Education in Physics Revista Mexicana de Física E **22** 020209 1–6 JULY–DECEMBER 2025

A simple proposal to measure the Planck's constant h with a ESP32 development board

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Received 20 August 2024; accepted 9 October 2024

Planck's constant h plays a fundamental role in the quantum theory. The numerical value of this universal constant can be experimentally obtained in a wide variety of physical phenomena. Determining the numerical value of h using LEDs and identifying the threshold voltage in which these devices emit light has become a favorite example of obtaining a rather precise value of h with a simple and cheap experimental setup. In this article, we propose a laboratory exercise with a fully automatized data acquisition framework based on a development ESP32 board. We used four LEDs of different colors, which were separately characterized by their wavelength. Each LED was fed, and the light intensity was measured. The threshold voltage was determined for each of the colors we considered, and then h was determined within a fairly good deviation from the world average value. Moreover, using this world average value of h we determined the deviation of the wavelength of an ultraviolet LED from the manufacturer's quoted value with remarkably good agreement.

Keywords: Planck's Constant; LED; photoelectric effect; ESP 32.

DOI: https://doi.org/10.31349/RevMexFis.22.020209

1. Introduction

The observations made in the experiment of the blackbody have been one of the most critical scientific milestones in the history of physics, representing a paradigm shift between classical (Newtonian) physics and the then-emerging quantum physics. At the dawn of the 20th century, classical physics could not explain why the predicted spectrum of black-body radiation, governed by the Rayleigh-Jeans law, diverged towards infinity as wavelengths decreased-a problem termed the ultraviolet catastrophe [1]. In 1900, Planck [2] introduced a revolutionary hypothesis that energy was quantized, being emitted in discrete packets or quanta. This led to the formulation of $E = h\nu$, where ν is the frequency of radiation, and h is a new fundamental constant, later named the Planck constant. Planck's law for black-body radiation reconciled theory with experimental data by predicting that emitted radiation decreases at higher frequencies, thus solving the ultraviolet catastrophe.

On the other hand, in his groundbreaking article on the photoelectric effect [3], Einstein extended Planck's quantum hypothesis to light itself, positing that it could be thought of as consisting of discrete packets of energy, which he called "quanta" or photons. Building on Planck's idea that energy exchange could only occur in fixed amounts, Einstein proposed that each photon carried exactly one quantum of energy. This explanation provided the key to understanding observed phenomena in the photoelectric effect, such as the immediate ejection of electrons from metal surfaces when exposed to light, which was inconsistent with classical wave theories of light.

Several pivotal experiments have played crucial roles in the quest to measure the Planck constant with high precision. X-ray crystallography and electron diffraction have also been instrumental in analyzing patterns formed by X-rays and electrons diffracted through crystals to obtain data sensitive to the Planck constant. The Josephson Effect and the Quantum Hall Effect, relying on quantum phenomena in superconducting junctions and two-dimensional electron gases, respectively, offer extremely precise measurements due to their fundamental quantum mechanical bases. The Watt Balance (now known as the Kibble Balance), which compares mechanical power to electrical power, was pivotal in the redefinition of the kilogram in terms of fundamental constants, including the Planck constant. Finally, atom interferometry, a more recent method, uses the interference patterns of atoms to achieve high precision in measuring the Planck constant. Each of these experiments has significantly advanced the accuracy with which this fundamental constant is known today. Nevertheless, a favorite experimental determination of the Planck constant continues to be the photoelectric effect, which relies on observing the emission of electrons from a metal surface when exposed to light of varying frequencies. By illuminating the metal with light and varying its frequency, the minimum light frequency (threshold frequency) that causes electrons to be ejected can be identified. According to the theory proposed by Einstein, the energy of these ejected electrons is directly proportional to the frequency of the incident light and is given by $E = h\nu$, where E is the energy of the photon, h is the Planck constant, and ν is the frequency. In practical terms, the kinetic energy of the ejected electrons is measured as a function of the frequency of the incident light. From these measurements, the stopping voltage–

the voltage needed to prevent the electrons from reaching the detector–can be precisely determined. By plotting the stopping voltage against the light frequency, the slope of the resulting line, when multiplied by the elementary charge, gives the value of the Planck constant $h = 6.62607015 \times 10^{-34}$ Js.

In this article, we use a LED (Light Emitting Diode) in a similar fashion as the original proposal of P. J. O'Connor and L. R. O'Connor in 1974 [4] that has been adapted and modified by many others [5-8]. A LED is a semiconductor device that converts electrical energy directly into light energy via electroluminescence. At the heart of a LED there is a chip made from a material doped with impurities to create a p-n junction, which consists of a p-type semiconductor closely bonded to an n-type semiconductor. When a voltage is applied across the LED, electrons from the n-type material are pushed across the p-n junction into the p-type material, recombining with holes. This recombination releases energy in the form of photons, whose specific color ranges from infrared to ultraviolet, depending upon the energy gap of the semiconductor material used in the LED, which dictates the energy, and hence the wavelength, of the photons released during this recombination process. The novelty of our proposal is the use of the ESP32 development board, which helps to simplify the experiment with an automatic data acquisition system to reduce human errors, while also facilitating the repeatability of the experiment. For the purpose of presenting our proposal, in the following sections, we introduce our methodology and the experimental setup in detail, along with the obtained results. Conclusions and general discussion are presented in Sec. 3.

2. Methodology

Our experimental setup is based on the straightforward series circuit depicted in Fig. 1. In this circuit, a variable voltage source, adjustable within a range of approximately 0 to 3.0V, powers a LED with a pre-characterized color (wavelength). Following the LED, a 1 kΩ resistor is included, serving as a current-limiting component.

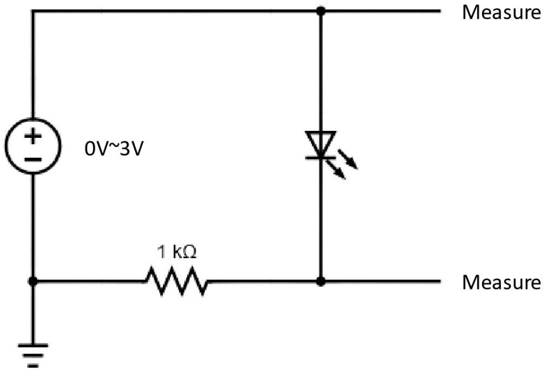

FIGURE 1. Simple series circuit in which a variable voltage source $(0 - 3.0$ V) powers an LED of known color (wavelength) in series with a 1 kΩ resistor.

The analysis of the circuit follows directly from Kirchhoff's circuit law of voltage, from which

$$V_l = V_{\text{in}} - V_r, \tag{1}$$

where V_l is the voltage that can be measured in the LED. It is calculated as the difference between the source voltage, labeled V_{in}, and the voltage across the resistor, labeled V_r. The latter can be determined using Ohm's law,

$$V_r = IR, \tag{2}$$

where I represents the current passing through the circuit and R represents the value of the resistor. In terms of this current, we determine the value of the voltage at which light starts being emitted from the LED; such a voltage is thus dubbed the threshold voltage V_{th}.

Additionally, it is well-established that the energy gap of the semiconductor in an LED corresponds to the threshold voltage of the LED and the energy of the light it emits, namely,

$$E_{\text{gap}} = E_{\text{light}} = eV_{\text{th}}. \tag{3}$$

Thus, exploiting these relations, we can calculate the value of Planck's constant as

$$h = \frac{E}{\nu} = \frac{\lambda e V_{\text{th}}}{c}. \tag{4}$$

This is the primary relation between the value of h and the variables of our experimental setup, which carries uncertainties that we should consider.

For the actual derivation of Planck's constant from our experiment, we first characterize the LEDs with an ocean optics spectrometer, USB4000. The light intensity as a function of the wavelength for LEDs of different colors is shown in Fig. 2.

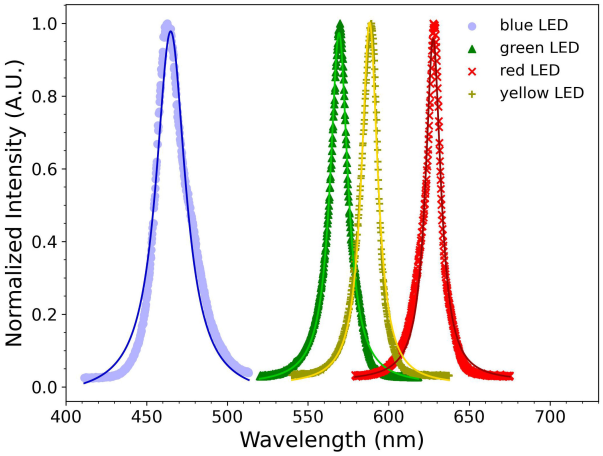

FIGURE 2. Normalized light intensity as a function of the wavelength for different LEDs with their respective fit (5). The center of the peak corresponds to the wavelength associated with each color, and the width can be interpreted as an uncertainty of measurement of λ.

TABLE I. Peak wavelength of LEDs of different colors obtained by fitting Eq. (5).

LED color	Wavelength (nm)
Red	628 ± 6
Yellow	588 ± 6
Green	569 ± 7
Blue	465 ± 11

To identify the peak wavelength and the width of the LED light intensity, the data was fitted with a Lorentzian function of the form

$$T(\lambda) = T_0 + \frac{2A}{\pi}\frac{w}{4(\lambda-\lambda_c)^2+w^2}, \tag{5}$$

where T_0, λ_c, w, and A are the offset (in our case $T_0 = 0$), the center of the peak, the full width at half maximum, and the area below the curve, respectively. The values for these parameters vary for every color (the blue LED deviates the most from this fit as expected, whereas the green LED follows the most to the fit). The width of each curve serves as a natural uncertainty in the wavelength associated with each color. Table I shows the LED peak wavelength values with their uncertainties ($w/2$) obtained from the fit function.

The rest of the experiment is conducted entirely using the ESP32 development board as depicted in the simplified diagram in Fig. 3. Using the 8 bits DAC (Digital to Analog Converter) pin, it is possible to inject voltage from 0 to 3 V, and with the 12 bits ADC (Analog to Digital Converter) pins, the voltage injected by the DAC is read and the drop voltage in the resistance can be measured (see Fig. 1).

For a correct data acquisition, it is important to be aware of the ESP32 development board behavior in every phase of the experiment. Thus, a DAC and an ADC calibration need to be carried out. The experiment to probe the DAC response output consisted of reading the output voltages using a digital multimeter to scan the DAC output from 0 to 255 bits. These results are shown in Fig. 4, where it is observed that the DAC response is linear to the eye; however, the line does not cross the origin.

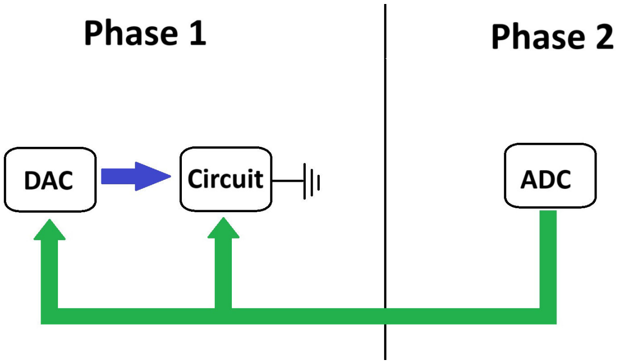

FIGURE 3. Conceptual diagram of the experimental setup.

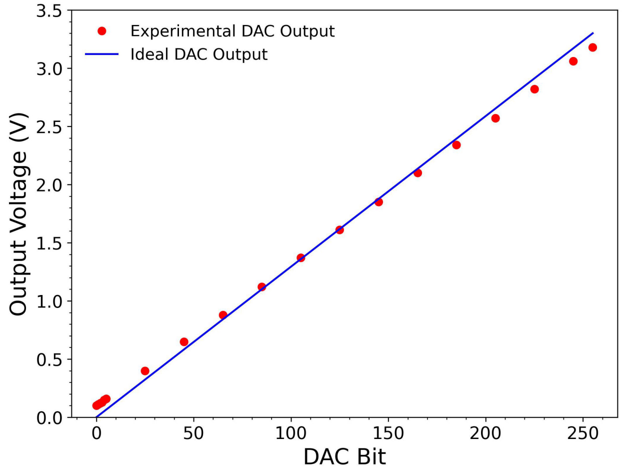

FIGURE 4. DAC output voltage behavior.

In order to determine the LED threshold voltage, we employ the ADC of the ESP32 board. However, the ADC does not exhibit linear behavior across its entire voltage range as mentioned by the manufacturer [9]. Consequently, understanding the ADC actual response characteristics is crucial to carry out a good experiment, necessitating a calibration procedure.

The calibration procedure under discussion involves injecting a known voltage into the ADC pin of the ESP32 board and recording the resulting digital output. By collecting this data, we can fit the curve to an appropriate function that accurately describes the behavior of this converter. This calibration allows for more precise voltage measurements, ensuring the accuracy of our threshold voltage determination for the LEDs. The DAC previously calibrated was used to inject the voltage to an ADC pin to determine its response. Figure 5 shows the ADC behavior. We can observe a linear behavior for values below 1500 mV, and this linearity is lost gradually as the in input voltage increases up to 3000 mV. Thus, it is

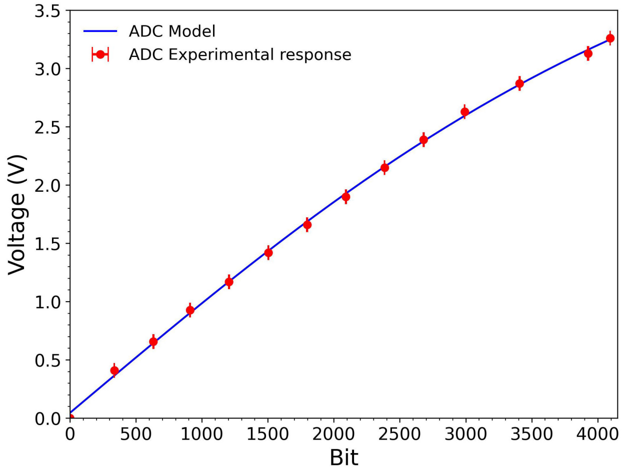

FIGURE 5. ESP 32 response of Analog to Digital Converter (ADC). Non-linear behavior is evident throughout the entire voltage range, a particular deviation can be seen once the voltage value of 3 volts is reached.

TABLE II. Parameters A_i of the fit given by Eq. (6).

Parameters	**Fit Values**
A_1	-4.68×10^3
A_2	4.77×10^3
A_3	2.48×10^3
A_4	6.78×10^{-13}

not appropriate to use the classical relation $V = V_{\text{in}}\text{bits}/4095$ in the entire voltage range. Using this proportionality law to approximate the voltage results in inaccurate values for Planck's constant, h [9].

By understanding and accounting for the non-linear behavior of the ADC, we can ensure that our measurements are reliable and that our determination of Planck's constant is as accurate as possible. This process highlights the importance of calibration in experimental physics, particularly when using digital measurement tools.

For instance, a function that fits the ADC voltage behavior (blue solid curve in Fig. 5) is given by

$$V(x) = A_1 - \frac{A_1 - A_2}{1 + \exp(\frac{-(x-A_3)}{A_4})}, \tag{6}$$

where the parameters A_i, $i = 1, \ldots, 4$ are tabulated in Table II and for convenience, this function returns millivolts values. With the methodology described above, we tackle the experimental challenge as we next explain.

2.1. Experimental setup

Equipped with the function that accurately describes the ADC voltage behavior, we proceed to implement the experimental setup as illustrated in Fig. 6.

In this experimental setup, we supply the circuit with an increasing voltage provided by the ESP32 native DAC, allowing for a voltage variation between 0 V and 3.0 V in 8-bit steps (0 to 255). Concurrently, we measure the voltage using the ESP32 native ADC, which offers a 12-bit resolution (0 to 4095). After obtaining the ADC value, we determine the corresponding current using Eq. (2). The results of this experiment are presented in Fig. 7.

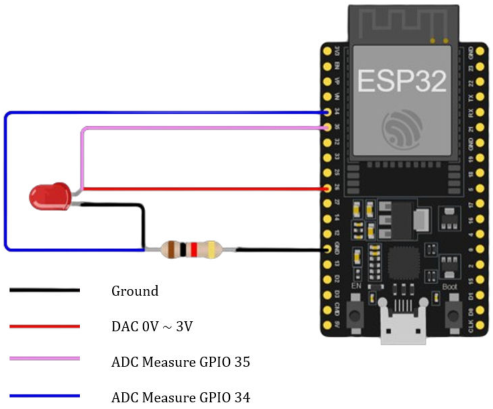

FIGURE 6. Experimental setup. The LED and resistor are connected to the ESP32 board as explained in the text.

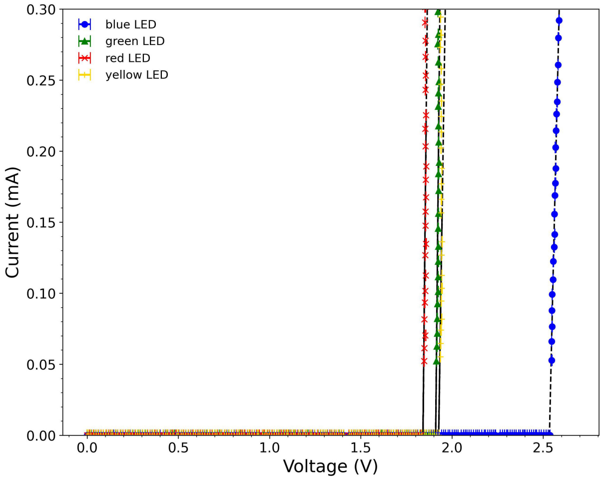

FIGURE 7. Current response of each LED as a function of the voltage. The threshold voltage V_{th} is easily identified for each color.

The threshold voltage was identified with a linear extrapolation to the horizontal axis. It should be noticed that the linear approximation is not far from the theoretical value of the current passing through the LED

$$I_D = I_s \left[\exp\left(\frac{V_D}{nV_T}\right) - 1 \right], \tag{7}$$

which is known as the Shockley equation [10]. It describes the current passing through a diode in a function of the voltage injected into the diode (V_D), the thermal voltage ($V_T = k_B T_k/q$, where k_B is Boltzmann's constant, T_K is the absolute temperature in kelvins and q is the magnitude of electronic charge), the reverse saturation current (I_s), and the ideality factor (n). These last two quantities have a dependency on a wide variety of factors specific to each diode. A simulation of the current given by the Shockley equation, with the values $n = 1$ and $V_T = 0.0026$ V (associated with a $T_k \sim 300$K), is depicted in Fig. 8, Table III shows the respective values of I_s for every simulation.

To ensure accurate measurements, the DAC smoothly increases the voltage and the ADC captures the resulting voltage values at each step. By plotting these values, we can analyze the behavior of the circuit. This process allows us to accurately characterize the LED response and validate our

TABLE III. Simulation constants for Shockley model.

Color	I_S, A
Red	1.5×10^{-32}
Yellow	5×10^{-34}
Green	6×10^{-34}
Blue	2×10^{-44}

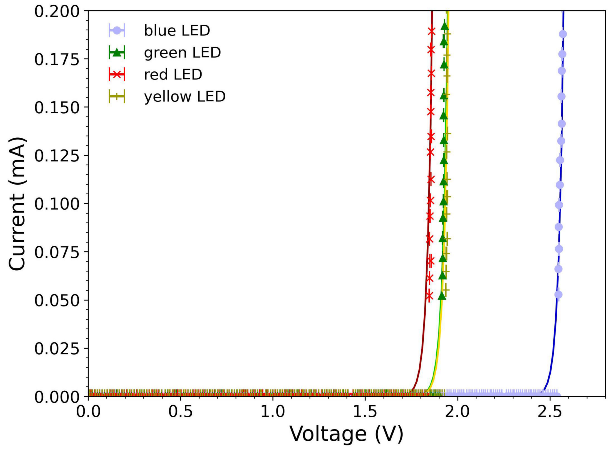

FIGURE 8. Shockley model of the current passing through a diode.

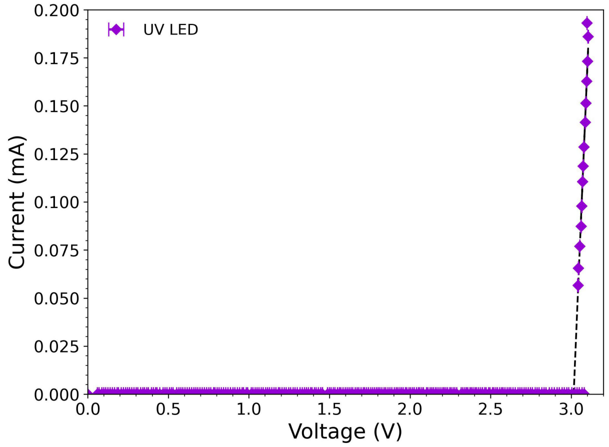

FIGURE 9. Current response of Ultra-Violet LED as a function of the voltage. The threshold voltage $V_{\rm tr}$ is easily identified.

TABLE IV. Experimental Measurements of Planck's constant.

Color	Threshold Voltaje, V	Experimental h $\times 10^{-34}$, J s	Deviation δh, %
Red	1.856 ± 0.002	6.23 ± 0.06	-6
Yellow	1.940 ± 0.001	6.10 ± 0.67	-8
Green	1.924 ± 0.002	5.85 ± 0.07	-12
Blue	2.534 ± 0.001	6.30 ± 0.15	-5

method for determining Planck's constant. The detailed results and analysis are illustrated in Fig. 7, showcasing the effectiveness and accuracy of our experimental approach.

The values of $V_{\rm th}$ for every color are used in Eq. (4). The values of the Planck's constant hence derived are tabulated in Table IV, where the deviation from h, δh, is given by

$$\delta h = \frac{(h_{\rm exp} - h_{\rm th}) * 100}{h_{\rm th}}, \tag{8}$$

where $h_{\rm exp}$ is the experimentally measured value and $h_{\rm th}$ the theoretical value.

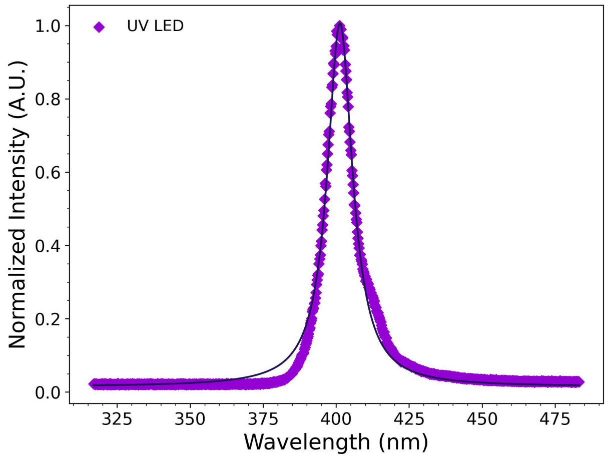

FIGURE 10. Normalized LED intensity as a function of the wavelength with its respective fit, Eq. (5). The center of the peak is close to the wavelength value given by the manufacturer [11] and the width can be interpreted as an uncertainty of measurement of λ.

TABLE V. Experimental measurement of UV wavelength.

Color	Threshold Voltaje (V)	Experimental value of λ (nm)	Deviation $\delta\lambda$, %
UV	3.021 ± 0.002	410 ± 1	2

In an alternative experiment using the same setup, we adopt the value of $h = 6.62607015 \times 10^{-34}$ Js as reported in the literature and make use of the expression (4) to determine the wavelength of a UV LED. The current response and its corresponding Lorentzian fit for this UV LED are presented in Fig. 9.

Once we have identified $V_{\rm th}$, using Eq. (4) we determine the value of λ as shown in Fig. 10. A comparison with the actual characterization of the UV-LED and the corresponding Lorentzian fit with Eq. (5).

The findings of this experiment are shown in Table V. We notice that the deviation in this case has a better value as compared to LEDs emitting in the visible light spectrum.

3. Conclusions

In this study, we have developed a method to determine Planck's constant using commercially available LEDs in blue, red, green, and yellow colors. The value we obtained for Planck's constant is $h = (6.7272 \pm 0.4) \times 10^{-34}$ Js, with an average percent deviation of approximately 1.53%. The experimental setup we propose can be effectively utilized in introductory high school or university physics courses that cover quantum physics concepts. It is essential for the instructor to have a solid understanding of electronics, particularly in working with development boards such as the ESP32, which includes both ADC and DAC functionalities.

Our procedure involves measuring the voltage and current characteristics of LEDs of different colors to derive the energy of the emitted photons. By analyzing the threshold voltage at which each LED begins to emit light, we can calculate the energy of the photons using the relation $E = h\nu$.

The experimental apparatus includes a power supply, a multimeter, and an ESP32 development board for precise voltage and current measurements. The ESP32 ADC and DAC capabilities allow for accurate data acquisition and processing, facilitating the determination of the LED threshold voltage. By repeating the measurements for LEDs of different colors, we can calculate an average value for Planck's constant and estimate the experimental deviation for the world average value. The inverse problem, assuming the value of h as reported in literature and determining the wavelength of the emitted light also leads to accurate results for UV-LEDs.

This hands-on approach not only reinforces theoretical knowledge of quantum mechanics but also provides practical experience with electronic components and measurement techniques. It bridges the gap between abstract concepts and real-world applications, making it an excellent educational tool for engaging students in the study of quantum physics.

Acknowledgments

PM and AR acknowledge support from Consejo de la Investigación Científica (UMSNH, México) under projects 44356 and 18371, respectively.

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1. L. de la Peña, Introduccion a la Mecánica Cuántica, Ediciones Científicas Universitarias Series (Fondo de Cultura Económica, 1996).
2. M. Plank, Zur theorie des gesetzes der energieverteilung im normalspektrum. *Verhandlungen der Deutschen Physikalischen Gesellschaft* **14** (1900) 237.
3. The Nobel Prize in Physics 1921 - nobelprize.org, `https://www.nobelprize.org/prizes/physics/1921/summary`
4. P. J. O'Connor and L. R. O'Connor, NOTES: Measuring Planck's Constant Using a Light Emitting Diode, *Phys. Teach.* **12** (1974) 423, `https://doi.org/10.1119/1.2350479`.
5. D. Zollman and I. Bearden, Determining Planck's constant with LEDs-what could possibly go wrong?, *Phys. Educ*. **55** (2020) 015011, `https://dx.doi.org/10.1088/1361-6552/ab525d`.
6. F. R. Pérez *et al*., Estimating the Planck's Constant, an undergraduate experiment with STEM approach, *Opt. Pura Apl.* **55** (2022) 1, `https://dx.doi.org/10.7149/OPA.55.1.51095`.
7. H. Venkatreddy *et al.*, Five decades of determining Planck's constant using light emitting diodes in Undergraduate Laboratories - A Review, *Mapana J. Sci.* **21** (2022) 75, `https://doi.org/10.12723/mjs.61.6`
8. C. Calvo-Mola *et al*., Determination of the Planck constant through the use of leds, *Rev. Cubana Fis.* **36** (2019) 125.
9. Analog to Digital Converter (ADC) - ESP32 - &x2014; ESP-IDF Programming Guide release-v4.4 documentation - docs.espressif.com, `https://docs.espressif.com/projects/esp-idf/en/release-v4.4/esp32/api-reference/peripherals/adc.html`
10. R. L. Boylestad and L. Nashelsky, Electronic devices and circuit theory, 11th ed. (Pearson, Upper Saddle River, NJ, 2012).
11. LED UV (ultravioleta) de 5mm - steren.com.mx, `https://www.steren.com.mx/led-uv-ultravioleta-de-5mm.html`
12. Defining constants - BIPM - bipm.org, `https://www.bipm.org/en/measurement-units/si-defining-constants`