to make the graphic of braking voltage V_b as a function of frequency ν to verify A. Einstein's explanation according to the following expression

$$V_0 = \frac{h}{e}\upsilon + \frac{\phi}{e} \quad (3)$$

Let us remember that h is Planck's constant, e is the charge of the electron and ϕ is the work function.

The matrix x contains the coefficients of the frequencies and the matrix y the values obtained from the braking voltage. We plot and apply a linear fit to verify Einstein's equation for the photoelectric effect.

```
In [ ]: import numpy as np
        import matplotlib.pyplot as plt

        x=[5.19,5.5,6.88]
        y=[0.14322822663849524,0.16854055263603726,0.7624619357116316]

        plt.scatter(x,y,color="red")
        plt.title("Photoelectric Effect")
        plt.xlabel("Electromagnetic Radiation Frequency $f$ Hz")
        plt.ylabel("Braking Voltage $V$")

        linear_model=np.polyfit(x,y,1)
        linear_model_fn=np.poly1d(linear_model)
        x_s=np.arange(0,9)
        plt.plot(x_s,linear_model_fn(x_s),color="blue")
        plt.grid()
        plt.show()
        uncertainty=np.var(linear_model)
        print("- The Uncertainty =",uncertainty)
        correlation=np.corrcoef(x,y)
        print("- The Correlation Coefficient =", correlation)
        print("- Linear Fit")
        print("- Slope and cutoff")
        print(linear_model)
```

Figure 14. Code

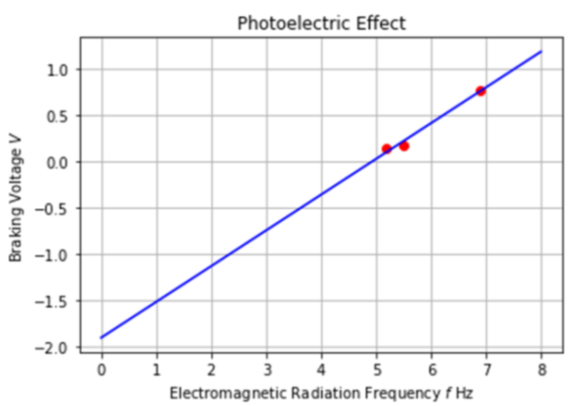

Figure 15. Relationship between stopping potential and incident frequency radiation
Fuente: Own.

- The Uncertainty = 1.308313113485414
- The Correlation Coefficient = [[1. 0.99062702] [0.99062702 1.]]
- Linear Fit
- Slope and cutoff [0.3858591 -1.90177122]

Now we do control calculations to ensure that the results are in a range of high acceptance. **Γ=0.99062702**, implies that the braked voltage and frequency data are highly correlated. Then the most probable slope that results from the linear fit is

$$Slope = \frac{h}{e} = 0.3858591 \frac{Js}{C} \quad (9)$$

Then

```
In [ ]: import scipy.constants as sc
        h=0.3858591*sc.e/(10**(14))
        print(h)
```

Figure 16. Code

6.182144340362694e-34

Planck's constant from observations of the photoelectric effect is

$$h = 6.182144340362694e^{-34}\ Js$$

The cutoff point is

$$\frac{\phi}{e} = -1.90177122 \frac{J}{s} \quad (10)$$

and to calculate the work function, we multiply by the charge of the electron and by the conversion factor to obtain the result in eV

$$-1.90177122 \frac{J}{C} 1.602 \times 10^{-19} C \frac{1eV}{1.602 \times 10^{-19} J} = -1.90177122\ eV$$

(11)

then, the work function is

$$\phi =- 1.90177122\ eV$$

The student will have to complement the code and conceptually and mathematically document a deeper data analysis using error theory and statistics.

8. Conclusions.

The implementation of the educational model does allow to reduce the gap between scientific praxis and teaching activity in the classroom.

The science and teaching-learning connection is gradually increasing.

Students are dynamically induced to adopt the strategies and tactics of scientific work in the context of their training.

Students make visible the high value of history of science and programming at science, education, and work.

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References.

Ajzenber. F. (1967). *Melissinos, AC-Experiments in Modern Physics*. 1st Edition, Academic Press.

Ayars, E. (2013). *Computational Physics with Python*. California State University. https://www.academia.edu/download/45517350/comp-phys-python.pdf

Baume, L. (2021). *Breve introducción a Google Colab.* http://fcaglp.unlp.edu.ar/~gbaume/grupo/Publicaciones/Apuntes/GoogleColab.pdf

De Aquino, F. (2014). *A New Approach on the Photoelectric Effect*. https://hal.archives-ouvertes.fr/hal-01092490/

Deaza, P. (2015) *Python Science*, UD Editorial, Compilación, paginas 79-85, Universidad Distrital Francisco José De Caldas. Primer Simposio Internacional de Formación de Profesores Universitarios.

Deaza, P. (2021) *Mediando Procesos Enseñanza Aprendizaje con Google Colaboratory*. Memorias, Universidad Distrital, Planestic VIRTUAL-UD.

Einstein, A. (1905). *On a heuristic point of view concerning the production and transformation of light*. Annalen der Physik, 1-18.

Eisberg, R. M., & Resnick, R. (1978). *Física cuántica*. Limusa.

Eisenstaedt, J. (2015). *Antes de Einstein: relatividad, luz y gravitación*. Fondo de Cultura Económica.

Gallardo, S. (2010, 8 marzo). *Historia de la luz: El primitivo deslumbramiento* (Capital Intelectual- Estación Ciencia) (Spanish Edition) (1.a ed.). CAPITAL INTELECTUAL.

Galili, I. (2008). *History of Physics as a tool for teaching*. Connecting Research in Physics Education with Teacher Education, International Commission on Physics Education, available in: http://web.phys.ksu.edu/icpe/Publications/teach2/index.html.

García Castañeda, M., & Ewert De-Geus, J. (2003). *Introducción a la física moderna* (No. 539 G164i Ej. 1). Universidad Nacional De Colombia.

Garver, W. P. (2006). *The photoelectric effect using LEDs as light sources*. The physics teacher, 44(5), 272-275.

Granés S., J. G. (1988). *Newton y el empirismo: una exploración de las relaciones entre sus concepciones del conocimiento del mundo natural*. Universidad Nacional de Colombia.

Güémez, J., & Fiolhais, M. (2018). *Relativistic description of the photoelectric effect*. American Journal of Physics, 86(11), 825-830. https://doi.org/10.1119/1.5052359

Hertz, H. (1887). *Ueber einen Einfluss des ultravioletten Lichtes auf die electrische* Entladung. Annalen der Physik, 267(8), 983-1000.

Liu, L. (2007) *Determination of Planck's Constant Using the Photoelectric Effect*. http://web.mit.edu/lululiu/Public/pixx/not-pixx/photoelectric.pdf

Llandres, M. Y., Béjar, C. C., & Illera, M. B. (1996). *La luz a través de la historia (I). De los griegos a Newton. La luz a través de la historia (II). el siglo de las ondas. La luz a través de la historia (III). La dualidad onda corpúsculo*. https://www.youtube.com/watch?v=rgh6azo9KeI.

Millikan, R. A. (1916). *A direct photoelectric determination of Planck's" h". Physical* Review, 7(3), 355.

Niaz, M., Klassen, S., McMillan, B., & Metz, D. (2010). *Reconstruction of the history of the photoelectric effect and its implications for general physics textbooks*. Science Education, 94(5), 903-931.

Portis, A. M. (1974). *Laboratorio del curso de física*. Berkeley. Reverte.

Rodríguez-Meza, M. A., & Cervantes-Cota, Jorge L. (2006). *El efecto fotoeléctrico*. CIENCIA ergo-sum, Revista Científica Multidisciplinaria de Prospectiva, 13(3),303-311. [fecha de Consulta 5 de octubre de 2022]. ISSN: 1405-0269.

Rossum, G. V. (2009). *El tutorial de Python*. Recuperado de: http://docs.python.org.ar/tutorial/pdfs/TutorialPython2.pdf .

Sanz, O. M. D. L. F. (2019). *Google Colab: Python y Machine Learning en la nube*. Adictos al trabajo, 4.

Trabulse, E. (2013). *La ciencia en el siglo XIX*. Fondo de Cultura Económica.