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Bringing the Physics Laboratory at home: Tools and methodologies for distance learning at the University of Trento

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Summary. — Experiments play an essential role in the scientific training of students. Therefore, a crucial challenge in distance learning is to offer students an authentic and meaningful, possibly collective, laboratory experience that requires rigorous data analysis and ensures an active learning environment. This challenge has become urgent in recent years, as the global education system has led to a rapid shift to distance learning and training and social distancing measures have required universities and schools to readily adapt to remote education methods, an adjustment that is particularly difficult for scientific laboratory courses. As part of a project called COSID-20 (COllaborazioni per le Scienze In laboratorio Didattico - 2020), we followed different approaches and methods to design a remote physics laboratory: experiments using tools and materials from a specially designed home kit, created and sent to the participants, "kitchen experiments", simulations, experiments pre-recorded by the teacher, remote access laboratories and virtual laboratories. With the aim of answering the crucial question of whether a physics laboratory course can be effectively delivered remotely, we will examine how students carried out the different activities and which of them are considered by students to be most effective and engaging. This will be done by discussing, for each methodology, whether the learning objectives for the physics laboratory indicated by the most recent research in Physics Education have been achieved.

1. – Introduction

Physics laboratory is an important part of teaching physics because of its inherently experimental nature, and there is an increasing awareness of the importance of the laboratory experience in this discipline and, more generally, in science education [1]. In recent times the objectives of laboratory instruction have been subject to numerous calls for revision [2,3]. In fact, it has been observed that if laboratory activities are organized in a way that provides overly detailed instructions and follows a confirmatory approach (where students are required to verify a result already known from theory), the effectiveness of such activities in terms of reinforcing theory and developing scientific skills is greatly reduced. In this context, online laboratories have emerged as a methodology that had to be adopted to a large extent during the pandemic period. Distance learning during the pandemic [4] has presented several challenges for physics laboratory courses. Some of these challenges include: 1. Lack of hands-on experience: physics laboratory courses typically involve a lot of hands-on experimentation and data collection. Without access to a real laboratory, students may not be able to gain the same level of understanding and experience as they would in a traditional in-person setting. 2. Limited access to equipment and difficulty to replicate experiments: many students may not have access at home to the same equipment that is available in a school laboratory. This can make it difficult for them to complete laboratory assignments and may limit their ability to understand and apply key concepts. 3. Safety concerns: in a distance learning environment, students may not have the same level of oversight and guidance when conducting experiments, which can increase the risk of accidents or injuries. 4. Limited interaction and support: distance learning can make it harder for students to interact with their classmates and instructors and to get help when they need it.

Motivated by the pandemic, several solutions have been implemented to facilitate physics laboratory work in distance learning [4]. One solution is to use online simulations and virtual labs [5, 6], which can provide students with an experience with equipment and experiments without the need to physically access a laboratory. Another solution explored by some groups has been the development of remote labs using iOlab (Interactive Online Lab), a device equipped with sensors [7,8]. Another solution is to provide students with equipment and materials, *i.e.*, a complete lab kit [9], along with detailed instructions and guidance from the instructor, that they can use at home to conduct experiments. Additionally, video conference tools can be used to allow students to remotely connect with the instructor and other students, and to share their results and observations in real-time. Another way is to use pre-recorded videos with step-by-step instructions, which students can watch and follow along to conduct experiments. Another option is to create a hybrid approach where students can come in-person to the lab at certain times, with proper safety measures in place, and use online simulations, virtual labs, and video conference to supplement their in-person lab work. Ultimately, the specific solution(s) that will work best will depend on the available resources and the needs of the students and instructors.

As our research focuses on designing Teaching Learning Sequences (TLSs) based on the experimental activities that are an integral part of our courses, one of the key aspects of the transition from face-to-face to distance learning is the ability to provide students with the opportunity to undertake experiment-based TLSs in a remote laboratory environment. To face the challenges of offering a laboratory course for physics students, the COSID-20 project was created with the primary aim of increasing the resilience of educational institutions in the face of emergencies. COSID-20 involved many different activities, and investigated many available solutions.

The aim of this paper is to describe some of these different proposals. Specifically, we have investigated undergraduate students' work and interaction with the offered learning environments to answer the following research questions:

(RQ1) Can a physics laboratory course be delivered effectively as a distance laboratory?

(RQ2) Have the learning objectives for the physics lab indicated by the most recent research in Physics Education been achieved?

(RQ3) Did the students learn the same concepts and to the same extent as in a traditional laboratory?

(RQ4) Have students changed their level of experience in their views on experimental physics than in previous years?

(RQ5) What were students' opinions on experimental physics that changed compared to previous years?

(RQ6) Is it possible to redesign learning teaching sequences so that they are implemented remotely? With what tools and what results?

(RQ7) Which of the different activities and methodologies of the distance laboratory are considered by students to be most effective and engaging?

With the aim of answering these questions, we will examine how the students carried out the different activities. We hope that a relevant part of the ideas and proposals here presented and discussed will continue to provide support and constitute a methodological inspiration to the activities in class even after the pandemic emergency.

The paper is organized as follows. In section 2 we will discuss the general topic concerning the physics laboratories in distance learning. In Section 3 we define the learning goals of the distance lab and the strategies to be implemented. In Section 4 we describe the home kit that has been developed at the University of Trento and a selection of experiments which can be performed at home with it. Section 5 is devoted to the results and to conclusions.

2. – Distance learning and Physics labs

Distance learning, also known as online or virtual learning, is a method of education where students can attend classes and complete course work remotely, rather than in a traditional classroom setting [10]. In fig. 1 we show the spatio-temporal model of distance education proposed by Coldeway [10], *i.e.*, a model which takes into account both the spatial and temporal dimensions of learning in a distance education setting. Thus, distance learning can be classified into several different types, including: 1. Synchronous learning: this type of distance learning involves real-time interaction between students and instructors, such as through video conference; 2. Asynchronous learning: this type

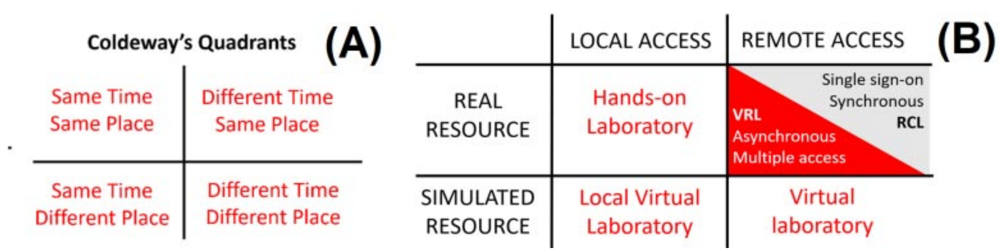


Fig. 1. – (A) Coldeway chart [10] with the division of the didactic typologies that make up the four quadrants of Coldeway. The Same Time – Same Place quadrant represents traditional classroom education. Student(s) and instructor(s) gather at the same time and location. This is the "control" quadrant; any system in this quadrant is not considered a form of distance education. The Different Time – Different Place quadrant reprenents the "purest" form of distance education – student(s) and instructor(s) engage in the educational activity at different times and in different places. (B) Experimentation environments adapted from [11].

of distance learning does not involve real-time interaction and students can complete course work on their own schedule; 3. Blended learning: this type of distance learning combines online and face-to-face instruction in a classroom setting.

2·1. *A taxonomy for distance laboratories.* – A taxonomy for distance learning physics laboratory [11] can be based on the location of the laboratory and the type of resources and access provided to the students. To characterize the different modalities of the experimentation environments and thus provide a precise definition of the online laboratories, two criteria have been proposed. 1. Depending on the way in which resources are accessible for experimental purposes, the environments may be local or remote; 2. Depending on the physical nature of the laboratory, the environments may be real or simulated.

Thus, according to ref. [11], as reported in fig. 1 we can have a Virtual Lab (VL) [6] when the experiment is simulated and the access is remote and a Remote Controlled Laboratory (RCL) [12] when the apparatus is located remotely and can be accessed remotely by the students. In this case students, one by one, conduct experiments by controlling the apparatus remotely in real time and acquire the data over the internet.

Remotely control labs are real laboratories which allow students to remotely access and control real laboratory equipment. This technology allows students to conduct experiments and collect data remotely, similar to how they would in a traditional in-person laboratory setting. RCLs typically use web-based interfaces that can be accessed by students through a computer or mobile device. These interfaces allow students to control the equipment, collect data, and perform measurements. These labs can allow for greater flexibility in scheduling and can help to ensure that all students have equal access to laboratory experiences. There are many universities all over the world that provide a number of laboratory activities which are remotely available. In a physics RCL, students do not physically interact with the instrumentation, so they do not acquire the hands-on experience that typically characterizes a real lab. However, the data are real, and every other part of the laboratory experience is authentic.

In this work we also use a new kind of distance lab: the Virtual Remote Lab (VRL) that is a pre-recorded remote laboratory. This definition takes into account the dichotomy of this apparatus: it is a virtual experience, as the students do not really control the apparatus while they interact with the interface; however, they work with a real experiments, prerecorded and reached remotely [13]. Usually, these labs are based on videos of physics experiments that have been recorded in advance and can be accessed by students in a virtual environment, *e.g.*, the experiments were virtualized to be made accessible remotely. In this case the virtualization allows users to remotely access the equipment and users work with it exactly in the same way of a remote lab. This kind of lab allows also a multi-user access which is not possible employing a RCL. VRLs can be helpful for students who may not have access to physical laboratory equipment or who may be unable to perform experiments in person. Additionally, virtual experiments can be paused, rewound, and repeated, which can allow students to gain a deeper understanding of the underlying concept.

Also for what concerns the Virtual Lab based on simulations we can introduce a different classification. In fact, according to [14], *current digital learning environments can be divided into two categories as "constrained" and "less constrained" [...] PhET simulations are considered an example of "constrained" simulations* [6] *and Algodoo* [15] *as an example of "less constrained" simulation environment.*

PhET (Physics Education Technology) is a very well-known collection of interactive simulations for teaching and learning physics, chemistry, biology, and maths. These simulations are designed to be used in classroom settings and are available for free online. They are developed by the University of Colorado Boulder and are available in multiple languages and platforms [5, 6].

Less constrained simulations are simulations that allow for a greater degree of freedom in the variables and parameters that can be adjusted and explored. This allows students to design the experiment to be simulated, to investigate a wider range of physical phenomena and to make accurate predictions and observations. Less constrained simulations also give students the ability to explore the relationship between different variables and to see the effects of changing one variable on another, which can help to deepen their understanding of the underlying physical principles. Among these kind of simulation, Algodoo [15] is a physics-based freeware 2D simulation environment for creating interactive scenes in mechanics and optics. It is designed to be easy to use and accessible to users of all ages and skill levels.

Each type of laboratory has its advantages and disadvantages. For example, the remote laboratory may be more realistic, but may require specialized equipment, while a virtual laboratory is more accessible but may lack realism. The choice of laboratory type, access and resource availability can depend on the learning objectives and the technological capabilities of the institution and students.

2˙2. *Hands-on experiments for distance labs*. – There are several alternatives to VRLs and to RCLs that allow students to perform experiments themselves and to see phenomena happen in front of their eyes. In this subsection we classify these alternatives.

2˙2.1. Kitchen lab. During the pandemic some physics instructors showed how it is possible to redesign an experimental course for a physics lab course in distance learning by incorporating the so-called kitchen experiments [16, 17], which are a type of hands-on learning activity that can be used to teach physics concepts and principles using everyday materials and equipment found at home. This approach can be an effective way to engage students in distance learning, as it allows them to conduct real experiments even if, quite often, these kinds of experiences are not considered adequate at university level. According to ref. [4], using household equipment can be a fast, easy, and effective way for students to have a hands-on experience while being remote. When implementing lab activities in which students are expected to use household equipment, instructors have to ensure as much flexibility as possible in terms of the kinds of materials students will be expected to use. However, we think that, when students perform an experiment at home, completely alone, with the only use of common objects, it is a challenge which stimulates creativity and pushes students to reinforce their problem-solving ability. What becomes really interesting is that students will learn physics in a really effective way, and moreover they will achieve a lot of transversal competences.

2˙2.2. Home kit. Home experiment kits were designed also before the pandemic to keep students engaged and achieve the learning goals typical of a laboratory course in a distance learning. A home physics laboratory kit typically includes basic equipment and is designed to allow students to conduct a variety of experiments at home as part of a distance learning physics course. Some companies offer customizable kits tailored to specific curricula, while other companies offer pre-made kits. However, the cost of commercial kits is often prohibitive and usually they do not match the specific goals of the existing university labs. Thus, especially during the pandemic, also cost-effective, custom home experiment kits were designed and tested [9, 18].

2˙3. *Tools for a distance Lab.* –

Smartphone apps. Besides the kit or household equipment, students could utilize their mobile phones as a portable lab, by exploiting the sensors on their smartphones to gather data. Smartphones are equipped with a variety of sensors, such as accelerometers, gyroscopes, magnetometers, and light cells, that can be used to measure various physical quantities. The apps employed in various experiments are Phyphox [19], Physics Toolbox Suite [20] and AndroSensor [21], and they are available for the main operating systems on their respective websites. All of them allow exporting data, using CSV file format, to a tablet, notebook or desktop computer.

Video analysis. This is a technique that can be used to gather information on the motion of objects in physics experiments. One popular software program for video analysis is Tracker [22], a free, open-source software that can be used to track the motion of an object in a video and generate data that can be used to calculate various kinematical quantities such as position, velocity, and acceleration.

Image analysis. Home-made spectroscopy employing a cell phone camera to acquire the images and using Tracker [22] is a technique that can be used to analyze light and determine its spectral components. To make a home-made spectroscope students usually are needed to build a small black tube, create an aperture to allow light to enter the spectroscope by cutting a small slit in one end of the tube and place a diffraction grating in front of the slit on the other end of the tube. A camera or a smartphone is then used adhering to the grating to record the light passing through the spectroscope and allowing Tracker software to analyze the photo.

3. – Teaching labs in a distance learning: goals and strategy

3˙1. *Learning goals of a physics laboratory.* – The objectives (disciplinary and transversal) of a lab course can be very varied and concern, for example, conceptual learning, the strengthening and application of contents, the construction of knowledge, the development of skills in the use of instrumentation, in carrying out measurements and in estimating uncertainties, the analysis and representation of data, the design of experiments, the enhancement of communication and teamwork skills, increasing skills in modelling or fostering motivation and interest [2, 23]. In the present work, we have utilized the framework developed in ref. [24] with certain modifications to establish our learning goals (see fig. 2). Our primary aims in conducting distance learning activities with students include the development of a model for making predictions to be compared with experimental measurements using data analysis techniques. Furthermore, we facilitate the design of experiments and aim to promote teamwork among students, even in a distance learning setting.

3˙2. *The POE strategy.* – To allow students to achieve the LGs and a well founded conceptual understanding we follow the "Predict-Observe-Explain" (POE) method. The POE strategy is a widely used approach in physics education that aims at promoting active learning and critical thinking among students. The POE strategy involves three main steps, which are outlined below.

Predict. Students are presented with a problem or situation and are asked to make predictions about the outcome based on their prior knowledge and understanding. This step helps students to engage with the material and to think critically about the problem.

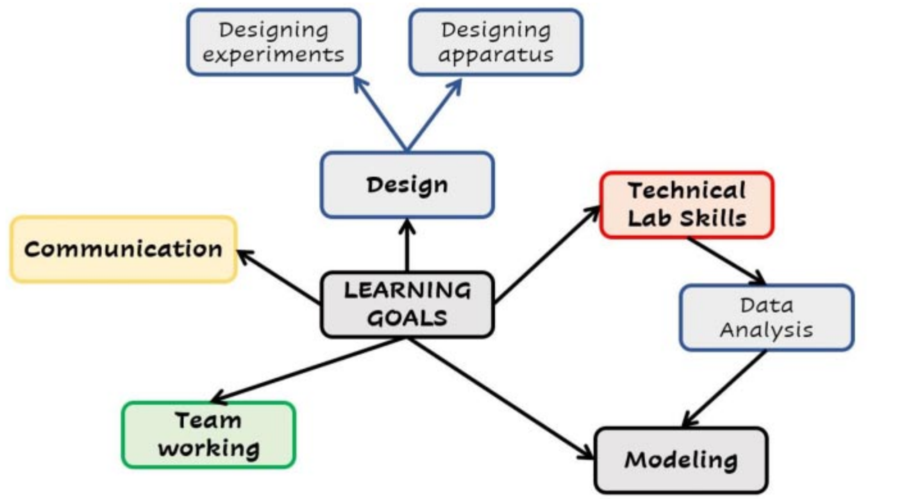


Fig. 2. – Scheme summarizing the learning goals of the laboratory adapted from [24]

Observe. Students conduct an experiment or collect data to observe the outcome of the problem or situation. This step helps students to gather evidence and to develop their experimental skills.

Explain. Students use their observations and data to explain the outcome of the problem or situation. This step helps students to connect their observations with their predictions and to develop their ability to reason and explain scientific phenomena.

The POE strategy can be used in a variety of contexts, such as laboratory experiments, computer simulations, and problem-based learning activities. It's a very effective way to help students develop their critical thinking and problem-solving skills, and to encourage them to take an active role in their learning.

It is also important to note that in this strategy, students are encouraged to revise their predictions and explanations if the observed results are not consistent with their predictions. This process helps them to identify and correct misconceptions, and to improve their understanding of the physical concepts.

4. – The distance lab at the University of Trento

4·1. *The Home Kit @UNITN*. – As discussed by ref. [9], "many of the commercially-available home kits did not match the specific learning goals of the existing university experiment labs. An alternative approach of using only household equipment would not have permitted all experiments to be done and may have created equity issues for students". In the context of the COSID-20 project a personalized home-kit was designed and tested at UniTrento. The kit was sent to students of a physics education course. The Kit is suitable for the contents of a laboratory-based course aimed at future physics teachers and designed to meet the general laboratory learning goals. The home-kit is shown in fig. 3.

The experiments were chosen with two objectives: to leave the curriculum of the course unchanged, as well as to maintain the overall learning goals, as discussed above.

Components of the Home Kit		
2 cables with crocodiles 12 electrical cables 12V bulb Capacitor	2 digital multimeters Universal power supply Power adapter Potentiometer	Mini breadboard 9 resistors 6 colored LEDs 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 Metal marble (8mm diameter)	150cm tape measure
Hook with 8 nuts Diffraction grating	Spring Polaroid sheet Colored filters	Base with hook Lens Copper wires
Filters (red, green, and blue)	Torch	Food coloring

Fig. 3. – Summary table and components of the home-kit provided to the students.

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 use it to perform entire 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's law, Galileo's study on projectile motion) to thermal phenomena (specific heat, Newton's cooling law, thermal equilibrium), from electric circuits (Ohm's law, RC, LED characteristics) to geometrical and wave optics (Snell's Law, the Beer-Lambert Law, light diffraction, measurements with a diffraction grating, wavelength measurements), measurements of spectral transmittance up to modern physics (measurements of the Stefan-Boltzmann Law, measurement of the Planck constant with a LED).

In fig. 4(A) we show how the contents of the kit were used to perform the measure of the Stefan-Boltzmann Law [25] using the electric tools (two multimeters, a bulb and a power supply) and the cell phone light sensor. In fig. 4 (B) we show the diffraction patterns which students obtained by using LEDs and copper wires of different thickness [26].

In fig. 5 we show how the tools supplied to students enable them to measure Planck's constant using a LED, which requires both electrical and spectroscopical measurements [27, 28]. The experiment requires evaluating the threshold voltage of several LEDs and plotting it against the frequency of the emitted light; Planck's constant is then evaluated from the slope of the fitting line (fig. 5(B)). This rests on a linear approximation to the LED $I - V$ characteristic, as shown in fig. 5(A). The threshold voltage can be evaluated either by visually evaluating the switching on of the LED, considering as threshold the minimum potential for having light emission from the LED. This approach has the advantage of being quick, however it brings with it an intrinsic difficulty, since the point of ignition of the LED is not well defined and could change as different students perform the experiment. Alternatively, students can measure both the current and voltage in the LED circuit: when the current begins to flow, the LED also begins to emit light, even though the light intensity can be too weak to see.

To provide a clearer explanation of how the previously suggested POE strategy is implemented when students use the kit, let's delve into the process of presenting this experiment to students. Initially, students are asked to measure the resistance of the LED. This task will bring to light two points: the need to apply the correct voltage polarization, and the fact that the LEDs characteristic I-V is not linear. At this point students are prompted to compare various LEDs. Through this comparison the students

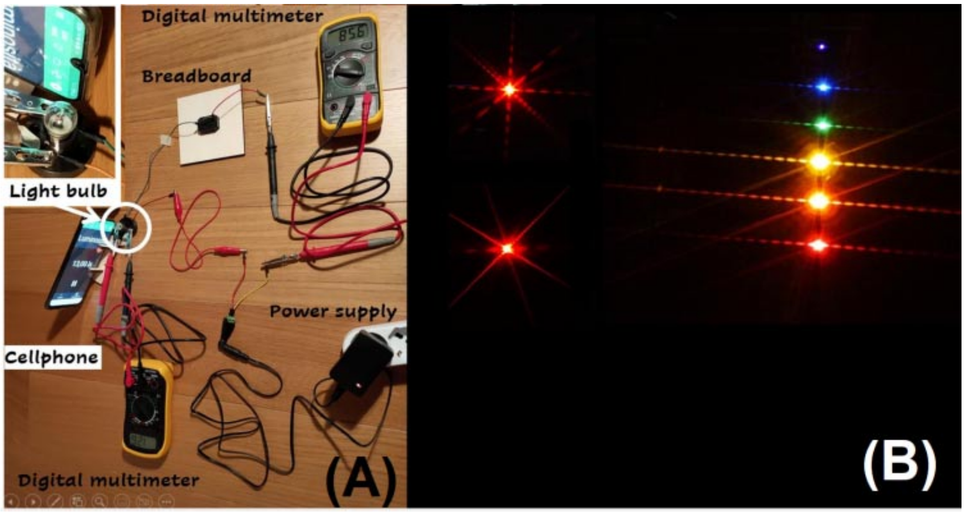


Fig. 4. – (A) Two digital multimeters are used, one to measure the potential difference across the incandescent bulb and the other used as ammeter to measure the current through the bulb. A resistor (chosen among those available in the kit) is placed on a breadboard in series with the lamp in order to obtain different voltage values from those supplied by the power supply (with nominal voltages of 3/4/5/6/7.5/9/12 V). (B, left) Diffraction patterns obtained with a red LED and using wires of width: (Top) 0.05, 0.08, 0.1, 0.2 mm and (Bottom) 0.05, 0.325, 0.5 mm. (B, right) Diffraction patterns obtained with LEDs of different colors and a fixed wire.

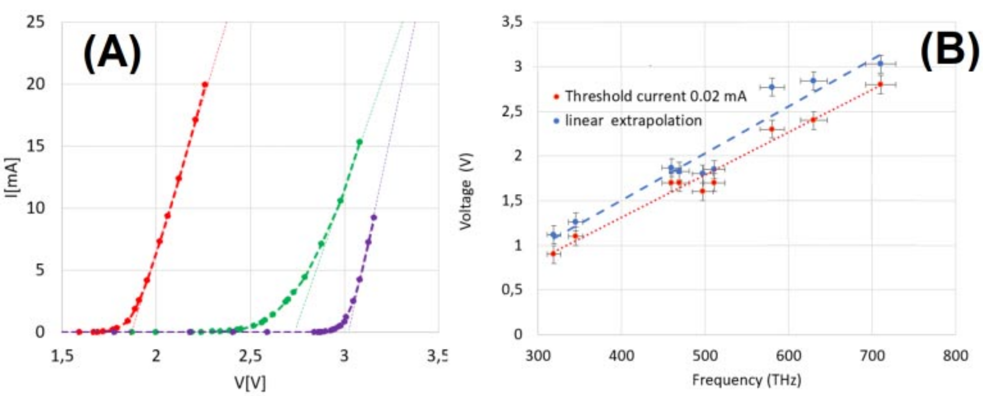


Fig. 5. – (A) The $I-V$ characteristics of typical LEDs, with their linear approximation. (B) A graph of threshold voltage versus frequency for a typical set of LEDs ranging from red ($4.69 \times 10^{14} Hz$) to violet ($7.5 \times 10^{14} Hz$). The voltages are measured as described in the text, while the frequencies are those given by the manufacturer. Alternatively, they may be measured using a home-made spectroscope of the kind described above. The dotted line is a linear fit to these data.

deduce that there is a dependence of the threshold voltage on the color of the LED. Then they are asked to measure the frequencies of the radiation emitted by the LED with the spectroscope and establish a relationship between frequency and threshold voltage.

4·2. *A remote teaching-learning sequence on the greenhouse effect with the home-kit.* – To conclude this overview of the kit's potential, we underline how it has been designed to allow the realization of a TLS, which addresses a complex issue such as the greenhouse effect (GHE) in a context of distance learning. The introduction of such a complicated subject requires a progressive conceptual construction, which implies the definition of a sequence of cognitive steps necessary to attain a coherent explanation of the greenhouse effect, *e.g.*, (i) to recognize and explain a steady state of temperature for objects exposed to the Sun or a lamp (energy balance), (ii) to differentiate heat and radiation and recognize that objects at any temperature emit radiation, and (iii) to differentiate visible and infrared radiation and the behaviour of a material for different kind of radiation. The experiments performed by students at home using the kit are aimed at: (i) recognizing the radiation emission of the body and its dependence on temperature, by measuring the Stefan-Boltzmann law for the emission of a light bulb; (ii) realising the selective absorption by measuring the transmittance as a function of wavelength and of thickness (Beer attenuation law); (iii) recognizing and explaining a stationary condition of temperature for objects exposed to the Sun or a lamp (energy balance) by measuring the solar constant or the power emitted by a light bulb. An overview of the experiments, together with some graphs showing quantitative measurements, is provided in fig. 6. These experiments, supported by the use of simulations [5] and by real-time demonstrations by the teachers, have made it possible to implement a distance TLS, achieving results with the students in line with those obtained in face-to-face teaching. As reported in ref. [29] students who attend the TLS can reach an effective understanding of the physical grounds of the GHE and the result is supported by the analysis of the answers to an assessment questionnaire [29], given to the students at the end of the sequence. A statistical comparison between the groups which attended the course on face to face and the one (2020/2021) which used the home kit at a distance show that there is no significant difference between the groups.

4·3. *Virtual Remote Labs.* – To show the potential of the use of VRLs we describe here a short TLS on magnetic forces that was implemented remotely. At the core of the sequence are two experiments designed to explore independently the characteristics of the magnetic force on a carrying current wire and on free moving charges. These experiments allow us to introduce a critical discussion about the connection between the macroscopic approach and its microscopic interpretation in terms of forces acting on charged particles inside the wire [30]. The experiments concerning moving electrons [31] were carried out by the students thanks to the VRLs available at [https://virtuelle-experimente.de/en/] and designed by Stefan Richtberg [13], while the experience on the force acting on a current carrying wire was made possible by a VRL laboratory developed by a member of our group [32].

A second VRL created by our group and tested with students, employed the tools contained in the home kit and reproduced the electrical and optical measurements which allow the estimation of the Planck constant by using LEDs, described in the previous subsection. These VRLs are shown in fig. 7(A) and (B), respectively.

When using the virtual laboratory, some steps of this sequence must be skipped and students are only focused on constructing the I-V curve of LEDs, studying the dependence of the threshold voltage on the frequency.

During and after the course, students also conducted some experiments using RCls. For instance, they could reproduce the measurements of the Stefan-Boltzmann law with

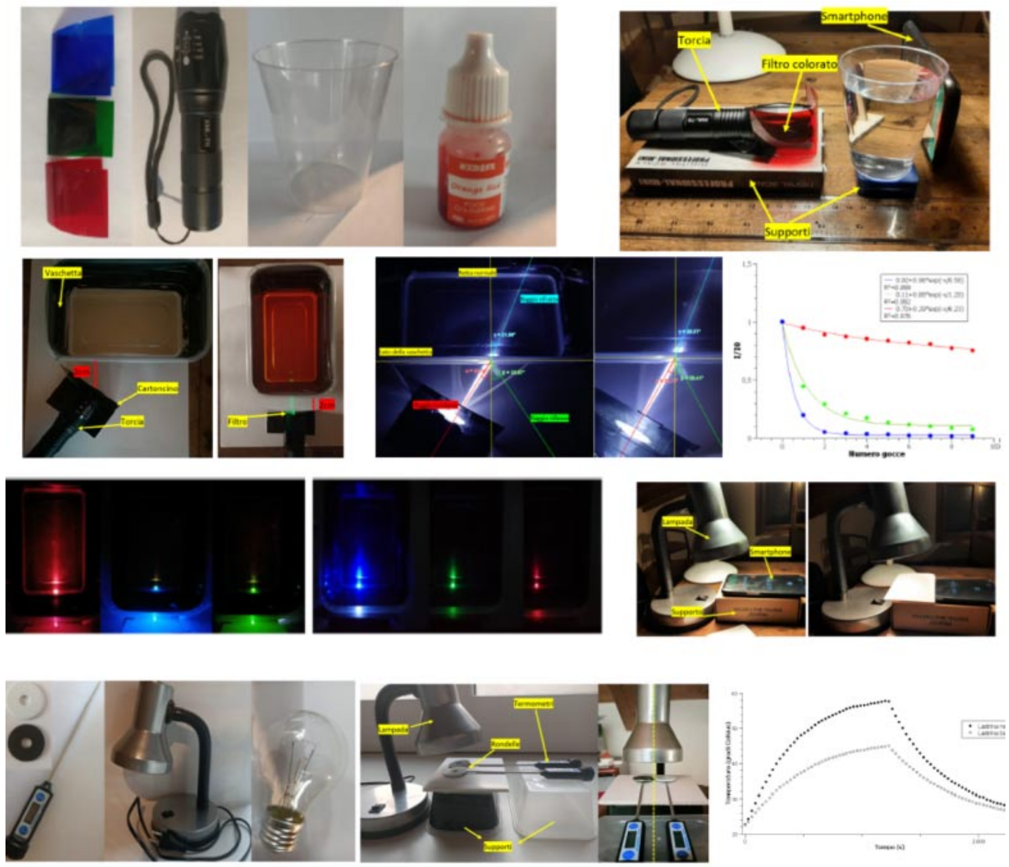


Fig. 6. – An overview of the experiments and the measurements included in the TLS on the greenhouse effect.

a light bulb [33], or perform the measure of the Planck constant in the photoelectric effect experiment [34].

4˙4. *Additional strategies for distance labs.* – During and after the pandemic we also encouraged students to explore other different approaches to distance laboratory.

1) *Pre-recorded experiments.* We sent students some photos reporting the spectra of different light sources acquired by the instructors. Students were able to analyze these pictures with Tracker and to measure the dominant wavelengths of some LEDs or estimate the Rydberg constant [35].

2) *Constrained Simulations and data collection from simulations.* Virtual labs are labs that simulate the real lab environment and are based on experiment simulations. Virtual laboratories are therefore conducted thanks to the use of simulations that allow students and teachers to perform some essential functions of experimental activities and laboratory instruments in a realistic way. Constrained simulations as some of the ones proposed by PhET enable students to acquire data as in a real

Fig. 7. – Two VRLs designed by a member of our group. (A) The measure of Current *vs.* Voltage curve for a LED. (B) The force on a current carrying wire.

experiment. For example our students performed experiments about the Beer law, the selective transmittance [5,6] and the Malus law [36] and then they explored data with a spreadsheet software or employing data analysis and visualization programs. Some examples are shown in fig. 8.

3) *Less Constrained Simulations.* Students designed some virtual experiments. They used both the data provided by the software, and sometimes they acquired and analyzed with Tracker videos of the simulated scenes.

4) *Kitchen labs.* In this approach, which was needed in the early phase of the pandemic to offer hand-on labs at distance, students employed only household equipment. This kind of approach stimulates critical thinking, design skill and creativity. Thus this method is now applied also in ordinary courses as homework given by the instructors, starting from the stimulating items of a multi-choice test. Some examples are shown in fig. 9.

The last two kinds of labs were proposed following POE strategy. Students answered a multi choice test about some topics and then designed, performed and analysed experiments. Starting from their predictions (answers to the items) they built a real model of the physical system (de-idealization), designed the experiment, acquired data and analysed them (they built a phenomenological model). At the end they compared their prediction with the model of data. This very effective strategy is very suitable when students use less constrained simulations and kitchen labs.

5. – Results and conclusions

Different remote laboratory approaches were tested with 35 undergraduate and 50 high school students, and learning materials were created that can support teachers (pre-service and in-service) in a number of activities. All the students performed the same experiments belonging to the various categories of remote lab solutions. At the end of the course students completed a Likert-scale survey to measure their attitudes

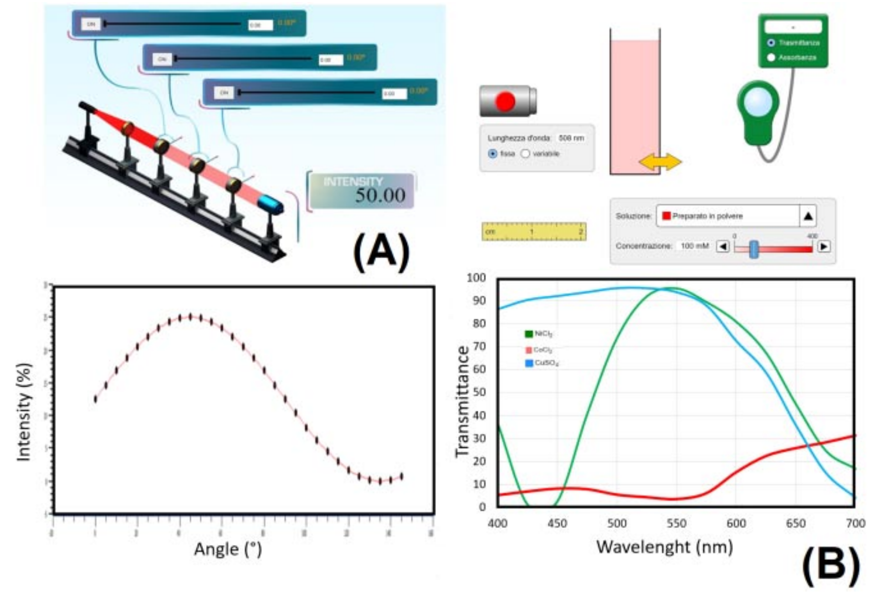


Fig. 8. – Screenshots from constrained simulations used to collect data, with some data analysis performed by students.

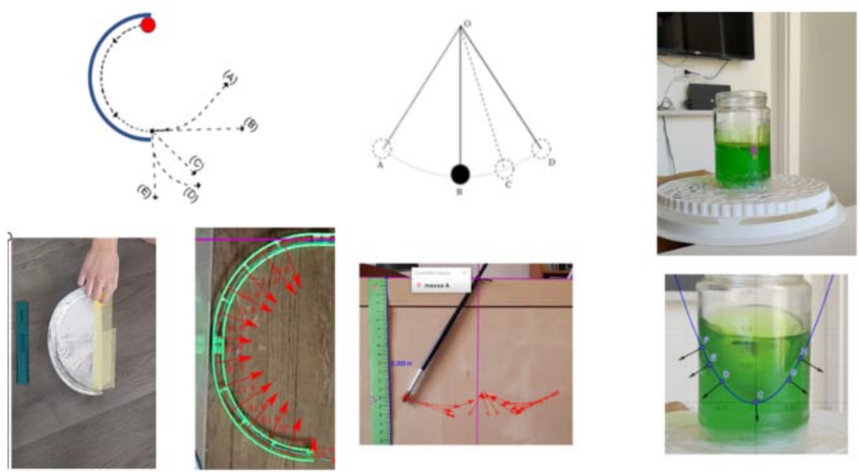


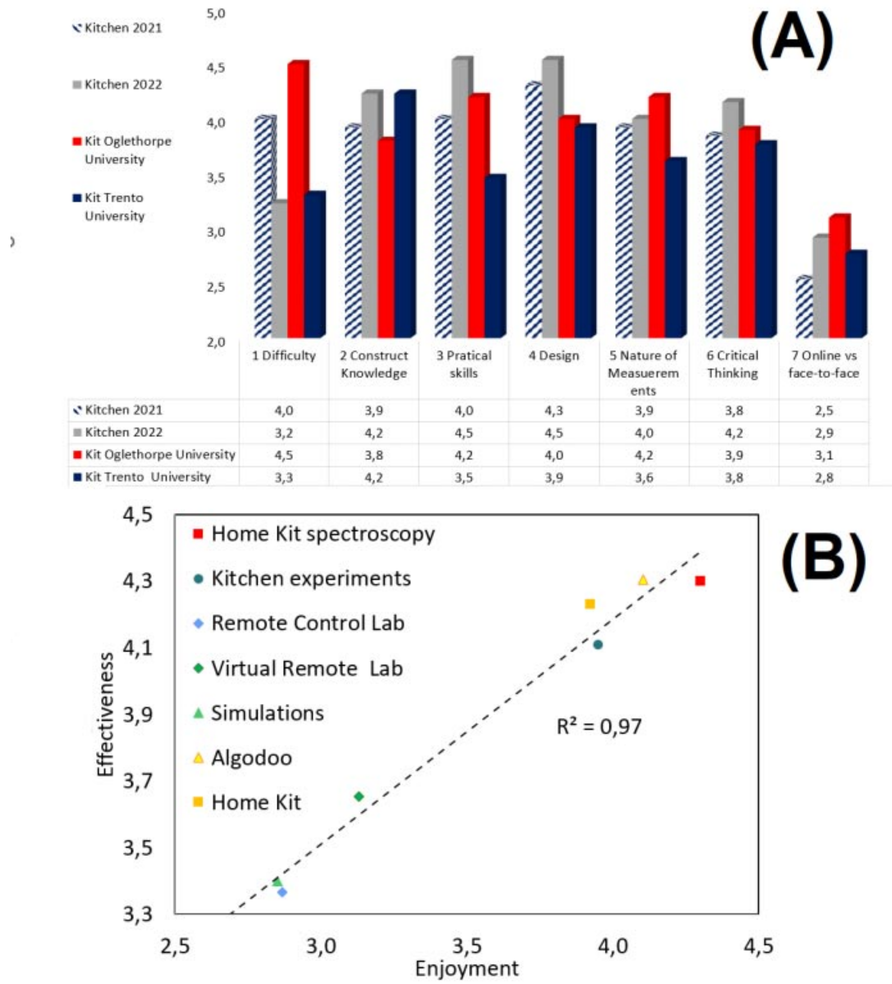
Fig. 9. – Items from multi-choice tests and experimental set-ups designed and built up by students at home to answer the questions.

about the different approaches and what they felt they learned from the experimental activities. Some questions are related to learning objectives, which were the basis for the development of all laboratory activities (see table 1). To evaluate the distance learning laboratories, we analyzed the students' perspective in on understanding the phenomenon of the planned activity (effectiveness), satisfaction during each laboratory activity, and a sense of personal interest during the activities (enjoyment). In this case, we ask stu-

TABLE I. – *End of Course Survey Questions*

Dimensions - Learning Goals	Questions
For the different activities	Rate the experience in terms of effectiveness Rate the experience in terms of enjoinment
1 Difficulty	Having to do the experiments by myself at home was harder than in a group onsite in the lab.
2 Construct knowledge and a deeper understanding of physics via direct experience;	My experiences with the lab kits will help me apply physics concepts to novel situations
3 Develop practical skills in running experiments/trials, problem-solving and trouble-shooting of experiments	As a result of running all experiments by myself, I feel I now have better troubleshooting skills for real-world experiment situations
4 Demonstrate experimental design and analysis of data;	The kit experiments and extensions helped me learn experiment design
5 Understand the nature of scientific measurements (repeatability, uncertainty, bias, and precision);	The kit experiments helped me understand the nature of scientific measurements (repeatability, uncertainty, bias, precision)
6 Develop scientific habits of mind (critical thinking);	The kit experiments allowed me to develop critical thinking for laboratory experiments
7 Effectiveness	I feel that I learned as much through this online experience as I would have in a face-to-face lab.

dents to compare different kinds of activities: home-kit, kitchen lab, remote controlled lab (RCLs) , virtual remote lab (VRLs), remote simulations and less constrained simulations. Figure 10 reports the results obtained. The upper panel reports results from two groups of students: those who used our home kit and those analyzed in ref. [9], who used a different home-kit. In the lower panel of the figure, the averages of effectiveness and enjoyment of different activities are shown. In fact, experiments involving hands-on work with objects and/or tools, done individually or in small groups, scored the highest in all dimensions. Moreover, we can observe a strong correlation between the perceived effectiveness of one activity and the students' enjoyment. Based on the analysis presented in this article, we have a preliminary answer to our main research question: *Can a practical physics laboratory be effectively provided as a remote laboratory?* Overall, we found that, according to the instructors, the final grades and laboratory competencies of the remote laboratory courses were comparable to those of previous traditional on-campus laboratory courses. The results of the student survey show that critical learning goals were met, student satisfaction with the remote lab was maintained, and collaboration was successful through videoconference group rooms. In summary, the students learned the same concepts and to the same extent as in a traditional laboratory and became experienced in their views on experimental physics as in previous years. Moreover we showed that it is possible to redesign learning teaching sequences so that they are implemented remotely, and we used both hands-on experiments available thanks to the home-kit and "virtual resources" (VRLs, RCLs, and simulations). Additionally, we showed how it is possible to realise a VRL starting from experiments with poor materials. Among the different activities and methodologies of the Distance Laboratory students consider more effective the more engaging ones, *i.e.*, the ones which involve active work (as hands on experiments based on the kit) and design (as Algodoo simulations and kitchen experiments). On the contrary, ready made simulations, VRLs and RCLs, even if they can be used



	1 Difficulty	2 Construct Knowledge	3 Pratical skills	4 Design	5 Nature of Measuerements	6 Critical Thinking	7 Online vs face-to-face
Kitchen 2021	4,0	3,9	4,0	4,3	3,9	3,8	2,5
Kitchen 2022	3,2	4,2	4,5	4,5	4,0	4,2	2,9
Kit Oglethorpe University	4,5	3,8	4,2	4,0	4,2	3,9	3,1
Kit Trento University	3,3	4,2	3,5	3,9	3,6	3,8	2,8

Fig. 10. – (A) Average scores of the survey items. (B) Effectiveness versus enjoyment for different activities.

productively as substitutes of real equipment in university laboratories are perceived by students boring and less effective.

* * *

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REFERENCES

[1] Etkina E., Van Heuvelen A., Brookes D. T., and Mills D., *Phys. Teach.*, **40** (2002) 351.
[2] Wieman C. E. and Holmes N. G., *Am. J. Phys.*, **83** (2015) 972.
[3] Wilcox B. R. and Lewandowski H. J., *Phys. Rev. Phys. Educ. Res.*, **13** (2017) 010108.

[4] Fox M. J., Werth A., Hoehn J. R. and Lewandowski H. J., arXiv preprint, arXiv:2007.01271v1.
[5] Perkins K., *Phys. Teach.*, **44** (2006) 18.
[6] Wieman C. E., Adams W. K. and Perkins K. K., *Science*, **322** (2008) 281.
[7] Bodegom E., Jensen E. and Sokoloff D. R., *Phys. Teach.*, **57** (2019) 382.
[8] Leblond L. and Hicks M., *Phys. Teach.*, **59** (2021) 351.
[9] Howard D. and Meier M., *Phys. Teach.*, **59** (2021) 404.
[10] Simonson M., Smaldino S and Zvacek S., *Teaching and Learning at a Distance: Foundations of Distance Education*, 6th edition (Information Age Publishing, Charlotte, NC) 2015, pp. 9–10.
[11] Dormido S., *Rev. Control*, **28** (2004) 115.
[12] Gröber S., Vetter M., Eckert B. and Jodl H.-J., *Eur. J. Phys.*, **2007** (28) S127.
[13] Richtberg S. and Girwidz R., in *Teaching/Learning Physics: Integrating Research into Practice: Proceedings of the GIREP-MPTL 2014 International Conference held in Palermo, Italy, July 7–12, 2014*, edited by Fazio C. and Mineo R. M. S. (Università di Palermo, Palermo) 2015, pp. 697–708.
[14] Euler E., Gregorcic B. and Linder C., *Eur. J. Phys.*, **41** (2020) 045705.
[15] Gregorcic B. and Bodin M., *Phys. Teach.*, **55** (2017) 25.
[16] Lyall R. and Patti A. F., in *Accessible Elements: Teaching Science Online and at a Distance*, edited by Kennepohl D. and Shaw L. (Athabasca University, Edmonton), 2010 pp. 83–108.
[17] Schultz M., Callahan D. L. and Miltiadous A., *J. Chem. Educ*, **97** (2020) 2678.
[18] Caprara C., Rosi T., Tufino E., Ambrosini V., Toffaletti S. and Onorato P., *Nuovo Cimento C*, **45** (2022) 1.
[19] Phyphox, `https://phyphox.org/`.
[20] Physics Toolbox Sensor Suite, `https://play.google.com/store/apps/details?id=com.chrystianvieyra.physicstoolboxsuite&hl=it&gl=US`.
[21] Androsensor, `https://play.google.com/store/apps/details?id=com.fivasim.androsensor&hl=it&gl=US`.
[22] Brown D. and Cox A. J., *Phys. Teach.*, **47** (2009) 145.
[23] Holmes N. G. and Wieman C. E., *Phys. Today*, **71** (2018) 38.
[24] Benjamin M., Zwickl N. F. and Lewandowski H. J., *Am. J. Phys.*, **81** (2013) 63.
[25] Onorato P., Rosi T., Tufino E., Caprara C. and Malgieri M., *Eur. J. Phys.*, **42** (2021) 045103.
[26] Onorato P, Gratton L. M., Di Mauro M. and Rosi T., *Phys. Educ.*, **57** (2022) 063003.
[27] De Ambrosis A., Malgieri M. and Onorato P., *G. Fis.*, **58** (2017) 281.
[28] Indelicato V., La Rocca P., Riggi F., Santagati G. and Zappala G., *Eur. J. Phys*, **34** (2013) 819.
[29] Toffaletti S., Di Mauro M., Rosi T., Malgieri M., Onorato P., *Educ. Sci.*, **12** (2022) 759.
[30] Karam R., Kneubil F. B. and Robilotta M. R., *Eur. J. Phys.*, **38** (2017) 055201.
[31] Onorato P. and De Ambrosis A., *Eur. J. Phys.*, **33** (2012) 1721.
[32] Onorato P. and De Ambrosis A., *Phys. Educ.*, **48** (2013) 766.
[33] Remote Lab, `http://remote-lab.fyzika.net/experiment/07/experiment-7.php?lng=en`.
[34] Remote Lab - Photoelectric effect, `https://www.ises.info/index.php/en/laboratory/experiment/photoelectric-effect-VA`.
[35] Pfaender J., Gratton L. M., Rosi T., Onorato P. and M. Malgieri, *Phys. Teach.*, **60** (2022) 220.
[36] Polarization of light: Malus' law, `https://www.uv.es/indoptic/applets/Malus/index.html`.