

PAPER

Cronpes: time measurement device suitable for teaching experimental physics in Brazil


To cite this article: M A Bulla *et al* 2024 *Phys. Educ.* **59** 065002

View the [article online](#) for updates and enhancements.

You may also like

- [Building a high quality photogate](#)
L A Ladino and S H Rondón
- [Building a propeller based-microcontroller timer system](#)
L A Ladino and S H Rondón
- [Using scratch programming to control photogates in educational physics experiments](#)
L F da Silva and P S Carvalho

Cronpes: time measurement device suitable for teaching experimental physics in Brazil

M A Bulla¹, T Oliviera¹, M K K D Franco^{2,*} 
and F Yokaichiya¹

¹ Departamento de Física—UFPR, Universidade Federal do Paraná, Curitiba, PR, Brazil

² Instituto de Pesquisas Energéticas e Nucleares—IPEN, São Paulo, SP, Brazil

E-mail: margareth_franco@yahoo.com.br



Abstract

Several public schools and also universities in Brazil have few or none financial resources to acquire certain equipment for teaching physics. Nevertheless, it is extremely important that institutions, schools and universities offer laboratory conditions for the students, mainly in engineering courses, in order to get the first contact with physics concepts in practice. For this purposes, it was proposed to develop a simple construction, low-cost and easy maintenance photogate (Cronpes) device, so that teachers, technicians and even students from the basic and high education network can build them for their schools, institutions and universities, thus improving the quality of teaching physics. This study aims to implement a photogate Esp32 microcontroller based programmed in MicroPython with good resolution, accuracy and user friendly in order to apply in experiments like simple pendulum, spring oscillations and conservation of mechanical energy. The main focus of this research was to demonstrate, through the development of Cronpes, that we can create solutions for educational laboratories, in a viable, creative and inexpensive way.

Keywords: low cost, photogate, Esp32 microcontroller, experimental physics teaching

* Author to whom any correspondence should be addressed.

1. Introduction

In Brazil, the Brazilian National Common Curricular Base [1] for High School, for the teaching of Physics must go beyond traditional theoretical teaching, promoting more playful and less abstract teaching. The alliance of theoretical knowledge in the classroom with experimental practice in the laboratory within Brazilian universities is fundamental to achieve more complete learning for the training of future professionals. Most of the physics experiments that involve the study of mechanics such as: Instantaneous vs average velocity, kinematics on an inclined plane, speed of a projectile, Newton's second law, the force of gravity, conservation of momentum, kinetic energy. Conservation of mechanical energy, Elastic–Kinetic Energy and pendulum motion, involve the use of detectors.

Photogates are motion detection devices most commonly applied in experiments to demonstrate mechanical movements. These devices detect the time interval of various events very accurately, are easy to use and allow students to easily concentrate on the physical phenomena being investigated. The low cost and simplicity of using photogates make them more widely used at different levels of education (elementary school to university), notwithstanding the fact that there are instruments for direct measurement of displacement, speed and acceleration. Commercial photogates can become financially unviable: (i) by involving many students in experiments in several laboratories simultaneously, or (ii) by enabling students to carry out experiments at home, by providing the device, as was the case during the COVID-19 pandemic [2, 3]. The construction of a homemade photogate proves to be an effective solution to drastically reduce costs, which will be described in this study.

This article will describe the design and manufacture of a photogate (Cronpes: time measurement, **Cronos**, photogate with **Esp32** microcontroller), as shown in figure 1(a), specifying the electronic circuit, in addition to creating the device design and printing with a 3D printer, using open-source and free software available on the internet. Unlike most devices that use Arduino, this project uses the Esp32 microcontroller and

software developed in MicroPython language to control the photogate operation. Moreover, a comparison will be made with the commercial device, using 3 classical physics experiments: (i) conservation of mechanical energy, (ii) simple pendulum, (iii) oscillatory movement of the spring. Future improvements associated with the software, cost minimization, implementation of various sensors and expansion of the range of experiments (e.g. collisions) will be discussed.

2. Materials and methods

The basis for the construction of the didactic prototype was constructed using a perfboard with dimensions: 70 mm × 90 mm area easily found on the market. In this way, projects can be carried out and replicated with precision and at low cost. Figure 1(b) shows the display board with the connections to be connected to the Esp32 board. Figure 1(c) shows the top view of the prototype with the Esp32 and the assembly of its parts.

The developed device will be reported in two parts: Hardware and Software.

2.1. Hardware

In figure 2, we present a schematic of the complete system created by KiCAD [4] in order to assist the identification of each part of the project during its description.

2.1.1. Microcontroller Esp32. The Esp32 [5] is responsible for the full instrument control. Like the Arduino [6], Esp32 is a programmable component that can connect other devices to send and receive signals. Thus, with Esp32, we might build personalized instruments like Cronpes photogate.

Basically, as shown in table 1, the Esp32 has more memory and processing clock speed than the Arduino. In addition, there is support for MicroPython [7].

The main Esp32's advantages is the use of the MicroPython language [7] support (Python is one of the most popular programming language in the world). Moreover, it is an excellent option for the beginner programmer, due to the big community [8] that can give support

Cronpes: time measurement device suitable for teaching experimental physics in Brazil

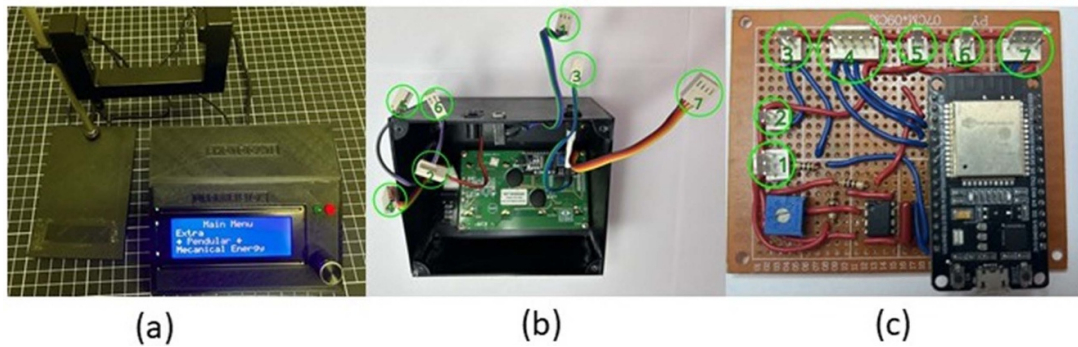


Figure 1. (a) Cronpes photogate, (b) case with 3D model and the display, (c) perboard and the controlled circuit with Esp32. Inside the photogate (Cronpes): the numbers in (b) and (c) indicate the connection between the display and the controlled circuit.

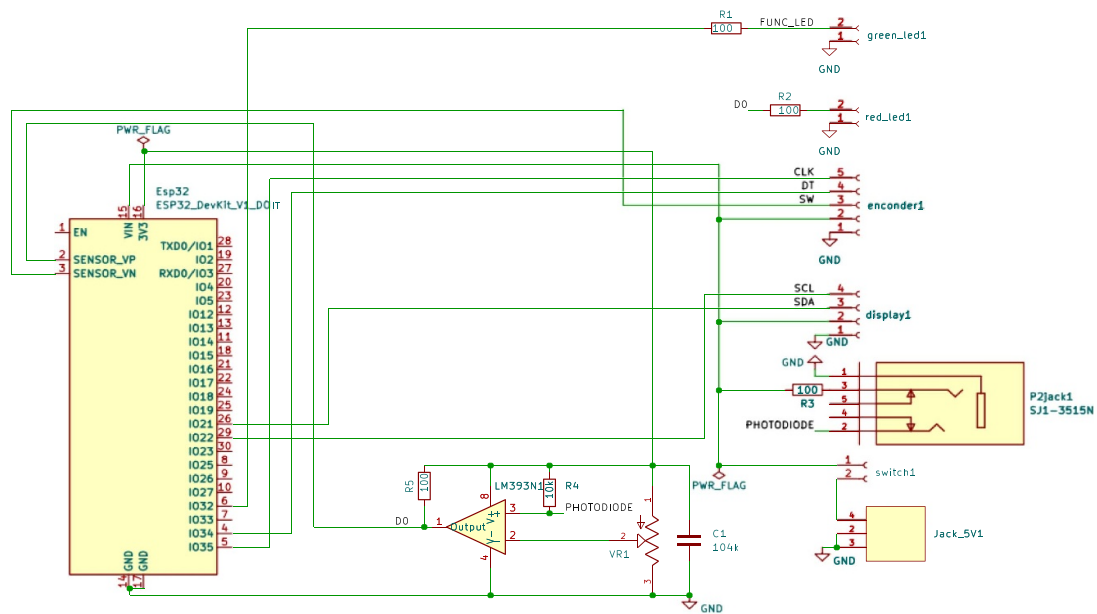


Figure 2. Cronpes photogate complete controller schematic.

Table 1. Esp32 versus Arduino.

| | Esp32 | Arduino Uno R3 |
|---------------------|---------|----------------|
| MicroPython support | Yes | No |
| Flash memory | 4 MB | 32 kB |
| SRAM | 520 kB | 2 kB |
| Clock speed | 240 MHz | 16 MHz |

with questions related to the program development. MicroPython is easier than Arduino language programming (C++), and makes it possible for more people to create homemade instru-

ment to replace expensive commercial instruments. In addition, Adafruit [9], one of the biggest enterprise that produces modules for microcontroller, develops the CircuitPython [10] that is

Table 2. List of components for the photogate (Cronpes).

| Quantity | Component |
|----------|------------------------------------|
| 1 | Esp32 Devkit V1 |
| 1 | Display LCD 2040 |
| 1 | PCF8574 module |
| 1 | Encoder KY-040 |
| 1 | LM393 |
| 1 | Green Led |
| 1 | Red Led |
| 1 | Transmitter led infrared |
| 1 | Receptor led infrared |
| 1 | Rocker switch 1 pole |
| 4 | Female and male Molex KK-254 2 Pin |
| 1 | Female and male Molex KK-254 3 Pin |
| 1 | Female and male Molex KK-254 4 Pin |
| 1 | Female and male Molex KK-254 5 Pin |
| 1 | Trimmer Resistor 10 k Ω |
| 4 | Resistors 100 Ω |
| 1 | Resistor 10 k Ω |
| 1 | Capacitor 100 nF |

based on MicroPython. So, its firmware will be more popular.

Moreover, according to table 1, we note that Esp32 [5] has more flash memory, SRAM memory and is faster than Arduino [6]. These features help to create an interface more responsive and consequently more user-friendly.

To assemble the photogate circuit as displayed in figure 1(c) we use the components showed in the table 2.

2.1.2. How the cronpes works. Simplifying our schematic circuit as presented in figure 3 (flow diagram) is a crucial step in order to understand its functionality. So, the signal from the Sensor IR (an infrared transmitter LED in front of a receptor LED that sends signal) is compared using the LM393 (a common integrated circuit with two comparators) with reference voltage that is calibrated by a trimmer. Thus, when LEDs infrared are obstructed, the LM393 turns on the Red Led and sends signals to Esp32. Moreover, to control the instrument, the user rotates and presses the Encoder, which sends this interaction to control interface.

On figure 4, we show the user's interaction with the Sensor IR and the Encoder KY-040 for navigating in the Display LCD 2004. The

Green LED ON shows that the instrument is ready to measure and blink when the measurement is complete.

2.1.3. Boards. Additionally, in this project, we create three options to build the photogate: (i) Printed circuit board (PCB) (figure 5(a)), (ii) PCB options with components, (iii) phenolite board (figure 5(d)) and (iv) perfboard (figure 5(c)). For building PCB version and phenolite board version all the files are available in the repository [11]. All the project was developed using KiCAD software [4] (free software). The DevKit's pin-out must be equal to the model displayed in the figure 6 for PCB and phenolite mounting version (figure 5).

2.2. Software

The file main.py uses the file encoder_menu.py to divide [12, 13], modify and apply to display LCD 2004, as display in the figure 7. Moreover, we wrote the file cronos.py that is an extension of encoder_menu.py, that includes each experiment. While the encoder_menu.py uses i2c_lcd.py and i2c_api.py for displaying menu into LCD 2004, the same file uses rotary.py and rotary_irq_esp.py for inputting data from the encoder KY-040. Furthermore, the file calibration.json allows to

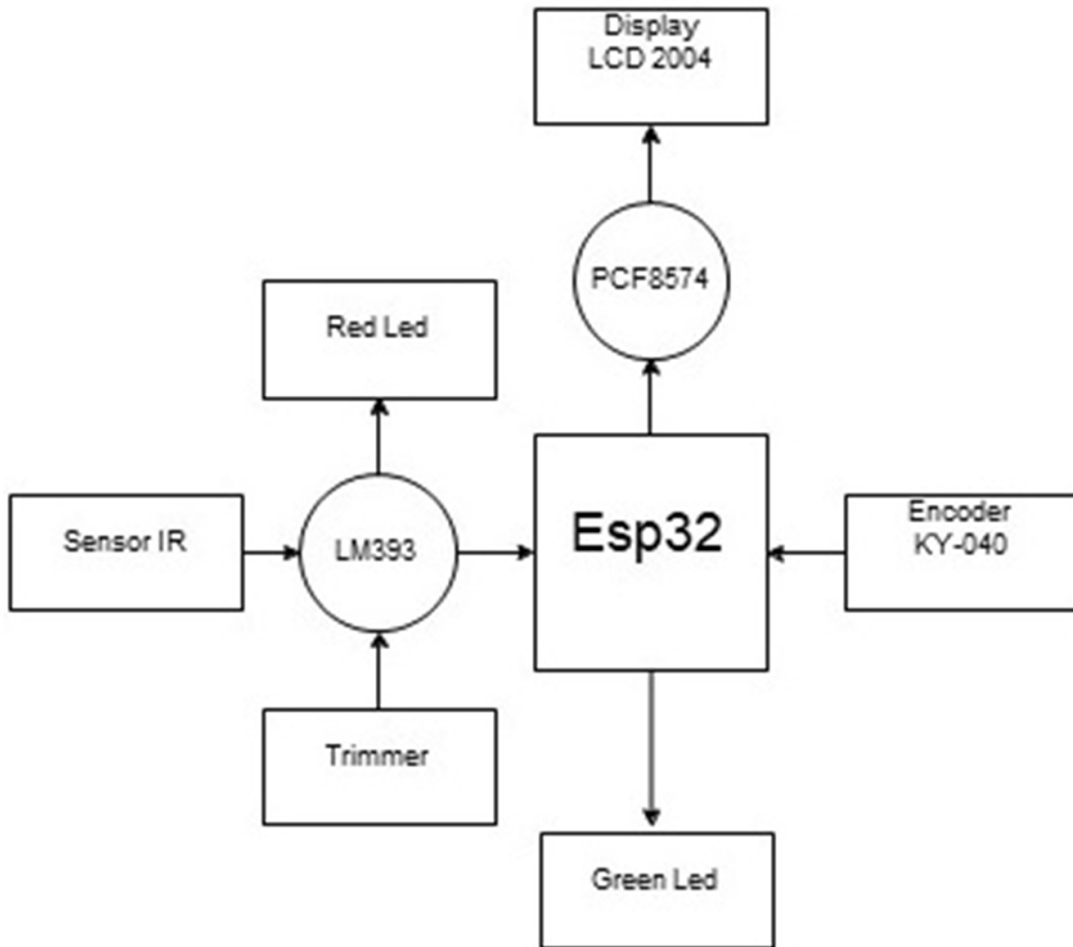


Figure 3. Flow diagram of figure 2: square is a microcontroller, circles are passive components and rectangles are components that we interact.

save calibrations. Therefore, on the file `main.py` we build the option's tree as menus and function mode as presented on figure 8.

2.2.1. User interface. Summarizing the figure 8, we have the following functions: (i) start (start reading the experiment), (ii) config (Configure properties from the selected experiment), (iii) history (show history of all readings), (iv) back (return to Root), (v) calibration (calibrate bias error), (vi) developers (show the photogate's developers) and (vii) submenus allows to organize all experiments. For more details, see our source code into repository [11].

3. Results and discussion

Time is one of the most basic variables in physics. Therefore, time measurements are essential in several experimental practices. In this study, measurements of time intervals were recorded in three experimental practices common to experimental physics teaching laboratories in the initial years of undergraduate studies, to demonstrate the feasibility of using Cronpes photogate. The practices are named: (a) pendular movement; (b) spring mass oscillator and (c) conservation of mechanical energy, as shown on figure 9.

For this, a comparative evaluation will be carried out between the Cronpes and a commercial model. The time measurements required for the

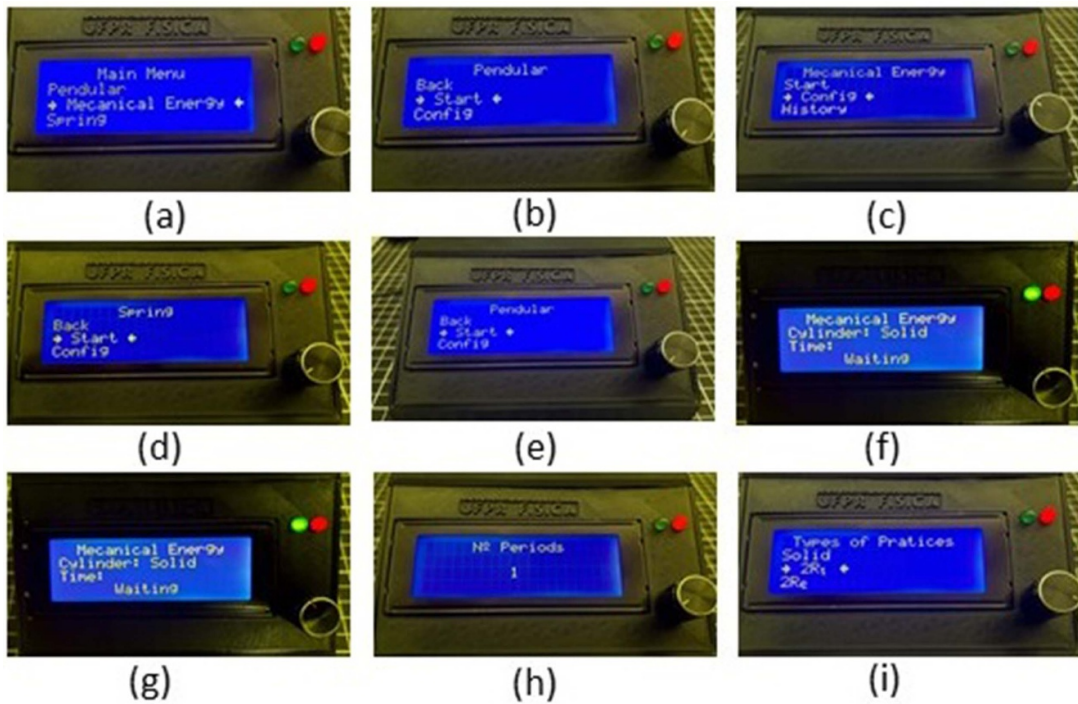


Figure 4. Photos of the display instrument, where the Green LED ON shows that the instrument is ready to measure and blink when the measurement is complete. (a) The Cronpes's main menu, (b) the Cronpes's pendulum menu. (c) The Cronpes's mechanical energy menu, (d) the Cronpes's spring menu, (e) the Cronpes starts reading pendulum, (f) the Cronpes starts reading mechanical energy, (g) the Cronpes starts reading spring, (h) the Cronpes's config pendulum and spring, (i) the Cronpes's config energy.

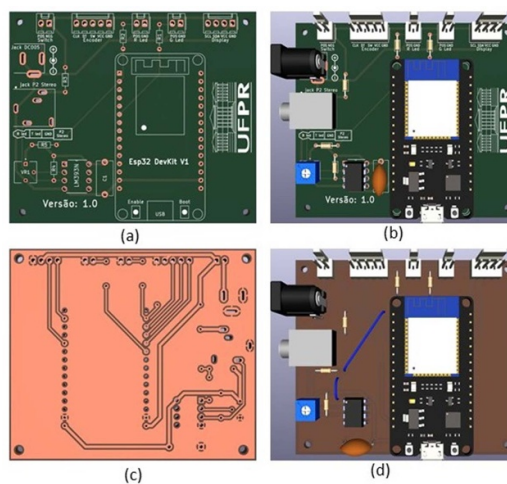


Figure 5. Alternatives to build photogate: (a) PCB option without component, (b) PCB options with components, (c) phenolite options backward, (d) phenolite options frontward.

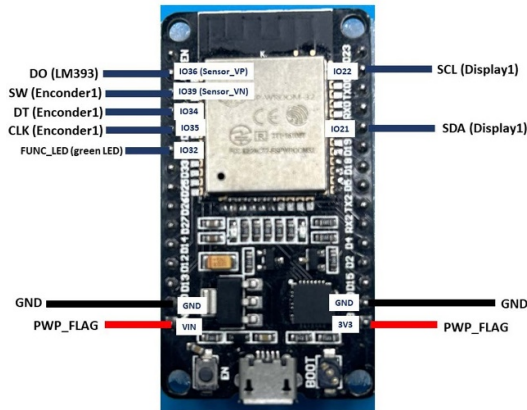


Figure 6. Esp32 DevKit V1 Pin-out used in the Cronpes circuit. The pin 29 (IO22) is connected to SCL (Serial Clock) pin in the display and the pin 26 (IO21) to the SDA (Serial Data) pin in the display.

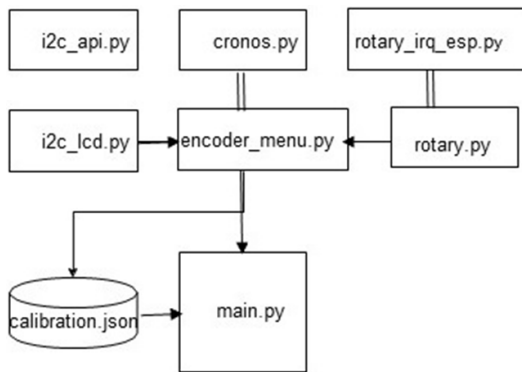


Figure 7. The flowchart shows libraries (rectangles), data to save calibration values (cylinder) and the main file that start all the processes (square). The connection with double lines means that files work together. The arrows point to the file that imports the libraries.

3 experiments were performed using both instruments under controlled conditions. The Cronpes follows the specifications provided previously, using widely available components and affordable assembly techniques, proved to be as effective as the commercial model chosen for comparison. This in turn is recognized for its good functioning and reliability in educational practices. All measurements demonstrate the quality of operation of the Cronpes and its advantages over more expensive commercial models.

3.1. Pendular movement

This experimental practice enables the mechanical analysis of harmonic movements through the apparatus shown in figure 9(a). During the oscillation of mass, forces such as gravity and the tension of the thread act. The tangential component of the resulting force acts to restore the movement to the fixed point of the pendulum, always acting in the opposite direction to the displacement of the mass [14]. For small amplitudes, the period of oscillation depends only on the length of the wire and the acceleration due to gravity.

Despite its simplicity, such an experiment proposes a rich theoretical framework within which a variety of natural phenomena can be understood. Through this experiment, it is possible to establish relationships amongst different physical quantities, such as the period, the launch angle and the thread’s length. Furthermore, students have the basic knowledge to understand how these variables are related to Simple Harmonic Motion (SHM) and can use simple measurements to assess local gravity.

For this experiment, a metallic object was attached to a thread of length $L = (60.8 \pm 0.1)$ cm attached to a base with a protractor to read the oscillation angle, as shown in figure 10. When placing the object to oscillate at amplitudes lower than 10° , the oscillation periods obtained through the photogates were on the table 3.

The specific ‘pend’ function was used in both sensors, which allows the pendulum oscillation time to be measured. The biggest difference between measurements is observed when comparing the intervals obtained when measuring 9 periods instead of 5. The inaccuracy generated by the commercial photogate, which does not record all the oscillations in sequence, added to the action of air resistance on the piece of metal tending to reduce the oscillation period. This advantaged reinforces the use of homemade photogate.

3.2. Spring mass oscillation

In this experiment, the same fundamental principles are applied. In the mass-spring pendulum, the weight is suspended by a spring, allowing up and down movements.

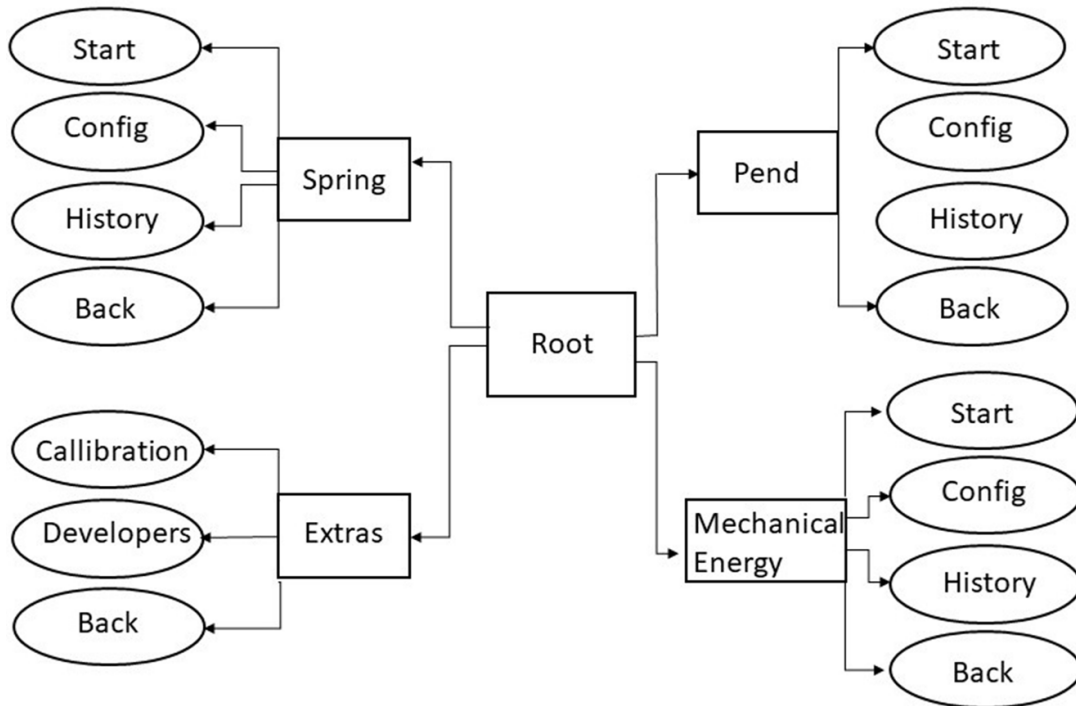


Figure 8. All the options that can access, where the main menu is square, the sub-menus are rectangles and the functions are ellipses.

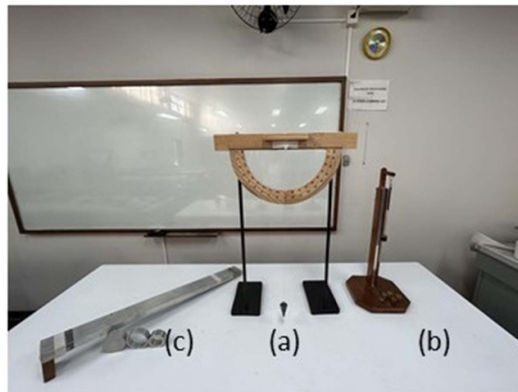


Figure 9. Equipment used for comparison between photogates. Experiments: (a) pendular movement, (b) spring mass oscillator and (c) conservation of mechanical energy.



Figure 10. Experimental apparatus used in experiment (a) pendular movement. Sensors positioned side by side recording periods oscillation. From left to right: Cronpes and commercial.

Table 3. Data obtained through the experiment (a).

| Photogates | Number of periods | Time [s] |
|------------|-------------------|----------|
| Cronpes | 5 | 7.99 |
| Commercial | 5 | 7.98 |
| Cronpes | 9 | 14.41 |
| Commercial | 9 | 14.35 |

In this scenario, kinetic energy appears in the system in its equilibrium position, transforming into gravitational potential energy as the spring stretches or compresses [15]. This experiment also represents an SHM investigation, incorporating the action of elastic force. The oscillations are initially described in just one coordinate, to simplify the system. For small displacements, the oscillation frequency depends exclusively on the spring constant k and the mass of the oscillating object.

Performing spring experiment, it becomes possible to understand that the frequency and consequently the period do not depend on the amplitude. This allows extrapolations and establishing relationships to understand the SHM in two articulations, expanding the concepts previously involved.

Using the wooden base containing a suspended spring, as shown in figure 11, a mass $m = (125.00 \pm 0.01)$ g was suspended.

A force was exerted on the mass so that it registered short oscillations. The periods of these oscillations across the two sensors were on table 4.

The commercial instrument was used in the ‘pulse’ function and Cronpes instrument, was



Figure 11. Experimental apparatus used in Experiment (b) spring mass oscillation. In this case, the measurements were not carried out at the same time.

used in the ‘spring’ option, amongst the other possible functions shown on figure 8.

The calculation of the standard deviation for the measurements obtained with both instruments, Cronpes and the commercial instrument, represents a pertinent approach to evaluating the consistency and accuracy of the results. Despite

Table 4. Data obtained through Experiment (B) spring mass oscillation.

| Photogates | Number of periods | Time (s) |
|------------|-------------------|----------|
| Cronpes | 1 | 0.73 |
| | | 0.73 |
| | 5 | 3.65 |
| Commercial | 1 | 0.73 |
| | | 0.73 |
| | 5 | 3.65 |

involving only three measurements, the standard deviation, as a statistical measurement, provides insights into the dispersion of values around the mean value. The results obtained reveal that the standard deviation (σ) for the commercial photogate was approximately $\sigma = 0.00026$, whereas for the Cronpes, it was $\sigma = 0.00153$. Both deviations, close to zero, demonstrate the consistency of the measurements.

The analysis of the values highlights the effectiveness of the Cronpes compared to its more expensive commercial counterpart. In the context for which it is being employed, the developed photogate performs its function exemplarily and furthermore, can be subject to modifications to enable the reading of measurements with an additional decimal place of precision, a feature akin to the commercial sensor in question.

When measuring five periods of oscillation, the obtained measurements were very close. The created photogate features an additional function that allows the pre-programming of the desired number of oscillations to be measured, providing valuable assistance to students during data collection. Meanwhile, the commercial instrument in question does not display any indication on the screen regarding the number of oscillations recorded, revealing only, in the end, the final value relative to the maximum number of oscillations it can measure.

3.3. Conservation of mechanical energy

Through this experiment, the students can visualize the principles associated with an energy



Figure 12. Experimental apparatus used in experiment (c) conservation of mechanical energy. The measurements were not carried out at the same time, due to the experimental impossibility of positioning both sensors at the same point.

concept. When observing different cylindrical objects roll over the ramp, it is possible to calculate the transformation of potential gravitation energy into kinetic energy, showing the conservation of mechanical energy. This is one of the most complete practices for introducing complex physics concepts like friction (difference between static and dynamic friction), moment of inertia, linear and angular speed and other variables.

In this experimental practice, a ramp and two cylinders of the same diameter (solid and hollow) were used, as shown in figure 12. The cylinders were put to roll over the ramp to a height difference $\Delta H = (5.9 \pm 0.1)$ cm, travelling a total horizontal distance $d = (59.6 \pm 0.1)$ cm.

Cronpes: time measurement device suitable for teaching experimental physics in Brazil

Table 5. Data obtained through the experiment (c) conservation of mechanical energy.

| Photogates | Cylinder | Functions | Time (s) | Standard deviation |
|------------|----------|--------------|----------|--------------------|
| Commercial | Solid | <i>Gate</i> | 0.0895 | 0.0001 |
| | | | 0.0897 | |
| | | | 0.0897 | |
| | Hollow | <i>Pulse</i> | 0.0967 | 0.0002 |
| | | | 0.0964 | |
| | | | 0.0962 | |
| Cronpes | Solid | $2R_e$ | 0.090 | 0.002 |
| | | | 0.092 | |
| | | | 0.089 | |
| | Hollow | $2R_e$ | 0.100 | 0.0006 |
| | | | 0.101 | |
| | | | 0.101 | |
| | | $2R_i$ | 0.090 | 0 |
| | | | 0.090 | |
| | | | 0.090 | |
| | | $R_e + R_i$ | 0.096 | 0.0006 |
| | | | 0.097 | |
| | | | 0.096 | |

Different functions were used in photogates that made it possible to read solid and hollow objects. Cronpes has 3 functions for this type of practice: (i) $R_e + R_i$; (ii) $2R_i$ and (iii) $2R_e$, where R_e is the external radius and R_i is the internal radius of the hollow cylinders. In addition to covering the functions of the commercial instrument, Cronpes has the additional function of measuring the period through the internal radius, which is more accurate than the commercial instrument.

Subsequently, it is possible to emphasize the standard deviation recorded for each specific function (as presented in table 5), revealing low dispersion amongst the measurements and reflecting the homogeneity of the obtained data. This analysis reaffirms the consistency of the measurements taken by Cronpes. The results indicate coherence and reliability in the device’s ability to provide consistent results across various applications. This pattern of low dispersion, highlighted by the standard deviation, validates the robustness of Cronpes and consequently strengthens its viability in educational contexts.

Cronpes also has the advantage of being able to store measurements in the device’s memory.

This function facilitates experimental group practice and subsequent evaluation by teachers regarding the activity.

4. Conclusion

Cronpes, a time measurement device for teaching experimental physics, proves to be viable even for a beginner programmer to build a functional and user friendly instrument. Due to its innovative design using Esp32 microcontroller, the instrument is around 50 times cheaper than the commercial one. Another advantage is its easy maintenance, making it useful for technicians, teachers and even students. Furthermore, Esp32 presents other advantages compared to the Arduino microcontroller, extending its application such as: (i) dual core, (ii) Wi-Fi, (iii) Bluetooth and (iv) supporting more interfaces (LVGL: Light and Versatile Graphics Library [16]). The continuous process of improving this project aims to create versions that cover more experimental functions, with precision and user friendly features allowing views from several devices in a unified way using Wi-Fi or Bluetooth. Therefore, it was demonstrated, through the development of Cronpes, that

creating solutions for educational laboratories can be done in a feasible, creative and inexpensive way. These solutions promote knowledge of physics, through the use of electronics, for the implementation and improvement of laboratories dedicated to experimental physics, covering the entire educational spectrum from elementary school to universities.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

Authors would like to acknowledge Professor Wilson Alcântara Soares from the Physics Department at Universidade Federal do Paraná (UFPR) for all the assistance in the development of this project.

ORCID iD

M K K D Franco  <https://orcid.org/0000-0001-5336-7701>

Received 9 February 2024, in final form 19 July 2024

Accepted for publication 8 August 2024

<https://doi.org/10.1088/1361-6552/ad6d23>

References

- [1] BNCC URL (available at: www.educacao.gov.br/sites/default/arquivos_restritos/files/)
- [2] Yan L, Whiteloc-Wainwright A, Guan Q, Wen G, Gasevic D and Chen G 2021 *British J. Educ. Technol.* **52** 2038–57
- [3] Franco M K K D, Serbena J, Mattoso Filho N P, Wiener D O, Yokaichiyaa F and Fujimoto M M 2023 *Phys. Educ.* **58** 035030
- [4] Souza V A 2011 *KiCad* (Clube de Autores)
- [5] Espressif 2023 *ESP32 Series Datasheet version 4.4* (available at: www.espressif.com/sites/default/files/documentation/esp32_datasheet_en.pdf)
- [6] Arduino 2023 *Arduino UNO R3 RRL* (available at: <https://docs.arduino.cc/respices/datasheets/A000066-datasheet.pdf>) (Accessed 11 November 2023)
- [7] George D P and Sokolovsky P 2014 *Micro python documentation* (<https://doi.org/10.4103/0972-9941.124479>)
- [8] Srinath K 2017 *Int. Res. J. Eng. Technol.* **4** 354–7
- [9] Branwyn G 2017 *Inside adafruit, the open-source manufacturing maker champions* (available at: <https://makezine.com/article/maker-news/open-source-ideals-engineering-genius-helm-adafruit-marker-revolution-manufacturing>)
- [10] Adafruti 2024 *CircuitPython* version 8.2.x (available at: <https://docs.circuitpython.org/en/8.2.x/docs/index.html>)
- [11] Marcio B 2023 *Cronômetro-Óptico* (available at: <https://github.com/MarcioBulla/Cronometro-Optico>)
- [12] Sgall17a 2021 *Encodermenu* (available at: <https://github.com/sgall17a/encodermenu>)
- [13] Marcio B 2022 *Endodermenu* (available at: <https://github.com/MarcioBulla/encodermenu>)
- [14] Halliday D, Resnick R and Walker J 2017 *Fundamentals of Physics* vol 1 (Wiley)
- [15] Tipler P A and Mosca G 2021 *Física para la ciencia y la tecnología* vol 1A (Mecanica (reverte))
- [16] LVGL (available at: <https://docs.lvgl.io/master/>)