Framework for using modern devices in introductory physics courses

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Abstract
In this paper we introduce a practical framework that guides teachers on how to integrate modern devices (MD) into an existing physics course without adding new topics. The framework has three components: using the device as a black box, using the device to learn the physics behind its operation and using the device to learn new physics. We used two devices (a laser distance meter and an LED) to illustrate how to apply this framework in instruction. We provide examples of learning activities and ideas that students bring in when they engage in these activities. We hope that the framework will encourage and help teachers to systematically use MD in their courses in suggested ways.

Keywords: modern devices, framework, introductory physics, teaching, learning, explanations

(Some figures may appear in colour only in the online journal)

1. Introduction

Today’s society depends on modern technologies more than ever. While the expectations of integrating the latest physics discoveries into introductory physics courses are growing, the number of topics that fit into a curriculum remains more or less constant. Because physics knowledge is hierarchical, it seems impossible to skip fundamental topics (Newton’s laws, momentum and energy conservation, etc) to make space for more contemporary ones.
(nanotechnology, gravitational waves, etc) even though the fundamental topics are commonly several hundred years old. The tension between the need to teach both the fundamentals and the growing number of contemporary issues in physics and the need to fit the courses into the same time frame is widely recognized [1]. Resolving this tension requires careful attention to multiple aspects of learning and teaching. In this paper, we focus on one aspect of this tension, specifically, on how to integrate student learning of modern devices (MD) into an introductory physics course without compromising the coherence of physics as a subject and without overloading the curriculum. This integration can happen in any learning environment: during lectures, in whole class discussions, during short hands-on experiences when students explore phenomena qualitatively or during instructional labs where the students collect and analyse large amounts of data and solve complex experimental problems.

2. The framework

What do we mean by a modern device? In this paper, a modern device means a device that students may meet in everyday life and which operation relies on technologies that were developed during the last two decades. In science education literature we meet the terms apparatus, instrument, equipment, technology [2]. In this paper the term ‘modern devices’ encompasses all of those terms. Examples of MD to which our framework applies are: a fluorescent light bulb, an infrared camera, a scanner, a GPS, and many others. The idea for a framework described in this paper comes from studying the literature and from our own experience while developing a systematic library of materials for teaching and learning about light emitting diodes, LEDs [3].

The framework consists of three different ways of using a MD (figure 1):

1. Using a MD as a black box.
2. Learning how the MD works.
3. Learning new physics using the knowledge of how the MD works.

The figure shows the relationship among the components of the framework. We envision it as a spiral where the components are stacked according to the conceptual difficulty. Learning concepts in one component prepares the students for the next one. The spiralling instead of linearity represents that at the next framework component the students come back to the same MD but in a different context. The proposed framework is intended as a guide that will help teachers and educators structure their thoughts about how to incorporate MD in an introductory physics curriculum.

Although the proposed framework is to the best of our knowledge new, we can find in the literature several cases in which a device (at the time of writing regarded as a modern or contemporary) has been used to help students learn certain phenomena. One of the oldest examples is Michael Faraday’s public lecture ‘The Chemical History of a Candle’, presented in 1848 and later written in a booklet in which he says [4]: ‘There is no better, there is no more open door by which you can enter into the study of natural philosophy, than by considering the physical phenomena of a candle.’ In his booklet, Faraday uses simple experiments with a candle to explain various fundamental phenomena such as surface tension, convection, combustion, condensation and more. Since then contemporary and MD have been used in numerous physics education papers either to explain the physics of the device at introductory physics level [5–10], or to use the knowledge of how a device works to learn new physics or deepen students’ existing knowledge [11–19] (the papers cited here present only a small sample of such literature). We consider the framework epistemological in nature.
as it addresses the question of the roles of MD in student knowledge construction. It is not about how the devices work but their roles as tools in construction of new knowledge [20, 21]. In the following sections, we discuss every element of the proposed framework using two MD: a laser distance meter (LDM) and a light emitting diode (LED) (see figure 2). These two devices serve as examples in applying the framework. For this reason, we decided to structure the paper elaborating each step of the framework for both devices rather than describing each device using all steps of the framework. The readers who wish to get a
A holistic view of a particular device may want to reread the paper, choosing only the text that refers to this device.

2.1. Using a MD as a black box

Using a MD as a black box allows students to get familiar with certain properties of a system of interest without going into the physics mechanisms of the device itself. However, even though we do not seek explanations for how the device works, black boxes offer several opportunities for connecting, comparing and contrasting features of a MD with other devices or phenomena already familiar to the students. Using a device as a black box can be seen as the first step in getting personal experience with the new device or a piece of technology, i.e. moving from the unknown and abstract, to the known and concrete.

2.1.1. Laser distance meter (LDM). A LDM is a relatively new device that allows measuring distances. Low cost versions (price below 30 EUR) allow measurement of distance from about 5 cm to 15 m with the uncertainty of few mm. Versions that are more expensive allow measurements up to several hundred meters. Students can use an LDM as a black box for measuring distances while studying different physics topics (for example in mechanics) or when engaged in sports activities.

In addition, using an LDM offers an opportunity to learn something new about the laser light when studying optics. We can ask students to estimate the divergence of a laser beam and compare it with the divergence of other light sources such as flashlights. In addition to an LDM, which serves as a laser light source and a distance-measuring device, students will only need a regular ruler in these experiments. Students will find out that the divergence of a laser beam is about 0.5 mrad, about hundred times smaller than the typical divergence of a flashlight. Let students work in groups and ask them to compare their results. Doing so, students make the comparison between the divergence of a laser and a flashlight quantitative while they repeat what they have already learned about radians and uncertainties.

2.1.2. Light emitting diode (LED). We often use LEDs as black boxes when teaching optics (light sources) [22, 23], when teaching electricity and magnetism (current indicators) or when teaching motion in kinematics (speed indicators via blinking; see figure 3) [24].

In addition to serving the respective purpose shown in parentheses, each of these cases offers students an opportunity to discover some special feature of an LED and to compare those with the features of some other devices already familiar to them. When using an LED as a light source, students can learn that LEDs are emitting almost monochromatic light.
white and pink LEDs, we will come back to these later. Comparing a small lightbulb and an LED, students can find out that the former is warm when touched and the letter is cold, although their brightness is about the same. When using an LED as a qualitative indicator of a current, students learn that a current as low as about 10 μA will already make an LED glow. When using a blinking LED to study motion, we can challenge students to investigate if a small incandescent lightbulb can also be used for the same purpose. Students can do this as a separate project task. Alternatively, the teacher can ask students to discuss the question after observing a high-speed movie of an LED and a lightbulb that are simultaneously switched on and off (see https://youtu.be/eQUdj7j81pc). Students will learn that the incandescent lightbulb needs about 100 ms to reach full brightness after switching on and about the same time to stop glowing once we switch it off, while LED switches on and off almost instantaneously.

Let us summarize. To use a MD as a black box the students do not need to know the physics that explains its operation. However, pointing to a specific feature of a device or comparing and contrasting a device with another device that is already familiar to students provides an opportunity to learn about a new property of a device and getting some personal experience with it.

2.2. Learning how a MD works

We can engage students in activities in which they learn the basics of how a MD works by utilizing their knowledge of unit-relevant physics to devise and test different explanations related to the operation of the device. The explanations can be either causal (relating cause and effect without referring to or describing a specific mechanism) or mechanistic (explaining the mechanism behind the phenomenon).

2.2.1. LDM. When we ask students to propose an explanation of how an LDM might work, they usually devise the following two explanations (the explanations below are mechanistic).

- Explanation 1: The device determines a distance \( d \) to the object by measuring a time delay \( \Delta t \) between the emitted and received pulse (time-of-flight method).
- Explanation 2: The device determines a distance \( d \) to the object by measuring a change (attenuation) of the intensity of received light compared to the emitted light.

Having two different explanations provides an excellent opportunity for the students to test them by designing new experiments whose outcomes they can predict using those explanations [25]. One of the most frequent testing experiments that students propose is to measure the same distance, first time by using a white object (such as piece of paper) as a target and the second time by using a black object (piece of paper) as a target. The prediction based on Explanation 1 is that the measured distances will be equal and prediction based on Explanation 2 is that when a black object is used, the measured distance will be larger, because the black paper absorbs more of the light incident on it. The outcome of the experiment matches the prediction based on Explanation 1, allowing the students to reject Explanation 2.

Once the students agree on the qualitative explanation about how an LMD works, we encourage them to construct a mathematical model used by the device to determine the distance. Once they agree that the correct model is \( d = \frac{c \Delta t}{2} \), where \( c \) is speed of light in air, we ask them to consider the assumptions that are inherent in this model. The students realize that they assumed that the speed of light in air is known to the device and is constant. Now students can make their analysis quantitative. Using the technical specifications that they can
find in the LMD manual and knowing the speed of light in air they can determine the shortest and the longest time interval that the device should be able to measure and the uncertainty with which these times should be measured to achieve the specifications reported in the manual. Students will learn that the device should be able to measure time intervals as short as few tenths of a nanosecond with uncertainty of picoseconds. In order to realize how short these time intervals are, let them compare them with a familiar short time intervals, for example blink of an eye (about 0.3 s) or typical shortest time exposure interval in an ordinary photo camera (10^{-4} s). These activities can be done when students are learning mechanics or optics.

If students already learned about diffuse and specular reflection, they will be able to explain the outcome of the following experiment using their newly developed knowledge of how an LDM works. Fix a plane mirror on a vertical wall, aim the LDM as shown in figure 4 and take a measurement. The LDM will show a distance that is evidently longer than the distance between the LDM and the mirror. Students should be able to realize that the laser light undergoes two specular and one diffuse reflection and thus the light pulse travels a total distance of 2(d_1 + d_2) before returning to the LDM (note that the distance shown by the LDM will be d_1 + d_2). Encourage the students to make an independent measurement of the total distance between the LDM and the bright spot on the wall and compare it with the distance measured by the LDM.

2.2.2 LED. Prior to learning the physics behind the operation of an LED the students need to be familiar with the basics of DC circuits, including the relationship between current and voltage \( I = \frac{\Delta V}{R} \). The first LED-related task is to make a green LED glow using two 1.5 V batteries and do the same for a small incandescent lightbulb [10]. By solving this task, the students discover that an LED glows only if connected to two batteries in series in a certain way—the LED’s long leg should be connected to a positive terminal of the battery\(^3\). This finding is in contrast to the lightbulb that glows either with one (dimmer) or two batteries (brighter), independently of the voltage polarity. This, once again presents an excellent opportunity for the students to propose causal explanations for the observed behaviour of

\(^3\) Note that most of green LEDs can be safely connected to a 3 V voltage source without using any resistor in series.
LEDs. In our experience students come up with the following two explanations: (1) an LED only allows current through in one direction and when there is a current, an LED glows; (2) an LED allows current in both directions, but only glows when current is in one direction. As described before for an LDM, the students need to propose testing experiments that eventually allow them to reject the explanation 2\cite{10}. The students then proceed to a quantitative investigation by measuring the current-versus-voltage characteristic $I(DV)$ of an LED and a lightbulb (see figure 5).

Analysing these graphs, the students see that their measurements are consistent with what they found out earlier in qualitative investigation. In addition, they discover that the $I(DV)$ graph is symmetrical for the lightbulb and asymmetrical for the LED. They also discover that the LED starts glowing at a certain voltage around 2.2 V (called opening voltage) and that this voltage is different for different colour LEDs. Students can also compare the electric power of a white LED and small incandescent lightbulb (by measuring voltage across and current through a light source) and find that at approximately the same brightness, a white LED needs about 10 times less electric power than the lightbulb \cite{24}. If we stop here, students will already learn some most important features of LEDs that will make this device more familiar to them.

If we decide to go further, we can engage students in the next activity that allows them to visualize the structure of an LED (thus preparing them to learn about a p–n junction), while applying their knowledge of geometrical optics (the students can do this activity if they are familiar with reflection and refraction). Using a simple magnifying glass, the students find that while the filament in a lightbulb is clearly visible, the interior of an LED is blurred due to a curved transparent plastic dome functioning as a lens. Asking the students to propose different ways how to get rid of the effect of the curved surface in order to see what is inside an LED often leads to an exciting discussion. Eventually someone will suggest immersing the LED in a liquid whose index of refraction matches the index of refraction of the plastic dome. Observing through a microscope an LED immersed in a glycerine or silicon oil is a fascinating experience for every student (see figure 6, watch video ‘Video 27.1’ at \cite{26} and the reference \cite{10}). The students will learn that the heart of an LED is a cake-like object that
consists of a thick layer covered by a thin layer of a different material that glows when an LED is connected to a battery.4

Let us summarize. Students can learn about some basic principles of how a MD works through investigations and using their existing knowledge. It is very important that the students start with qualitative investigations that allow them to have physical experiences with a MD and images about it [27, 28], before they proceed to the quantitative treatment. The investigations can be done in a lab component of a course or in lecture/class. Depending on the setting in which the activity is done, the instructor assumes different roles. When in the laboratory environment, the students do experiments in groups and the instructor invites them to discuss findings, explanations, testing experiments and predictions first in groups and then share with the rest of the class. When in a lecture environment, the instructor performs the experiments and asks students questions which they discuss with their neighbours and then share with the rest of the class.

2.3. Learning new physics using the knowledge of how the MD works

The main idea of this step of the framework is to build on the knowledge about a MD that students obtained through the activities in the previous step, while engaging students in additional explorations with a MD. These explorations can have one of the two goals (or both). Either the students learn about new phenomenon (that is a part of the curriculum) in a new context or they deepen and broaden their understanding of the physics with which they are already familiar.

4 The sequence of LED physics investigation follows the progression used in the textbook [29].
2.3.1. LMD. If students are not yet familiar with diffuse and specular reflection, then the activity with a mirror that we described at the end of the previous step can be used at the beginning of geometrical optics to discover and learn about these phenomena. However, we can use an LDM in another, even more exciting activity, which fits naturally into geometrical optics. An LDM allows us to compare the speed of light in air with a speed of light in a transparent medium, such as water [15]. We can motivate students for an investigation by providing historical context. After observing the refraction of light, tell students about the two competing ideas in history that physicists proposed to explain this phenomenon: (1) corpuscular particles that speed up when entering a transparent medium and (2) waves that slow down when entering a transparent medium (see the details of how these models explain refraction in [29], chapter 22, pages 704–705). Even 200 years after these ideas have been proposed, scientists still did not have suitable equipment to compare the speed of light in air and other media (e.g. water). Is it possible to use an LDM to design an experiment that will allow us to determine the ratio between the speed of light in air and speed of light in water? The students, working in groups, quickly come up with an idea to use an LMD to first measure a certain distance in water (for example the length of a fish tank filled with water) and second, to measure the same distance in air (for example, emptying or removing the fish tank). Although students’ intuition may tell them to divide the two distances to obtain the result, asking them to show mathematically why this is the correct result often proves to be a challenge. In order to solve the problem, the students have to be able to interpret the device reading when performing the measurement in water, taking into account that the assumption that the speed of light is equal to the speed of light in air is not valid. Usually they start by expressing the distances as measured by the LDM in each experiment as

$$d_{\text{air}} = c_{\text{air}} \frac{t_{\text{air}}}{2},$$  \hspace{1cm} (1)

$$d_{\text{water}} = c_{\text{air}} \frac{t_{\text{water}}}{2},$$  \hspace{1cm} (2)

where $t_{\text{air}}$ and $t_{\text{water}}$ are time intervals for the pulse to return to the LMD in case medium is air and water respectively (note that the device operates under the assumption that the speed of light is constant and equal to $c_{\text{air}}$). Because the device measures distance and not time, students need to express the time interval in the last equation with $t_{\text{water}} = \frac{d_{\text{water}}}{c_{\text{water}}}$, which allows them to obtain the solution

$$d_{\text{water}} = c_{\text{air}} \frac{d_{\text{air}}}{c_{\text{water}}} \Rightarrow \frac{c_{\text{air}}}{c_{\text{water}}} = \frac{d_{\text{water}}}{d_{\text{air}}},$$  \hspace{1cm} (3)

We found that even the best students need some time to analyse the problem correctly and come up with clear mathematical reasoning. One can increase the difficulty of this task by asking the students to solve the problem graphically by plotting position-versus-time graphs for light traveling from and to the LMD in water and air and the graph ‘interpreted by LDM’ when the beam travels through water (see figure 7). While we did not observe any students spontaneously devising the graphical solution, when asked to do it, the students rise to the challenge and enjoy it.

At the advanced level courses, the students can examine the time variation of the brightness of the laser beam (using an oscilloscope) and find out that it periodically switches on and off at frequency of the order of 10 MHz. At this point students are ready to learn about
the modulation-based phase shift method for measuring distances and compare and contrast it with the pulse time-of-flight method (see for example [30])

5.2.3.2 LED. Once the students have learned the basics of LEDs as described in the previous subsection, we can engage them in an activity in which they discover fluorescence (a new phenomenon) while investigating how a white LED works [17]. We assume the students have also learned the basics of colour light mixing, including the concept of complementary colours and the basics of wave optics. The students need gratings or diffraction glasses (with about 500 lines mm$^{-1}$) to observe spectra of red, green and blue LEDs. They then observe the spectrum of a white LED and compare and contrast it with the spectra of red, green and blue LEDs (figure 8).

The next step is for the students to propose several mechanisms that explain the spectrum of a white LED and how a white LED might be made. The students usually come up with the following explanation: a white LED combines red, green and blue LED that are connected either in parallel or in series. How can students test this explanation using the knowledge that they developed before? Two testing experiment ideas that frequently appear are the

\[ \text{Figure 7. Graphical representation of the measurement of the same distance in water and in air using LDM and the derivation of the ratio of the speeds of light.} \]

\[ \text{Figure 8. Photos of what students see through a diffraction glasses when observing a red, green and blue LEDs (top) and a white LED (bottom).} \]

5 Our understanding is that the LDM that we used combines a phase shift method (to minimize uncertainty) with a time-of-flight method (to determine that measured distance is within the required interval). Unfortunately, we were not able to verify this explanation, as the manufacturers of LDMs do not reveal the details of how the devices work.
following: (a) measure an $I(\Delta V)$ characteristic of a white LED and compare it to the characteristics of the red, green and blue LEDs and (b) gradually increase the voltage across a white LED starting from zero and observe the colour of the emitted light. Students usually have no problems making the predictions for the outcomes of testing experiments for the two proposed connections of red, green and blue LED (we leave to the readers to make the predictions). The outcome of the first testing experiment shows, that the $I(\Delta V)$ graph for a white LED has similar shape as graphs for other colour LEDs. In addition, the students will also notice that the opening voltage of a white LED is about 2.4 V, which is equal to the opening voltage of a blue LED. This finding helps students come up with a new explanation that a white LED is actually a blue LED covered with a material that changes some blue light into yellow light when the blue light passes through it. Some students even notice that the blue part in the white LED spectrum is brighter than other colours, which gives them an idea that the blue LED is a constituent element of a white LED. The students may want to observe a white LED under the microscope and find out that it looks very similar to a blue LED except that the reflecting dish, in which the glowing element (p–n junction) is located, is covered with some yellow material. This gives them the idea for a new testing experiment in which they cover a blue LED with ‘filters’ that they make by colouring a white paper with yellow markers of different type [17]. They find out that only filters made with certain markers (fluorescent markers) turn blue light into white light, when observed through the paper. At this point students are ready to learn about a new phenomenon: fluorescence.

Let us summarize. When using MD to learn new physics, students combine the basic knowledge about a MD and the rest of their physics knowledge with additional explorations with a MD in order to either learn about new phenomena that are part of the curriculum, or deepen/broaden their understanding of physics with which they are already familiar. In our experience, the activities that are included in this category are suitable for advanced high school courses and introductory courses for physics and engineering majors, for courses for prospective physics teachers, and for teacher professional development programs.

3. Summary

In this paper, we introduced a guiding framework that helps a teacher seamlessly integrate MD into an existing physics course without adding new topics. We have also demonstrated how to implement the spiralling nature of the framework. Table 1 below summarizes the main examples that we provided in the paper—a LDM and an LED. A similar approach can be used for learning about fluorescent bulbs, airbag sensors, microwaves, LCD monitors and many other devices that are familiar for our students and can be used in all three steps of our framework. In addition to the introduction of the framework, we also provided suggestions on how to engage students in scaffolded inquiry investigations and reasoning using the Investigative Science Learning Environment (ISLE) approach to learning and teaching physics and gave examples of student ideas that arise in those investigations. The readers can learn more about ISLE in [10, 25, 29].

Using our framework, the teachers can examine their curriculum with the following questions in mind when they or the students interact with any MD:

Question 1: In this activity, is the device used as a black box? Or the purpose of the activity is that the students learn the physics on the basis of which the device operates? Or the activity helps students learn new knowledge building on their understanding of the physics on the basis of which the device operates? Depending on the answer to the question the teacher
will choose on what aspect of the device operation the students should focus in a particular activity.

Question 2: If the device is used as a black box, then what specific attributes of the device operation should students focus on? If the device is used to develop the physics knowledge of its operation, then what prior knowledge is necessary for the students to be successful in this learning process? If the device is used to develop new knowledge using the knowledge of the device’s physics, then what aspects of the device operation should be understood by the students prior to using it as a tool?

Question 3: How many devices are needed for the class? When can all students observe the operation of one device or when each group needs access to the device.

The answers to these questions will help teachers make decisions concerning the placement and timing of activities, assessments and the budget for procuring the devices. The answers will also provide the teachers with the tools for the analysis of the papers that they read in journals such as *European Journal of Physics, Physics Education* or other journals for physics teachers.

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