Teaching and Learning Physics with Smartphones

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Abstract

The use of mobile technologies is reshaping how we teach and learn. In this paper we describe our research on the use of these technologies to teach physics. On the one hand we develop mobile applications to complement the traditional learning and to help students learn anytime and anywhere. The use of this applications has proved to have very positive influence on the students engagement. On the other hand, we use smartphones as measurement devices in physics experiments. This opens the possibility of designing and developing low cost laboratories where expensive material can be substituted by smartphones. The smartphones' sensors are reliable and accurate enough to permit good measurements. However, as it's shown with some examples, here special care must be taken if one doesn't know how these apps used to access the sensors' data are programmed.

Keywords

mLearning, teaching/learning strategies, mobile applications, low cost laboratories, engagement, lifelong learning, physics

Introduction

The last forty years have shown an increasing association between technology and education. One consequence of this linking is that the inclusion of technological elements in everyday learning activities has grown with an increasing pace, parallel to that of the improvement in technology capabilities and availability. While in the seventies or first eighties the necessary technological resources were available only for a limited number of institutions and students, nowadays there is a nearly worldwide access to a much capable and Internet connected technology. As a consequence, along these last years the use of computers in education has dramatically evolved following the change in computers capabilities and their availability from schools to universities. Moreover, the worldwide spread of wireless technologies has produced a shifting from computer-assisted learning to web-based learning to mobile learning (Vavoula and Karagiannidis, 2005). The ease of access to telecommunication technologies, as well as the, more or less, affordable cost of mobile personal devices and communication connections has had as a consequence the rise of the so-called mobile learning (mLearning) (Caudill, 2007; de Castro, 2014; Keegan, 2002, Prieto, Migueláñez and García-Peñalvo, 2014b), that together with the MOOCs (massive open online courses) (Kellogg, 2013; Mackness, Mak & Williams, 2010) has risen the aim of a personalized, nearly ubiquitous and permanent learning for the new educational demands. All these circumstances also ease the evolution of learning towards conditions in which the students contribute actively to the design of their own virtual learning environment for the new educational demands where schools or universities were no longer the only center of information (Molnar 1997). Furthermore, the interest of students in mobile technologies as well as their expertise using those devices can be used as a powerful tool to reinforce their interest in learning and to ease their access to learning resources.

There is a general agreement that mLearning facilitates the access to education but, besides, some characteristics of mLearning can contribute to change the way in which we teach or learn. An important feature of mLearning is that one of its goals, different from those of a traditional transfer of knowledge from teacher to student, is to empower students to actively participate in the construction of their own learning (de la Pena-Bandalaria, 2007). Also, mLearning can facilitate designs of real learning by targeting problems of interest to the learner (Traxler, 2007), as well as ease lifelong learning by supporting learning that occurs during the many activities of everyday life (Sharples, Taylor and Vavoula, 2005). About the inclusion of mLearning within a formal learning environments, teacher involvement occupies a fundamental position as has been analyzed in recent works (Prieto, Migueláñez and García-Peñalvo, 2014b). Concerning physics learning, mobile devices are not only mere intermediate tools between the learner and the teacher or the available contents. Smartphones can also be used for learning physics by allowing the students to do experiments using the smartphones' sensors as measurement devices. In this way the students can play a really active role in their own learning.

Different works have explored the use of mobile technologies in the learning environment. Some of these works analyze the framework and effectiveness of mLearning while others propose activities based on mobile technology to improve the teaching. Within the first group, Liu *et al.* (Liu, Wang, Chan, Ko & Yang, 2003) propose that the integration of mobile devices in the classroom can make them a way to attract students to learning, ease their communication and collaboration and even follow their advances by the teacher, being the benefits of class computers enhanced in the highly interactive classroom (Wang, Liang, Liu, Ko, & Chan, 2001). A different case is the work by *Gay* et al. (Gay, Stefanone, Grace-Martin & Hembrooke, 2001) who studied the change of student's computing behavior when using wireless computing in a collaborative learning environment. Their results showed a trend that has increased with the use of mobile technologies and that may be a turning point in the evolution of learning technologies: wireless technologies facilitate social relationships that can potentially transform the learning community, blurring the boundaries between where and when collaborative work can take place. Another works exploring and encouraging the interactivity between students using mobile devices are described in (Markett, Sánchez, Weber & Tangney, 2006; Scornavacca, Huff, & Marshall, 2009). In those works improved learning environment in the classroom, increased student engagement and participation and improved teacher awareness of student difficulties were facilitated by using short message service (SMS), which nowadays could be done more easily using instant messaging apps. A possible limitation of these works observed in (Markett et al., 2006; Cavus & Ibrahim, 2009) was the cost associated with the use of mobiles in learning. This is an issue that would also affect the use of learning applications, so that the influence of the communications costs, between students or with the teacher, is an interesting point of study if mLearning is considered as a tool to extend education to less favored environments.

Another problem that appears when developing or using mobile apps in the classroom is the diversity of mobile devices. As pointed out in (Gedik, Hanci-Karademirci, Kursun, & Cagiltay, 2012), “when learners' own phones are used, the minimal technical conditions need to be coordinated with the most effective pedagogical approach”. Then, the demands (memory, graphics, calculations, etc.) of the mobile applications that are going to be used or developed must be parameters carefully considered in the implementation of learning applications. Correspondingly the students' experience on these factors must be surveyed not only to improve future developments, but, more important, also to investigate the influence of those characteristics in the students' interest on using the applications, as well as on their learning results.

A second point of interest in the development of mobile apps for learning is how their contents are organized. The granularity of the content delivered within the mobile applications, so that they can be productively used even in short periods of time, has been studied in several works as in (Holzinger, Nischelwitzer, & Meisenberger, 2005; Motiwalla, 2007) and according to their conclusions “... the power of m-learning technology can be leveraged by complementing the existing courses with value-added features …. that help users to convert their dead-time to productive activity”.

As mentioned above, a second interesting use of smartphones for learning is using them to experiment and learn out of the classrooms. In (Chen, Kao & Sheu, 2003) a mobile (Personal Digital Assistant) system for bird watching learning is described. In this work, quite before the smartphone age, mobile devices support an outdoor activity and the benefits of the use of mobile devices were evaluated comparing the learning results of those using the PDAs with the results of a control group who used a guidebook in a more traditional way. Based on that comparison, the authors concluded that the children using the PDA system improved their learning above the expected. This is an example of how smartphones can take learning to everyday activities. In the case of physics, smartphones have the advantage of their powerful electronics and built-in sensors, as the accelerometer, gyroscope, magnetic sensor or light detector, that allow their owners to use them as measurement devices to experiment and learn. Then, physics teachers can also take advantage of this second characteristic in order to improve students' learning by designing low-cost real experiments with the smartphones. Then, students and teachers will be able to use the smartphones as measurement devices both in learning laboratories and in many other activities, where the students can apply the contents learned in the classroom (Falcão, Gomes, Pereira, Coelho & Santos, 2009; Vogt, Kuhn & Müller, 2011). This is a second aspect of our work: to teach the students how they can use their smartphones in everyday activities, as for example in an amusement park (Cabeza, Rubido, & Martí, 2014; Vieyra & Vieyra, 2014), in the playground (Monteiro, Cabeza, Marti, Vogt, & Kuhn, 2014) or in an elevator ride (González et al. 2014) to learn physics.

In this paper we describe our work with mobile devices to teach physics along two complementary lines. First, the development of mobile applications and their implementation within a learning environment. This will be described in section “Development of learning apps”. Second, the use of smartphones' sensors as measurement devices in physics experiments and their use in teaching labs and in everyday activities outside the laboratory. This line will be described in section “Using smartphones as measurement devices”.

Development of learning apps

The main interest of this part of our work is to design a mLearning framework that can be used to complement formal learning and also to provide pieces of information for independent learners. In order to ease the access to small pieces of learning, the framework will be based upon independent applications. Each of these applications will deal with different concepts or contents but, as a whole, they will form a body of contents similar to a formal learning course. As the development of quality educational material is a hard work, we pretend that this framework will be based on applications developed by different authors that share their work. This shared applications will be available to all the teachers using the framework, so that they will be able to choose between the available applications in the framework those that fit best to the contents of his/her course. Furthermore, the teachers using the framework will also be able to establish the temporal path for the applications that the students should follow along the course. The applications within the framework will also be available to independent informal learners who aren't enrolled in any course. These independent learners will be able to use the full applications except for the parts concerning the communication with the teachers.

The use of independent applications on specific concepts is justified both for formal an informal learners. On the one hand, the use of mobile devices in short periods of time recommends designing the applications so that they supply the learners with small pieces of information. This allows the students to stop the learning with the mobile in a given time and re-start it easily anytime later (Holzinger, Nischelwitzer, & Meisenberger, 2005). Besides, due to their technical characteristics, mobile devices aren't able to run software tools as complex and complete as those developed for desktop computers, so that it is advisable to divide a subject into different independent parts (Holzinger, Nischelwitzer, & Meisenberger, 2005). On the other hand, for informal learners, we must also remember that, when they want to learn on a specific concept, they will not use a tool designed to teach on the complete body of matter. Instead, they would prefer to use smaller knowledge pills concerning only the knowledge and skills that will be useful to him/her (Tough, 1979). For these reasons, the availability of specific applications, that can be consulted anywhere and anytime, dealing with acquiring a particular competence will be more useful than the use of more complete resources. On the other hand, for the learners following specific courses, the teachers should be able to evaluate the student's work with the applications, so that both, the independent applications and the global framework must include tools for the assessment of the student's work.

Figure 1

With these requirements in mind, the system structure is modeled following the diagram shown in Figure 1. As can be seen in that figure, a server stores the applications shared by different developers. Teachers decide which of those applications are interesting for their courses and propose them to their students, who download them into their smartphones when necessary. In order to reduce the cost of data transfer, this downloading can be performed whenever a wireless connection is available. Once each application is installed the whole contents are stored in the smartphone, and none other connection will be necessary until sending the students' results to the server. That is, the applications allow the students to work without needing a permanent data connection or an access to the server. This permits each student to work at his/her own pace, review the contents of related applications, do the tests as he/she learns, etc., which is an important aspect in the design of mLearning environments (Gedik, Hanci-Karademirci, Kursun, & Cagiltay, 2012). As can be seen in the diagram in Figure 1, different courses can share applications (for example the courses followed by students 1 and 2 in the figure), which optimizes the work of developing the learning materials. Also, in our model of the framework, any student (for example student 3 in the figure) can download and use any other application not included in his course, in order to complement and improve his/her learning, defining his/her own virtual learning environment.

Figure 2

Each application within the framework will have different contents but a basic structure is depicted in Figure 2 with the example of an application on direct current. The first part of each application consists on different theoretical contents, including definitions, formulas, examples or solved problems. After this passive elements, self-evaluation tests would allow the student to check his/her knowledge. These tests will also allow the teacher to know the advance of each student or even his/her learning difficulties. Finally, a simulation or a graphical calculation, in this case to help learning how to solve direct current circuits, will allow the students to “put their hands” on the studied phenomenon and learn actively.

As can be seen in Figure 2, the work done by the student using the application is evaluated considering whether the student has read the theoretical contents or not, the results obtained in the tests, and the use and results obtained in the simulations. The applications store the student results and only if the student is following a course and authenticates successfully with the server those results are sent to the server. As before, in order to reduce data transfer costs, the data sending can be postponed until the smartphone/tablet is using a wireless connection. This part of the process is also depicted in Figure 1, where student 1 sends the results to the server that stores them in the corresponding course database. As each teacher can grade differently the work with a given application, the applications send the assessment of the students work to the server as a normalized value (together with a more detailed description of the work done by the student in the different parts of the application, just in case the teacher wants to check it). This normalized value only depends on the application and is independent of the course followed by the student. Thus, as each application can be used in different courses, the teachers can weight differently the work done using each application, depending on the interest of its contents for a specific course. Figures 3 and 4 shows some screenshots of two applications developed within this work. Figure 3 shows two screenshots of an application on DC current and on solving simple DC circuits while Figure 4 shows two screenshots of an application developed to teach how to calculate the impedance in an AC circuit.

Figure 3

Figure 4

Considering the currently developed applications we have done a preliminary study on the students' interest on the work with those applications, and on the influence of that work on the students grades and engagement. The interest of the students have been analyzed qualitatively by doing a survey to obtain a feedback from the students that have used some of the developed applications. Also, at the end of the term a quantitative study of the effects of using the experimental platform on the students grades and engagement was performed. For the survey, a set of questions on different aspects of the applications were considered. The use of a survey (usually as Likert-like questionnaires) as a primary research method is a usual technique in most studies of mobile learning (Wu, Wu, Chen, Kao, Lin & Huang; 2012). The questions used in the survey ranged from technical or usability aspects of the applications to others connected with the learning process, in a similar way as was also done in (Georgieva, Smrikarov & Georgiev 2011). The questionnaire, with a Likert 5-point scale format (with “strongly agree” as 4, “neutral” as 2 and “strongly disagree” as 0 on the Likert scale), consisted of 23 questions divided into four categories: technical design of the applications, didactic efficiency, cost effectiveness and general conclusions on the student's experience with the applications and with mLearning. The survey was open along the term, so that students could download and test the applications as they study the concepts described in them, and then answer to the questionnaire (only once) after working with them.

For the questions of the survey dealing with the didactic effectiveness of the applications we obtained, in general, very positive results. For example to the question “*The application offers tools that support learning*” we obtained approximately a 3.5 result in our Likert scale. From this result, it is clear that students appreciate the use of these applications as a good method for helping them learning. This result is also reinforced by the average values answers to the questions ”*The application stimulates curiosity and learning*” and ”*The use of the application is interesting and amusing*”, with values 3.03 and 2.85, respectively. These results show that students consider that these mobile applications stimulate learning and that the work with them is interesting for them. These are also important factors to enhance the students engagement and autonomous work, which were two of the aims of the development of this platform. Another interesting result is that students consider as very positive the inclusion in these apps of communication tools to ask questions or discuss concepts with the teacher or other students. This is not surprising because both types of interactions, with the teacher or with other students, are important for improving learning (Vavoula and Karagiannidis; 2005) and mobile devices can represent a good tool to allow it anytime and anywhere (Motiwalla; 2007). Concerning the costs associated with mLearning, the students considered that its cost was affordable (3.03 in the Likert scale) and that what they can learn using the mobile applications compensates the associated expenses (2.95 in the Likert scale). Finally, a set of questions dealt with the students experience on the use of the developed applications and with mLearning in general. The more interesting result is that a majority of students see mLearning as a very positive experience as they would recommend it (average value of 3.3 in our Likert scale) or use again this type of applications (average result 3.2). It was also interesting to see their positive opinion on mLearning, as they considered that it facilitates learning (average value 3.5). More details on the results of this survey can be seen elsewhere (*Reference not detailed for anonymity reasons*).

We also analyzed the influence of the work with these applications on the students interest on the subject and on their engagement. This quantitative measurement was done analyzing the participation of all the students in the final exam and in the proposed activities related to the contents of the developed apps. The results of this analysis show that the students who used the applications were more engaged with the subject and participated more in the course activities, being their percentages of participation higher than those corresponding to the students who didn't use the applications (around 20% in average for the course activities and around a 23% for the participation in the final exam).

Using smartphones as measurement devices

Smartphones can also be used as experimental measurement devices to teach/learn physics. This can be done by using their variety of sensors either via applications available in the app stores or by using *ad hoc* implemented applications. The use of smartphones as measurement devices permits to have less expensive laboratories (i.e. low-cost laboratories) by replacing some expensive data acquisition devices (mostly designed for a unique task) by the more versatile smartphones. Furthermore, as teachers we would probably want our students to think and work on our subjects beyond the teaching hours and even outside the classroom. As physics teachers we are lucky because the students can learn physics by the simple observation of the world around them. We must only provide them with tools that can be used not only to observe, but also to measure so that they can make a more critical thinking to contrast or reassure their knowledge of physics. Currently most of our students have smartphones that can be used with that aim.

Many recent works have shown the utility of free applications that access the smartphones sensors to record measurements of physical quantities in several fields of physics, as mechanics (Briggle, 2013; Castro-Palacio, Velázquez-Abad, Giménez & Monsoriu, 2013; Gómez-Tejedor, Castro-Palacio & Monsoriu, 2014; Hochberg, Gröber, Kuhn & Müller, 2014; Shakur & Sinatra, 2013; Vogt, P. &Kuhn, 2014), acoustics (Kuhn & Vogt, 2013; Kuhn & Vogt, 2014; Parolin, & Pezzi, 2013), electricity (Forinash, & Wisman, 2012) magnetism (Silva, 2012) or optics (Sitar, 2012; Thoms, Colicchia & Girwidz, 2013; Yu, Tan & Cunningham, 2014). As examples of how smartphones can be used to do physics measurements Figures 5 and 6 show the results of two different fundamental physics experiments performed with smartphones. Figure 5 shows the acceleration results obtained placing the smartphone in an oscillating physical pendulum. The smartphone was placed with its Y-axis along the pendulum axis. Then Figure 5 shows the variation of the Y component of the acceleration along time as the pendulum oscillates. Clearly from those results the students can obtain easily, either by a proper fit or by a search of the best harmonic fitting function, the frequency of the oscillation. In the inset of this figure we see the three components of the acceleration, showing the typical noise of the start and stop of the pendulum. In order to have better results the fitting was done selecting a central part of the measurement so that the transitory movement due to a not very careful start of the pendulum have already vanished.

Figure 5

Figure 6 shows results of an experiment with two bodies connected using a not stretchable string via pulley. One of the bodies, of mass m_1, hangs vertically and falls due to the gravity when left free, while the other, of mass m_2, stays on an horizontal air track. This second body includes a cart holding one smartphone to do measurements of the movement. When the first body falls, it pulls the second body that moves without friction with an accelerated motion. With the smartphone on this second body the students can measure the acceleration of the movement and compare it with the theoretical result that they know $a=\left[m_1/\left(m_1+m_2\right)\right]g$. In the experiment shown in Figure 6, the masses of the bodies were m_1= 29.99 g and m_2=318.76 g, so that the theoretical value of the acceleration obtained with the expression given above is 0.843 m/s^2, which, as can be seen in Figure 6, agrees well with the experimental results that can be obtained using the smartphone. The inset in Figure 6 shows the three components of the acceleration recorded by the smartphone. The students can see from it that there is only acceleration along the direction of the string pulling the body, while the other two components of the acceleration remain constant (within the experimental noise). Another important result that the students can observe in that figure is that once the first body reaches the floor the acceleration of the second body cancels, though the second body can continue moving along the frictionless air track. This can help the students to understand how one body can move (along straight lines with constant speed) when there is no force acting on them. In fact this is a source of usual misunderstandings of many students who associate movement with forces and accelerations and that, in this way, can be confronted easily with their own observations.

Figure 6

The accuracy of all the measurements described in these works rely in two points. On the one hand, the quality of the hardware used in them, that is the sensors and electronics of the smartphones used. On the other hand, the software, that is, the application, used to retrieve the data recorded by the smartphone. While the quality of the hardware can be assessed from the technical manuals of the device, many times it's more difficult to know the quality of the software, as these applications behave like black boxes that give results without a description of the libraries or algorithms used to obtain those results. Furthermore, most of these applications don't allow any kind of calibration either, so that their results are hardware dependent, what can be confusing or produce misunderstandings in the students. For example, if we use the app Accelerometer Monitor (https://play.google.com/store/apps/details?id=com.lul.accelerometer) to measure the value of the gravity acceleration in the same point using two medium or high quality devices of the same brand, as the Samsung S3 mini and the Samsung S4 we obtain g= 9.6 m/s^2 and g=10.2 m/s^2, respectively. That is, a difference of nearly a 6% for a direct measurement obtained with the same application by placing the two smartphones on a horizontal table without any other additional requirement. We can also find in other apps other errors that can confuse the students when doing this same simple measurements. For example other apps lack a correct representation of the results, giving values without expressing their units, as in Sensor Box for Android (https://play.google.com/store/apps/details?id=imoblife.androidsensorbox) or giving them in units of 'g' as in Physics Toolbox Accelerometer (https://play.google.com/store/apps/details?id=com.chrystianvieyra.android.physicstoolboxaccelerometer) but without specifying what is the value of 'g' that is used as reference. These are some examples on simple details that can appear when using these applications for teaching or learning. However, as we'll see now, other problems can be harder to detect and affect negatively the students learning.

Figure 7

As an example of one of these problems we show here measurements obtained using one application (Acceleromenter Monitor) but with different options selected. In this experiment we studied collisions between two bodies on an air track so that they were moving frictionless. For this experiment we have used the two smartphones mentioned above, a Samsung S4, with a STMicroelectronics K330 accelerometer sensor, with a range of ±19.6133 m/s^2 and a resolution of 5.985504 10^{-4} m/s^2, and a Samsung S3 mini, with a MPU-6050 accelerometer, with a range ±39.24 m/s^2 and a resolution of 0.15328126 m/s^2. Both smartphones were placed on carts that slide without friction on the air track with their accelerometer Y-axis along the direction of the air track, as can be seen in Figure 7. This arrangement allows the students to analyze elastic and inelastic collisions, by replacing the two pieces indicated with arrows in Figure 7 by a needle that stuck both carts together after the collision. By using this arrangement one can measure collisions when one or the other smartphone is initially at rest, or when both are moving before the collision, either in the same or in opposite directions. In order to have a more general set of cases the students can also do these experiments adding different masses to the carts, so that the experiments include collisions between bodies (cart plus smartphone sets) with equal or different masses. Another experiment with the same equipment would consist on the study of the movement of a body along an inclined plane by changing the height of one of the legs of the air track. Figures 8 and 9 show the acceleration results obtained in an experiment with a collision between two bodies with the same mass when initially one of them is at rest. Data used to prepare Figure 8 were obtained with the 'Remove Earth gravity' option selected in the app, while data in Figure 9 were recorded without activating that option. Comparing Figures 8 and 9 one immediately notices the weird behavior of the Y acceleration components in Figure 8. The change of sign in those components after the collision has no physical meaning (indeed it would mean that after the collision the smartphones were pushed forward in the direction of their initial movement). Evidently this is an artifact due to the option 'Remove Earth gravity' in the measurements of Figure 8. As can be seen in Figure 9, this strange behavior doesn't appear when that option is unchecked, being now reasonable measurements. Similar effects have been observed in other experiments using this same application. Clearly, not being sure of how an application works or how it is programed are sources of uncertainty and can lead to misunderstandings when the students obtain results that can not be properly explained. This is one reason why we also develop applications to do experimental measurements using the smartphone sensors.

Figure 8

Figure 9

One of these applications developed by our group permits the students to do acoustic measurements by using the microphone (acoustic sensor) of the smartphone to analyze different phenomena. An important additional advantage of this application is that it can be calibrated by comparing its results with those obtained by scientific instruments under the same conditions. This is a quality that lack most of the freely available apps used to access sensor data, so that their results are really device dependent. Figure 10 shows the calibration of this app in two different smartphones with a sonometer. This application allows the smartphone to be used in the teaching laboratories instead of more expensive experimental devices as in the arrangement shown in Figure 11. There, the application is used to measure the resonance in a beaker when waves with different wavelengths are emitted by the smartphone speaker (or alternatively when one wavelength is used but the height of the liquid changes in the beaker). We have also used this application to measure and analyze Doppler effect, interferences, beats, frequencies spectra, wavelengths, etc. or to study other phenomena in combination with some other fundamental physics laboratory equipment such as Kundt or Quincke tubes. The use of this type of calibrated applications allow us to have *low-cost laboratories* where some expensive laboratory material is substituted by the more versatile smartphones which, depending on the application, can be used with very different purposes. Furthermore, these applications also allow the students to do by themselves reliable experiments that can go quite beyond the initial aims of the application. For example, this same application can be used to measure the value of the gravity by recording the sound performed by a bouncing ball that has been dropped from a known height (Kuhn, J., & Vogt, 2013b) as can be seen in the results shown in Figure 12, or to analyze the behavior of a material depending on its temperature, so that an application initially intended for acoustic measurements can be also used in mechanics or materials science experiments.

Figure 10

Figure 11

Figure 12

Conclusions

Mobile technologies can lead us to an important change in the way we teach and learn. In this work we have described two different lines of work that we're following to improve our teaching of physics: Firstly, the development of mobile applications together with a learning framework, and, secondly, the use of smartphones' sensors to do easily physical measurements.

From our results with the development of mobile applications, the students consider those applications an interesting and useful complement to the traditional teaching, as they allow them to access to multimedia resources easily, and study nearly anytime and anywhere. These applications include theoretical concepts, simulations and self-evaluation tests to guide the students learning by showing them what concepts or techniques should be reinforced. These applications can also be used as a help in the laboratory work performed by the students, either by allowing them access to remote experiments or by adding extra information, as for example by using enhanced reality, to the information available in the laboratory. From our analysis of the influence of the use of these applications in learning, we have observed that the students who used them were more engaged with the subject. Since only a very small set of applications was tested, the results learning outcomes weren't conclusive.

On the other hand, current smartphones are rich in built-in sensors that can be used in many different physics experiments. This opens the possibility of designing low-cost laboratories by substituting some expensive laboratory equipment with smartphones. This can represent an important advantage for academic centers with high number of students and/or short budgets. Smartphones also allow the students to do measurements by themselves in many everyday activities where they can study concepts like acceleration, force, oscillations, light or sound intensity, propagation and interferences, or magnetic field, just to give some examples, with the sensors included in the smartphones. For doing these measurements the students can use free applications that access the smartphones' sensors or specifically developed applications, as some of the developed in our group. From our experience some of the available free applications, probably not designed or tested by physicists, lack the necessary conceptual accuracy and can induce errors in the students learning, so that a previous check from the teacher is necessary before advising the students on the use of those applications. Giving the students the possibility of doing experiments by themselves facilitates their understanding, not only of concepts or theories, but also of the scientific method and experimentation, as they learn the importance of accuracy, reproducibility, analysis and interpretation of the results. At the same time, when the students play an active role in their own learning and see how the studied physical concepts affect their lives they get more engaged with the subject and the learning outcomes notably improve.

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