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Smartphysicslab: a creative Physics Laboratory using Arduino and smartphones

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Abstract. We address aspects of innovation in the practice of experimental physics that are made possible thanks to the availability of ubiquitous and/or cheap digital technologies having the potential to improve the experience and learning outcomes throughout the physics curriculum. The ongoing pandemic poses specific challenges on the traditional approach to laboratory teaching in large labs. The innovation described here, developed independently by us over many years, aims to help maintain or even improve the development of experimental skills also in this new context. We present an analysis of the current situation and describe our proposal with a call for action, centering on the development of an open and bottom-up "Smart Physics Lab" community for the sharing of resources and good practice.

1. The need for innovation

The need for an engaging teaching programme is acute on the experimental side of physics which needs to stay in touch with technologies, areas of current research and frontier problems [1].

Traditionally, in colleges and universities, practicals have been conducted in relatively large laboratories where groups of students work on the same experiment, following a detailed set of steps provided by instructors, using dedicated equipment. The main aim of these experiment is usually the measurement of some physical quantity, for example, the gravitational acceleration g, the time constant of an RC circuit or the specific heat of a substance. Little space is left for creativity, or for the design of the experiment itself. The methods to obtain the "result" are fixed by the instructors. Often, the setup is prepared in advance and students are responsible only for taking and analysing data. Experiments are typically designed to follow closely lectured material and reinforce it, thus linking experiments necessarily to 'old' physics and often to equipment that resembles the original discovery and is then out of date, if not from the technological point of view, in terms of the ways in which the experiment would be conducted in a research setting.

Traditional practice in laboratories for students thus differs significantly from the way in which physics is done in research laboratories: sure, also in research we test current theories setting up experiments aiming at the measurement of physical quantities predicted by them, but experiments that *disagree* with theory, rather than giving expected answers, can be considered "successful". Theories are then developed (or improved) starting from such new experimental results. Such a process is completely hidden in traditional practicals, where the aim is to "confirm" the expectations of a theory, and not to provide guidance for the development of it.

In schools, the situation is often even worse [2]. At least in the experience of authors, many schools do not have a dedicated physics laboratory or, if so, it is poorly equipped; in several cases, there is no technical staff to support teachers in setting up and conducting experiments. Even when the school is well equipped, experiments are usually conducted by a teacher or a technician: pupils merely observe what happens during its conduction.

Most of the above considerations are shared by the physics educators, indeed, not only as a common perception, but as the result of formal investigations made by the community of physics education. However, the great effort of such a community has not yet had a wide impact in either school or university physics student laboratories, with only few exceptions [3]. There are many reasons for that, some very meaningful, but, as a matter of fact, the opportunity to innovate in the practice of laboratory has not changed since the beginning of the XX Century.

Recently, an unprecedented ‘democratisation’ of experimental science has been enabled by communities of ‘makers’, spontaneously formed, that have a great potential of innovation in science and technology, facilitated by the availability of cheap digital technologies that allow people with limited knowledge to design and build complex projects, leading to an increase in curiosity and fostering further learning.

We think it is the right time to bring elements of this into the physics curriculum, leveraging on these communities and the availability of new technologies, bridging the gap between traditional physics laboratories in education and common practice in state-of-the-art physics experiments. For the latter, many new competences and abilities are required: coding, data management, electronics, manufacturing, etc. Traditionally, in a science or technology higher education degree these competencies would be acquired in dedicated courses that, however, are often unrelated to laboratory practice that remains traditional in its core, even when new technologies are adopted. We argue that a more joined up practical teaching will have significant pedagogical advantages [1].

Finally, the COVID-19 pandemic has led to several months of lock-down and social distancing requirements, leading much of the educational activity to switch to remote online. Laboratories have, in most cases, simply been cancelled. Rather than being an insurmountable obstacle, this could be an opportunity for instructors to try out some of the innovation that one would want to introduce anyway. If done well, this effort would lead to a different and hopefully better teaching experience than the practicals in current forms.

In this paper, we propose to exploit modern, digital tools to help students become physicists, i.e., not just learning the history and grasping the background to successful branches of physics, but also developing the ability to use a working set of tools that will allow them to contribute to real world problems (be they in academia or business, curiosity or application driven) in the unique way that physicists have done over the last 150 years.

These tools will promote the ability of abstracting information to form a conceptual model of mechanism; the ability to calculate (analytical or numerical) and the ability to measure phenomena. This applies not only to high school, where measuring will spark curiosity and give a sense of empowering, but also to university courses, where we need to show data as affected by uncertainty, and data collection presenting challenges that can be overcome by creativity.

In our model, learning to use digital tools is not an end in itself, but the means by which one can truly understand the meaning of physics as the science that starts from experimental observations, albeit affected by uncertainties, to build a knowledge as complete as possible of the mechanisms that underlie the functioning of the Universe.

2. Enabling technologies

Innovative, open and stimulating experiments can be designed out of a variety of materials and tools. We focus here on a set of experiments where digital data can be readily obtained, and we have identified at least two modern technologies with a great potential for the innovation of laboratory practice in physics education: smartphones and Arduino.

2.1. Smartphone physics

Smartphones come laden with a significant computing power and a large number of sensors. They all have at least a microphone, a speaker, a camera and an accelerometer. Many hold a GPS receiver, magnetic field and pressure sensors, as well as gyroscopes. These sensors can be exploited as measuring devices, their precision and accuracy being, in many cases, compatible with those of dedicated professional instruments used in students' laboratories. Few Apps have been developed for that. In particular, PHYPHOX [4] is an award winning App that has been specifically designed to carry out physics experiments by a team in RWTH Aachen.

The App automatically detects the available sensors and provide raw data extracted from them, as well as preprocessed ones in few, selected, experiments. Raw data are plotted during data acquisition directly on the phone's display, and can be exported in a variety of formats for offline analysis. Sampling rates depend on the hardware, however, they are usually much higher than that which can be obtained with any manual instrument and comparable with that of commonly adopted computer assisted measuring devices. PHYPHOX includes functions for easily launching a scheduled run and to control the experiment remotely, by means of an embedded server that transmit data over the Internet. Remotely accessing the device is as simple as using a common web browser.

Smartphones, indeed, are not particularly cheap. However, if they are bought for other purposes then they can be effectively considered as a free measuring device. In an Italian setting, 100% of students owned at least one smartphone, according to the results of a questionnaire that one of us administered during the past three years running a course on computing and programming.

Smartphones in physics laboratories can effectively substitute many devices and allow to design and setup precise and accurate experiments in many fields [5]. Given the type of sensors commonly present in these devices, most of the experiments that can be done using them are in the domain of mechanics for systems that can either be treated as point-like particles or rigid bodies, as well as in the domain of wave mechanics, by exploiting the microphone and the loudspeaker as sound waves detector and generator. Many smartphones are equipped with a magnetometer, too, that can be exploited for many experiments in the field of electromagnetism. The camera, and, similarly, experiments based on webcams, would deserve a review paper by itself, as we think video based projects are generally more advanced in terms of the data processing required.

A great advantage of such a tool is that it can be used in an extremely creative fashion. A recent challenge, for example, came up with 61 ways to measure length with a smartphone [6]. There are, moreover, mature examples that could inspire several experiments that can be done even at home or, in any case, using commonly available equipment. The sensitivity and the accuracy of smartphone sensors are often competitive with respect to ordinary dedicated laboratory instruments and, where they are not, they provide an invaluable mean to explore the domain of systematic uncertainties and to investigate the degree of approximation between a model and a real system. The general availability of the devices also opens up unprecedented opportunities for "citizen science" and crowdsourcing data.

2.2. Arduino physics and automatic data acquisition and filtering

Arduino [7] is a family of open source microcontroller boards which has become very popular in small projects. Thanks to its low cost and a friendly programming language, Arduino provides a very easy introduction to digital electronics, data acquisition, automation, mechanical and instrument control. It is possible to introduce Arduino starting from high school to replace or augment many of the traditional experiments or to make new ones that might be closer to current research interests, and in so doing providing some coding skills at the same time.

In our view, exposure and a certain familiarity with this technology is appropriate and desirable for everyone in a scientific track and, in particular, for physicists and engineers, and represents in itself an enabling and transferable skill. Besides promoting the acquisition of abilities in the domain of basic electronics and coding, its open nature fosters the development of soft skills such as the ability to search for information over the Internet, as well as communication abilities.

Arduino can be regarded as complementary to smartphones. The latter allow for an easy and fast execution of experiments, while Arduino require some preparation. While PHYPHOX shields students from the problems connected to data acquisition, Arduino necessarily involves them in this phase, letting them experience the related problems and the solutions that can be exploited.

Moreover, Arduino allows for experiments in domains for which smartphones cannot be employed. Arduino comes with a set of analog inputs connected to a 10-bits ADC, allowing the digitisation of electrical signals of up to 5V. It then allows for many experiments in the domain of electricity. The availability of a plethora of sensors that can be easily interfaced with Arduino allows for the measurement of a variety of physical quantities such as temperature, pressure, magnetic fields, etc.

With Arduino one can setup complex, yet simple and affordable, experiments allowing for the precise determination of quantities that often require expensive or uncommon devices to be obtained with traditional methods. As an example, observing the charge and discharge of a capacitor in an RC circuit either requires large capacitors and resistors, if conducted with common multimeters, to obtain large enough time constants, or the availability of tools like oscilloscopes to observe fast signals. The same experiment can be quantitatively made [8] with extremely common components: a 4.7 μF capacitor and a few kΩ resistor are enough to observe a clear exponential growth or decay, just connecting the leads of the capacitor to the Arduino's analog input. Similarly, observing the emf that develops in an experiment on electromagnetic induction requires a sensitive galvanometer and a coil with thousands of turns. Arduino allows to spot the signal generated by a common magnet sliding along an incline and passing through just few tens of turns of conducting wire.

2.3. Limitations of the proposed approach

As any other approach, even those proposed above have their own limitations and drawbacks. Smartphones, for example, can be used almost as "black boxes". One should trust the values read by the various sensors without any possibility of controlling data acquisition. In most cases, even the technology adopted by the sensors is hidden. For example, a spring dynamometer used as an accelerometer clearly shows how it works. On the other hand, using a dynamometer, it is quite difficult to spot the effect (at least, the free fall of a dynamometer should be filmed to appreciate its elongation due to the absence of the gravitational acceleration in its reference frame). Moreover, smartphones are relatively fragile and precious, and, often, it is not worth to endanger their integrity to perform a physics experiment. Also, their form factor does not always fit with the needs of the experiment.

Some of the above drawbacks can be overcome using Arduino. As stated above, it requires some extra knowledge to be acquired. As a matter of fact, it requires some extra training and learning, detracting from the time devoted to traditional teaching. Moreover, boards and sensors are not usually built for being very robust and the chance to break them while manipulating them can be appreciable. Fortunately, the cost for replacing broken hardware is affordable.

3. The proposed road map for Smartphysicslab

Given the above consideration, we independently started, together with many other colleagues around the world, experimenting with the above mentioned devices, to design meaningful experiments. We realised that some of these experiments proved to be useful during the pandemic, as they allowed students to remain engaged with practicals even in those months when laboratories had to be closed. As a matter of fact, initially skeptical colleagues turned out to appreciate the results. In certain cases, we were told that students' reports were even of better quality with respect to those to which they were used. This way of conducting practicals will continue to be tested in the current year.

Encouraged by these initial steps, we identified the need for a good coordination and sharing of efforts across like-minded people. We have started preparing an IT infrastructure to help ease the transition from old fashioned laboratory activity to a new, digitally equipped, one. It comprises a domain (www.smartphysicslab.org) which hosts a detailed description of our aims; invitation to take part, project templates; a collection of both well-defined and more "open" projects. We have also created a corollary set of tools in Slack and Google Groups to allow the participants to develop into a community, to post questions and comments, and provide support to newcomers.

The aim of such a project is to bring together a number of educators from all over the world to discuss new ideas and, at the same time, support those who want to start working using these tools. In the long term, we aim at maintaining the level of the experiments aligned with research projects, continuously providing new ideas and resources to exploit state-of-the-art technologies, leading to a modernisation of laboratory practice in schools, colleges and universities.

With this paper we call for collaboration and to converge interest into such a portal to share best practice, stimulate ideas, and discuss materials efficiently.

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