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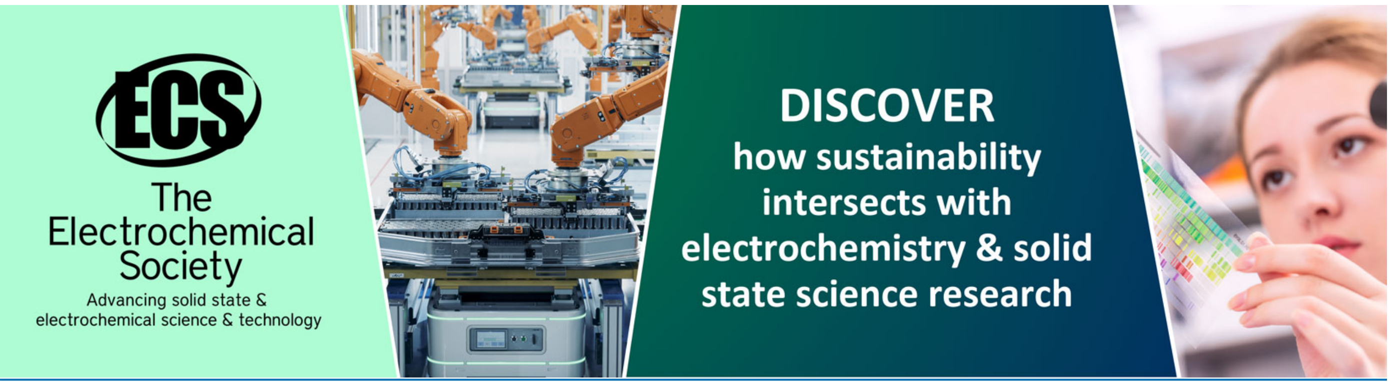

First results using a Home-Kit designed in the COSID-20 project: teaching physics laboratory at a distance

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Abstract. We designed and tested a personalized home-kit that was distributed to students in a Physics Education course during the pandemic as part of the COSID-20 project. A goal of the design of the kit was to be inexpensive enough to be attractive to schools and universities: a collaboration with a local start-up has proven very valuable in this sense. In this work we will present our kit, discussing how to be able to perform many different experiments with low-cost, easy to find materials and tools.

1 Introduction

The Covid-19 epidemic has had a significant impact on school and university teaching, as well as teacher training. The worldwide education system suffered a sudden transition to distance learning (DL) in 2020, and social distancing measures forced universities to quickly adapt to distance education methods [1], an adjustment that is especially challenging for science lab courses [2–4]. A major difficulty has been to provide students with an authentic and relevant laboratory experience, possibly based on groups activities and requiring careful data analysis, always ensuring an active learning environment.

A wide variety of creative approaches was proposed and employed by physics lab instructors after the diffusion of the pandemic in order to continue to offer opportunities for students to access lab-like learning during these challenging times [3,5–9]. As reported in Ref. [10], where these lab activities were classified, the main possible methods for a distance lab were: (i) instructor provided data; (ii) collect data from simulations; (iii) students watched a video of the instructor doing the lab; (iv) student collected own data at home; (v) analysis of data previously gathered by students; (vi) physical equipment controlled remotely.

Moreover, some other approaches were conceived: among them, the use of cost-effective, custom home experiment kits for remote teaching were proposed, sending kits home to students (among the various examples is this one [11]).

In this work we present a home-kit designed and tested by our research group and distributed to students in a Physics Education course during the pandemic as part of a larger project created to address the difficulties of teaching physics labs in a distance learning environment. The COSID-20 (COllaborazioni per le Scienze In Laboratorio Didattico – 2020) project was designed with the overall goal of increasing university resilience in the face of emergencies such as pandemics, particularly with regard to laboratory-based courses. Professors and researchers from various scientific fields contributed to the project.

2 The Home-Kit

The problematic of providing hands-on laboratories in a distance course was addressed by designing and assembling a Home-Kit laboratory, which is an effective and practical instructional technique for beginning science courses [2–4]. We used the kits in a Physics Education course aimed primarily at students interested in teaching mathematics and physics in middle and high schools. We gave each student a kit so that they could perform laboratory activities at home while collaborating with other students through videoconferences.

Apart from the kit's equipment, students were frequently required to use their mobile phones as a pocket lab [12–14].

The kit was also tested with 50 high school students in a structured teaching-learning environment.

Table 1. Summary table showing the components of the Home Kit provided to the students.

Components of the Home Kit		
2 cables with crocodiles	2 digital multimeters	Mini breadboard
12 electrical cables	Universal power supply	9 resistors
12V bulb	Power adapter	6 colored LEDs
Capacitor	Potentiometer	Compass
Digital scale	2 transparent glasses	2 clear plastic containers
2 food thermometers	3 polystyrene glasses	
	3 polystyrene glass lids	
25W incandescent bulb	Polystyrene support	
	1 black washer	
	1 white washer	
Galileo's trampoline (4 pieces to assemble)	2 sheets of carbon paper	150cm tape measure
	Metal marble (8mm diameter)	
Hook with 8 nuts	Spring	Base with hook
Diffraction grating	Polaroid sheet	Lens
	Colored filters	
Filters (red, green, and blue)	Torch	Food coloring

In the next sections we will discuss some of the experiments that the students performed at home with the kit. The experiments were chosen with two objectives: to not change the curriculum of the course, as well as to maintain the overall learning goals, as described in [11].

Because students would have had to work without being supervised, the kit had to be safe and designed in such a way that students could have used it to perform entire laboratory experiments on their own.

The experiments that students carried out at home using the kit covered a wide range of topics, from classical mechanics (Hooke law, Galileo' study on projectile motion) to thermal phenomena (specific heat, Newton cooling law, thermal equilibrium), from electric circuits (Ohm's law, RC, LED characteristics) to geometrical and wave optics (Snell Law, Beer Lambert Law, measurements with a diffraction grating, wavelength measurements), measurements of spectral transmittance up to modern physics (measurements of Stefan-Boltzmann Law, measurement of Planck constant with LED).

3 Some examples

3.1 Classical mechanics (Hooke’s law, Galileo study on projectile motion)

There are several experiments regarding classical mechanics that can be performed with the kit: here we will discuss two.

3.1.1 Hooke’s Law. This experiment is aimed to investigate how a spring behaves when it is stretched under the influence of an external force. To verify that this behavior is accurately described by Hooke’s Law, students at home hang a nut under the spring and measure the elongation of the latter; then they repeat the procedure for different masses, adding multiple nuts one by one (Figure 1). The mass of each nut can be measured using a digital scale. The linear dependence of the elongation versus the external force can be computed using the acquired data.

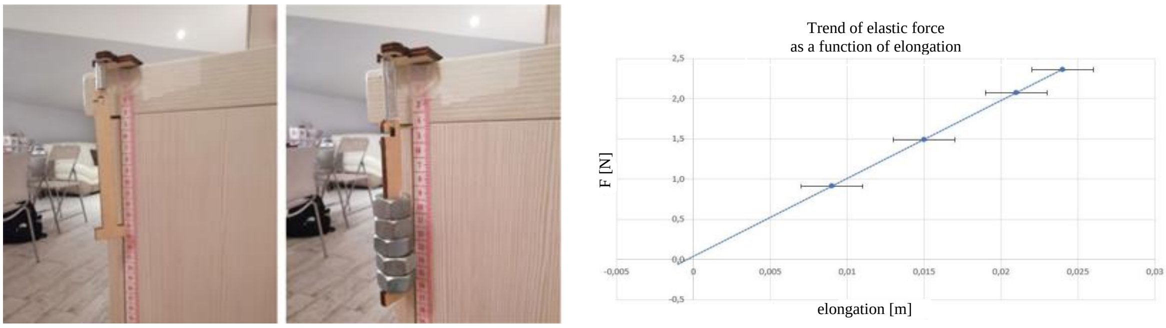

Figure 1. (Left) The experimental apparatus for the Hooke’s law and **(Right)** an example of experimental data obtained and analyzed by a student at home.

3.1.2 Galileo's experiment about projectile motion. In this experiment students investigate motion in two dimensions, showing that the orthogonal motions are independent. A wooden ramp, included in the kit (see Figure 2), is clamped to a table, and a steel ball can be let go from fixed positions along the ramp. To measure the horizontal distance travelled by the ball a paper sheet and carbon paper are used, which are stapled together, and allow to mark the spot where the ball hits the floor. The students measure the vertical distance from the floor to the bottom of the launch ramp and then analyze the data. This experiment, reproducing the one performed by Galileo and reported in Folio 116v [15], is used in the course as the starting point for a discussion about history of physics and the nature of science.

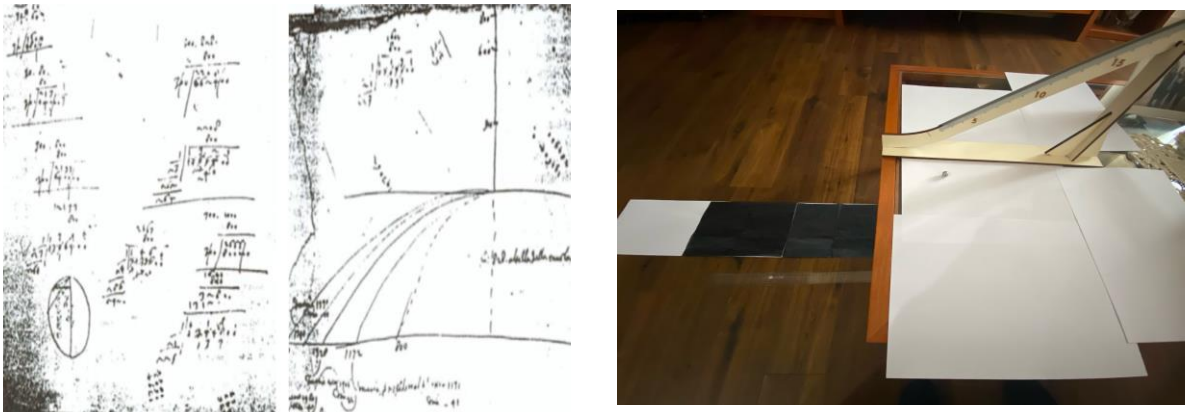

Figure 2. (Left) The Galileo's folio 116v where the experiment was described and **(Right)** the wooden ramp included in the Kit to perform the experiment at home.

3.2 Thermal phenomena (specific heat, Newton cooling law, thermal equilibrium)

Among the experiments about thermal phenomena that can be performed using the kit, we will present here just two very classical experiments.

3.2.1 Newton's cooling law and response time of a thermometer. We proposed the use of a smartphone based time-lapse and slow-motion video techniques together with tracking analysis as valuable tools for investigating thermal processes such as the response time of a thermometer [16] or, more in general, the Newton's law of cooling which states that the rate of change of temperature of an object is proportional to the difference in temperature between the object and its surroundings. A typical simple exponential dependence on time is obtained from data acquired by a student at home (see Figure 3).

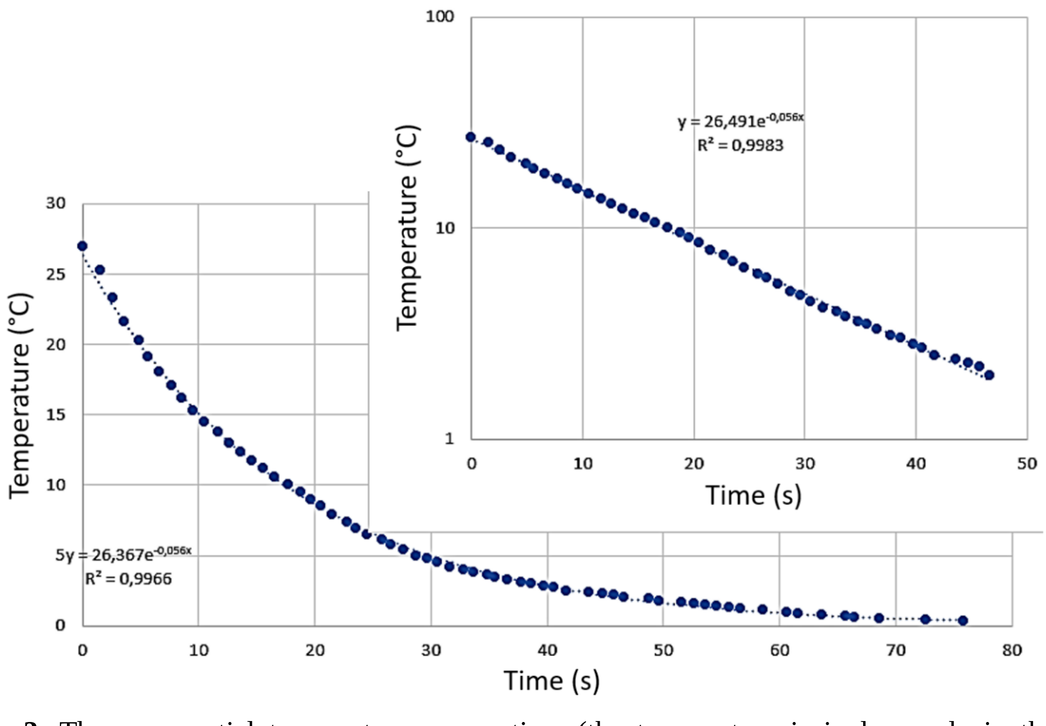

Figure 3. The exponential temperature versus time (the temperature is in log scale in the inset) obtained by a student in a measurement of time response for the digital thermometer (in air).

The latent heat of ice and the specific heat. A small amount of ice (≈ 30 g at 0°C) is placed in a low-cost calorimeter (a polystyrene cup with a plastic top, see Figure 4), then small amount of hot water (150 g at 40°C) is added. By knowing the masses of the ice, of the water, and of the calorimeter, and the resulting temperature change after the ice melts, the latent heat of fusion of ice can be found by students: the values are generally in good agreement with the known value. The procedure to measure specific heat is very similar and can be performed using the iron nuts used in the Hooke's Law experiment.

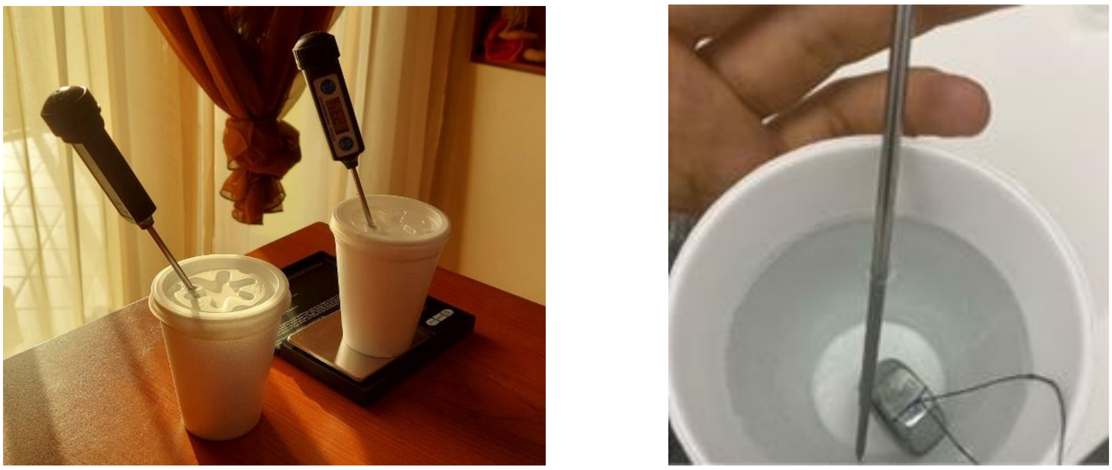

Figure 4. Polystyrene cups, digital scale and thermometers employed in a measurement of latent heat of ice. Only one cup and one thermometer are needed for this experiment. By also using a steel nut used in the Hooke's Law experiment, the specific heat of steel can be measured.

3.3 Electrical Measurements

3.3.1 The Ohm's law and the measurement of an unknown resistance. Two digital multimeters, the cables with crocodiles, the power supply and resistors can be used to test the Ohm's law as shown in Figure 5.

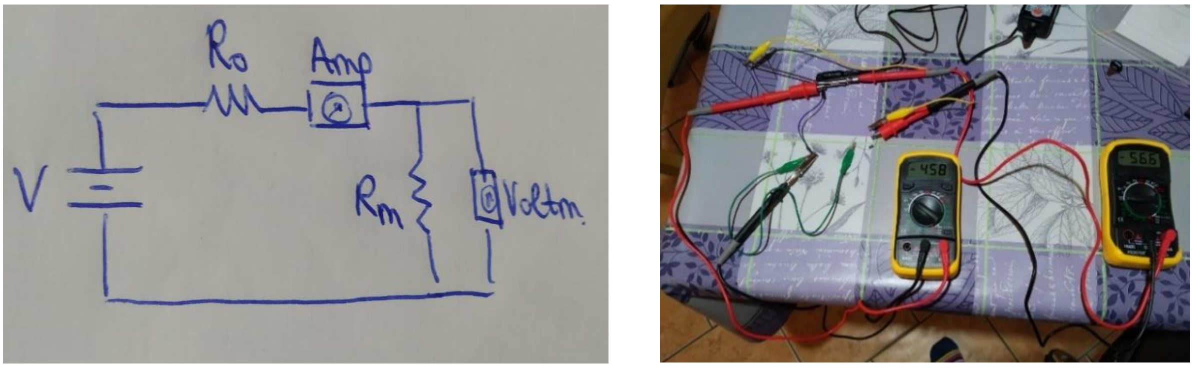

Figure 5. Experimental apparatus used by a student to measure the resistance of a graphite tab.

3.3.2 Studying the blackbody radiation with a light bulb. With an experimental setup consisting of a smartphone and two digital multimeters, resistors, a breadboard, a light bulb, and the power supply, it is possible to study the law of thermal radiation of an incandescent light bulb. The measurement of the filament temperature is obtained indirectly from the temperature dependency of the resistivity. The light sensor of the smartphone is used to measure the light intensity. By analyzing the graph of the dependence of the logarithm of light intensity on the inverse of temperature, in the limit of the Wien approximation of the Planck distribution, it is possible, with a linear fit, to obtain an estimation of the spectral response of the sensor or, alternatively, if this is known, an estimation of Planck's constant. More details about this measurement, which employs the apparatus in Figure 6, are included in Ref. [13].

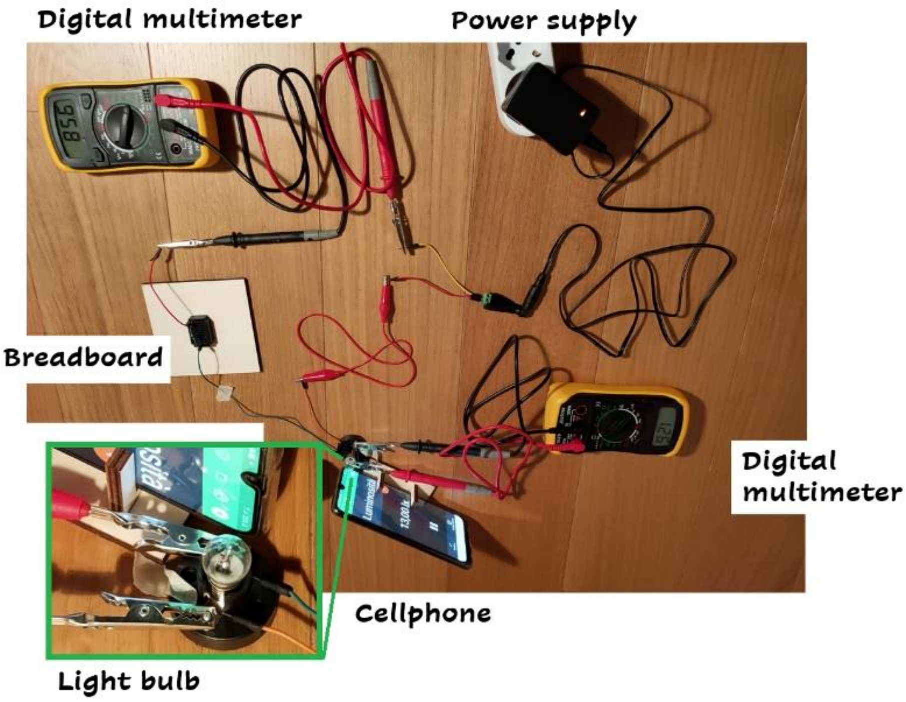

Figure 6. Two digital multimeters are involved, one to measure the potential difference V across the incandescent bulb and the other used as ammeter to measure the current I through the bulb. A resistor (chosen from those available in the kit) is placed on a breadboard in series with the lamp in order to obtain different voltage values from those supplied by the power supply (with nominal voltages of 3/4/5/6/7,5/9/12 V).

3.4 Spectroscopy and the Planck's constant

In this section we discuss an experiment in which students combine electrical and optical measurements. This common experimental activity reported by several authors in several articles [17–24] is aimed at determining Planck's constant using light emitting diodes, a smartphone camera and low-cost equipment. The technique to measure the Planck's constant relies on the energy of the light emitted by the LED and its relation to the energy gap (E_g=eV_g) between the conduction and valence bands of the semiconductor of which the diode is made of.

In most of the cited papers which propose this experiment, expensive (e.g., the spectrophotometers used in Refs. [25,26]) and specific (e.g., power supply, voltage current sensors, etc.) equipment was employed to perform the measurements.

In our experiment designed to be performed with the home kit, the LED spectra were acquired using a low-cost grating spectrometer based on a smartphone camera, while the input current versus the applied voltage was obtained with the equipment which we provided to students. The photos and the analysis of the spectra make students aware that for some LEDs the energy of the light emitted from the LED can be quite different from the gap energy.

The experimental apparatus is shown in Figure 7 and all the components are included in the kit. Measurements are carried out by using 7 LEDs.

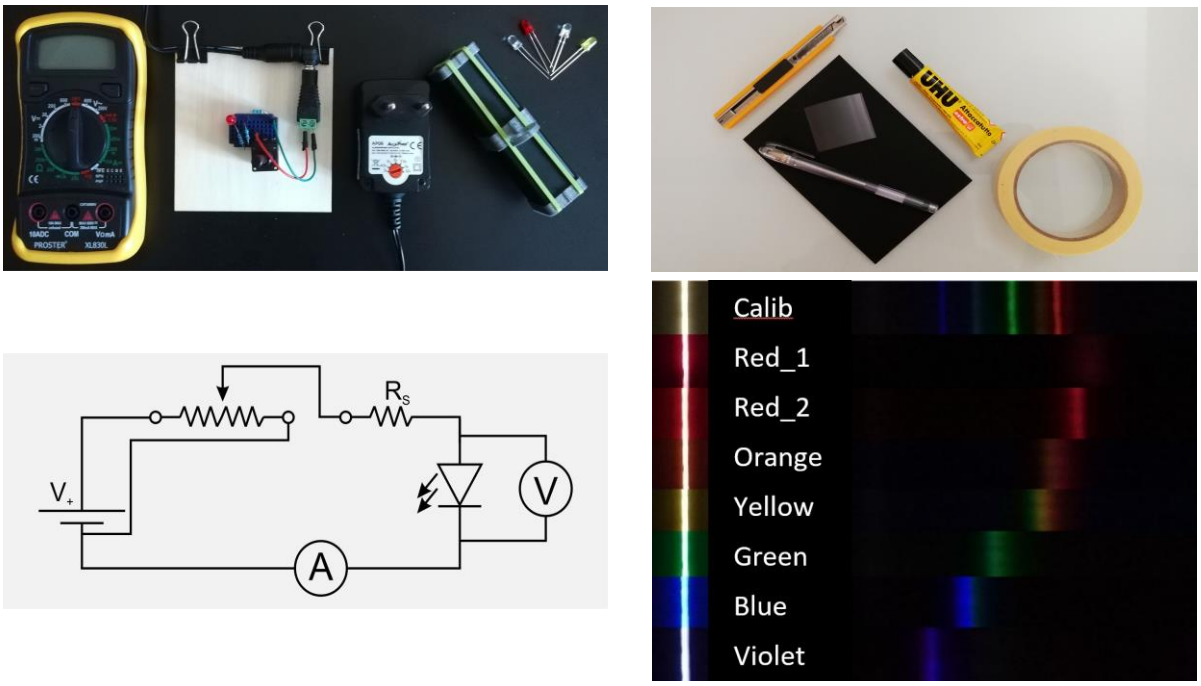

Figure 7. The experimental apparatus, consisting of two digital multimeters (one used as a voltmeter to measure the voltage drop V across the LED and the other used as an ammeter to measure the electric current I), a breadboard and a cheap potentiometer inserted into the circuit in series with the LED is shown in the top right image. The home-made spectroscope can be assembled with low-cost materials shown in top right.

3.4.1 The home-made spectroscope. The home-made spectrophotometer is assembled by using a 500 lines mm-1 transmission grating, a black cardboard, and a cell phone camera. This apparatus is analogous to the ones proposed in Refs. [27–31] and spectral measurements are performed using the free and open source video analysis software Tracker and the techniques described in Refs. [27–29]: (i) for the wavelength calibration we use a commercial fluorescent lamp (the full procedure is described in Refs. [27–29]); (ii) to obtain the measure of corrected “light intensity” (luminance) from RGB values we use the transformation formula needed to revert the gamma correction [32].

3.4.2 Spectral Measurements. In the first activity students, after the construction and the calibration of their own spectrophotometers, measured the emission spectrum of each of the 7 visible LEDs, to check the peak wavelength and evaluate the width of the wavelength distribution. The spectral composition is rather broad, with an RMS of the distribution ranging from 8 to 15 nm. Alternatively, students can assume as uncertainty of the measured dominant wavelengths the full width at half maximum (FWHM).

3.4.3 Determination of the Planck’s constant. A value of the Planck’s constant can be determined either from the ratio between the *turn on* voltages of the LED and the frequency of the light emitted or from the slope of the line fitting the frequency versus the threshold voltage data. Thus, combining the two ways to measure the threshold voltages and the two methods to deduce from these data the value of *h*, students obtained 4 different estimations for the Planck’s constant.

The measurements based on the ratio between voltages and frequency averaged on the complete set of LEDs gave to the students the value of $h = (6.4 \pm 0.7) \times 10^{-34}$ J·s for the linear extrapolated voltages and $h = (5.6 \pm 0.6) \times 10^{-34}$ J·s for threshold current. The measurements based on the fitting the frequency versus threshold voltage give the value of $h = (8.4 \pm 0.8) \times 10^{-34}$ J·s for the linear extrapolated voltages and $h = (7.6 \pm 0.5) \times 10^{-34}$ J·s for threshold current.

4 Results

The kit underwent testing with 35 undergraduate students, and instructional materials were developed to aid teachers in conducting various activities. A comparison with traditional on-campus laboratory courses revealed that our remote laboratory experience yielded comparable final grades and laboratory competencies, as reported by instructors. Upon completion of the semester, students were asked to participate in a Likert-scale survey aimed at examining their perceptions regarding the utilization of the kits and their perceived learning outcomes. The survey questions were aligned with the learning goals that informed the design of all laboratory activities, which include building knowledge and a deeper comprehension of physics through hands-on experience; enhancing practical skills in conducting experiments, problem-solving, and troubleshooting; demonstrating proficiency in experimental design and data analysis; grasping the principles behind scientific measurements, such as repeatability, uncertainty, bias, precision; developing critical thinking.

Based on the findings from this survey (with an average score of 3.8 on the Likert scale) it can be concluded that the essential learning objectives were met, student satisfaction with the remote laboratory remained high, and effective collaboration through video-conferencing breakout sessions was attained.

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