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Measurement of the magnetic field of small magnets with a smartphone: a very economical laboratory practice for introductory physics courses

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Abstract

In this work, we propose an inexpensive laboratory practice for an introductory physics course laboratory for any grade of science and engineering study. This practice was very well received by our students, where a smartphone (iOS, Android, or Windows) is used together with mini magnets (similar to those used on refrigerator doors), a 20 cm long school rule, a paper, and a free application (app) that needs to be downloaded and installed that measures magnetic fields using the smartphone's magnetic field sensor or magnetometer. The apps we have used are: Magnetometer (iOS), Magnetometer Metal Detector, and Physics Toolbox Magnetometer (Android). Nothing else is needed. Cost of this practice: free. The main purpose of the practice is that students determine the dependence of the component x of the magnetic field produced by different magnets (including ring magnets and

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sphere magnets). We obtained that the dependency of the magnetic field with the distance is of the form x^{-3}, in total agreement with the theoretical analysis. The secondary objective is to apply the technique of least squares fit to obtain this exponent and the magnetic moment of the magnets, with the corresponding absolute error.

Keywords: university physics, lab physics, new technologies, active learning, experimental

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

1. Introduction

Meaningful study of physics in the early college courses in science and engineering is, on many occasions, relatively complex. In addition to theoretical classes and problems, it is necessary for students to complete laboratory practice, because we are convinced that the words of Benjamin Franklin: '*Tell me and I forget, teach me and I may remember, involve me and I learn*' continue to be paradigmatic in physics instruction at any level of education, but especially at the university level. According to Vygotsky [1, 2], the practical activity is conducive to promote the development of higher mental processes which are very characteristic of human beings. This allows the generation and acquisition of constructivist knowledge that is developed favourably through the participation of the subject in cooperative group processes and in the exchange of ideas which encourages the acquisition of knowledge.

As we well know, physics (along with other sciences) is different from other subjects, because, most of the time, the answers to the questions we ask are not found in books, but through reasoning and inferences, which sometimes become laborious. The knowledge of physicists comes from observing evidence obtained in a laboratory and a subsequent detailed analysis. The exception might be theoretical physics and its beautiful theories, some so difficult to verify. For instance, the history of the Higgs boson: forty years after his theoretical prediction, its existence was experimentally confirmed, although in a very complex and indirect manner.

The laboratory is almost 'sacred': it is where physics is studied. There, the students learn (or should learn) to make themselves question, to follow protocols, to answer doubts, and to germinate new questions in their minds which allow them to explore the knowledge in a more autonomous way. Our students must learn precise acquisition, whether noted in a notebook or personal computer, and treatment of the experimental information from their laboratory study. They must also learn to perform the adjustment and subsequent interpretation of this data, to calculate errors, and to achieve an auto sufficient graph, all of which is typically done in pairs. Conducting laboratory experiments allows students to acquire experience—different and complementary to theoretical classes and finding the solutions to problems—on the phenomena, laws, and theories of physics and also increases their ability to synthesize ideas and translate them into writing from memory. This provides our students with the opportunity to familiarize themselves with the measuring devices, to breathe in an atmosphere of scientific work, similar—although on a different scale—to the one in a research laboratory. The physics laboratory is a vital complement to the theoretical classes because students are involved in their own learning in a highly significant manner. Laboratory classes are teaching activities in which the student is the main character.

We advocate that students should perform accurate measurements using different laboratory devices: ammeter, voltmeter, capacitance meter, etc. In our opinion, the practices of an automated laboratory (in which the measurements go directly to a computer through an interface) are more applicable for advanced rather than introductory physics courses because we intend to have freshmen students be more involved in data collection. The increase of sophisticated and expensive practices in physics laboratories has led to the need to increase economic investment, which is difficult in many technical schools and university faculties. This has also led to fewer jobs. Sometimes there is only one position—which is used by the teacher for a class demonstration.

Recently, portable devices have appeared in almost all levels of education. Numerous studies have been published on laboratory experiments in which digital cameras or webcams [3–7], optical mice [8, 9], and game consoles and wireless controllers [10–14] are used. In addition, smartphone sensors are beginning to be used to make precise measurements [15–20]. These sensors allow us to carry out direct measurements of physical magnitudes if we have previously downloaded specific applications, most of which are free, that allow us to show measurements on the screen of the smartphone, store these measurements, and even graph the results.

Bearing this in mind, in this work we are going to centre on the use of the magnetic sensor of smartphones to measure the dependence on the magnetic field produced by a magnet in function of the distance to the same one, and compare the results with the theoretical predictions.

2. Material and motivation

In this work, we propose a very cheap laboratory practice that has been very well received by our students. The required materials include a smartphone for every two students (iOS, Android, or Windows) a small magnet, a 20 cm school rule, paper, and a pencil. Because most students own a smartphone, we can affirm that the cost of this practice of laboratory is zero dollars.

The penetration of current-generation cell phones (smartphones) amongst our students was close to 100%. In addition, the students are perhaps the greatest experts in using them, certainly much more than teachers. We believe smartphones are valuable new laboratory tools for several reasons: they are tremendous motivators; they are versatile; they are filled with sensors that, if properly used, allow instant direct measures; and students feel a special attraction to new technologies and that interest can be taken advantage of, indirectly, to teach physics.

3. Basic theory

The x component of the magnetic field created by a small magnet of length d and magnetic moment with module m at a point located at a distance x along the axis of the magnet (which coincides with the direction of the magnetic moment of the magnet) is given by the equation (see figure 1) [21]

$$B = \frac{\mu_0 m x}{2\pi\left(x^2 - d^2/4\right)^2} \qquad (1)$$

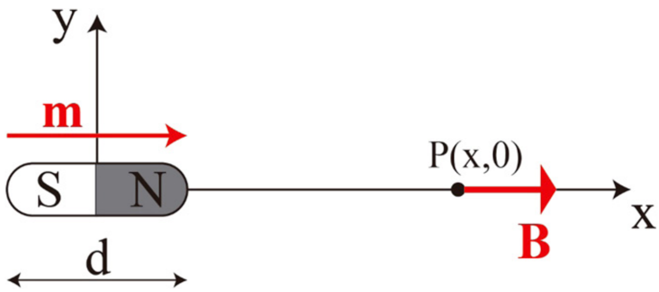

Figure 1. Small magnet of length d and magnetic moment with module m placed on the x-axis centred at the coordinate origin, and the x component of the magnetic field at a point P over the x-axis.

where μ_0 is the magnetic permeability of the free space ($\mu_0 = 4\pi{\cdot}10^{-7}\,\mathrm{N{\cdot}A^{-2}}$ or H/m). In the SI, the units of the magnetic moment of a magnet, m, are $\mathrm{A{\cdot}m^2}$ or J/T. If we evaluate this magnetic field at a distance x, much larger than the size of the magnet, d, we can simplify the previous result, taking into account that for $x \gg d$ the previous expression takes the form of

$$B = \frac{\mu_0 m}{2\pi x^3}. \tag{2}$$

In this way, it is obtained that the x component of the magnetic field of a magnetic dipole is proportional to x^{-3}, appearing in the proportionality constant the magnetic permeability of the vacuum, μ_0, and the magnetic moment of the magnet, m. With these mathematical tools, we measure the x component of the magnetic field of a small magnet in function of the distance to the centre of the magnet using a smartphone [21–24].

4. Methodology

To carry out this laboratory practice, we need to install an application that measures the magnetic field on our smartphone. It is important to install an application that is able to determine the three spatial components of the magnetic field, not only its module, because with the module is not sufficient. On the Internet, there are different apps that allow one to make these measurements. We recommend the Magnetometer app. In figure 2, we show a screenshot of this app running on smartphones with an iOS operating system [25]. Other interesting apps are Magnetometer Metal Detector and Physics Toolbox Magnetometer that can be used on smartphones with the Android operating system [26].

These apps often have a settings screen, in which the update frequency reading appears that is usually between 2–10 Hz. It is difficult to read the decimal part for high values because it varies very quickly, due to the fact that the app takes data from the sensor every tenth of a second. If we adjust it to 2 Hz, it takes data every half-second and it is easier to write down both the whole part and the first decimal digit. It is not necessary to have more precision; whenever we take three measurements (at least), we calculate the arithmetic mean, which is better than any single measurement.

Since the objective of the practice is to determine the dependency of the magnetic field with the distance, we will consider only a component of the magnetic field, for example, the x component. But, how do we know the availability of the XYZ axes in our smartphone? It takes only a small discovery process that consists of bringing near a small magnet (the ones we use on the refrigerators) to our phone in different directions and observing the component

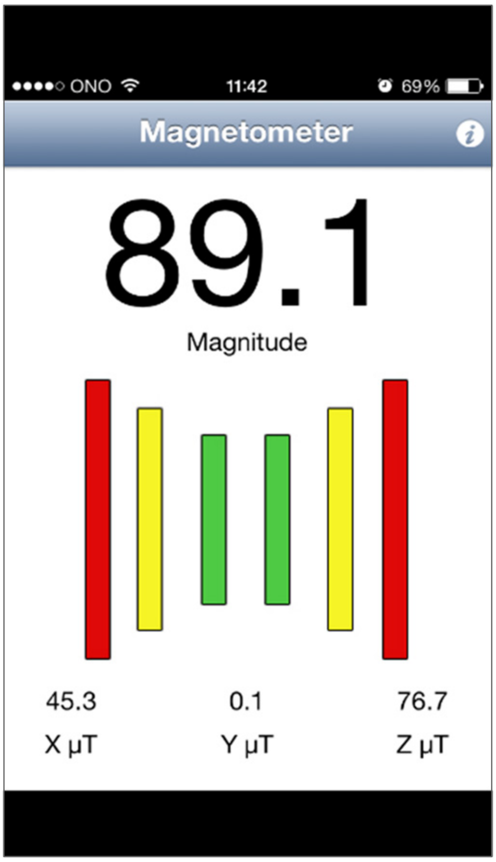

Figure 2. Screenshot of the Magnetometer app that allows us to determine the three components and the module of magnetic field from a small magnet.

Figure 3. Orientation of the spatial axes on a smartphone.

Figure 4. Location of the magnetic sensor in the interior of an iPhone 5.

that varies. In this way, we can determine the direction of the XYZ Cartesian axes, which are oriented as shown in figure 3.

Another relevant aspect to take into account is the position of the detector in the interior of the smartphone. Once again, and on an experimental basis, we move the magnet slowly on the phone screen and note the position in which the module of the magnetic field is higher. At that point exactly, within the smartphone, the magnetic sensor will be located. In figure 4 it is shown, as an example, the position of the magnetic detector in an iPhone 5. That distance must be added then to the x variable.

As we well know, the Earth itself is a magnet. Its geographical North Pole is relatively close to the magnetic South Pole, which is the reason why a compass needle points to the geographical North of the Earth. We also know that the Earth's magnetic field is of the order of 50 μT. The magnetic field produced by the laboratory magnets lies in the range μT−mT, depending on the distance from the detector to the magnet. From this data, we can conclude that

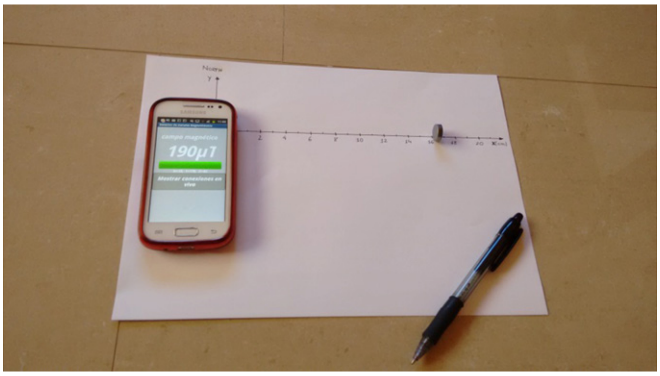

Figure 5. Experimental assembly in which you can perceive the small magnet and the smartphone with its head oriented towards the geographic North (South magnetic).

Figure 6. Diverse magnets used: spheres, ring, and two typical refrigerator magnets.

the Earth's magnetic field will influence our measurements because it has similar or superior orders of magnitude. To avoid having a background of the magnetic field coming from the terrestrial magnetic field, the only thing we have to do is to direct our smartphone in a particular position when making measurements. Experimentally, we will turn the smartphone slowly until we detect a position in which the value of the component of the magnetic field x is practically null. If we do not manage to display the value 0, we must enter the minimum value (the average of three observations), and we will call them B_{x0}. Later, we will have to subtract or add from our measures in function of it being positive or negative, respectively. If we analyse this position, we will realize that the phone has just stayed oriented in N–S direction, and therefore, the x-axis is perpendicular to such direction, as shown in figure 3.

Once we have taken into account all these preliminary adjustments, we can perform the experimental assembly of the practice, which is very simple (as shown in figure 5). We place our smartphone at a suitable orientation on a sheet of paper size DIN A4 and draw the corresponding x-axis of the phone that must pass through the sensor. Then, we place a magnet at different distances and write down the value of the x component of the magnetic field provided by the application. It should be recalled, taking into account figure 4, that we have to add the distance to which the magnetometer is located from the coordinate origin, because this sensor is inside the smartphone (1.5 cm for an iPhone 5).

5. Results

Next, we will analyse the results obtained with different models of smartphones and with magnets of different forms and magnetic moments (see figure 6).

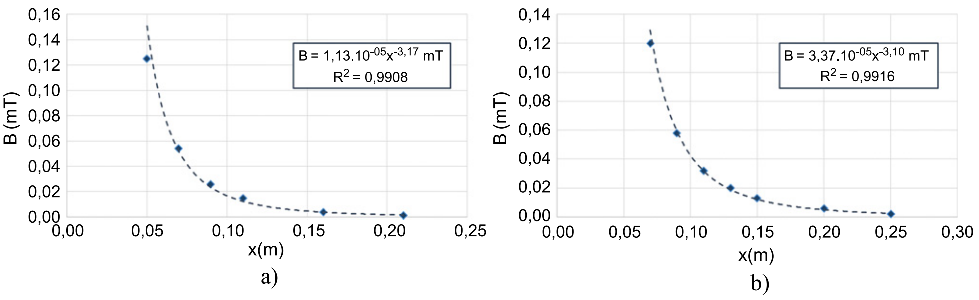

Figure 7. Experimental measures (♦) of the magnetic field of a refrigerator magnet using the sensor of the smartphone and potential adjustment of the experimental measures (—) by two different smartphones: (a) Sony Xperia Play with the Physics Toolbox, Magnetometer function application and (b) Jiayu G3 with the Physics Toolbox, Magnetometer function application.

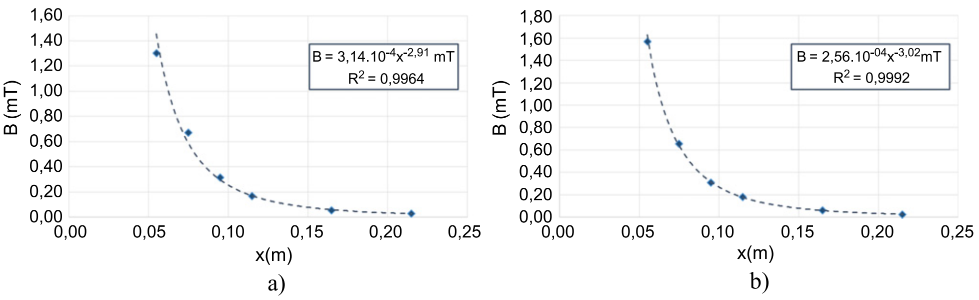

Figure 8. Experimental measures (♦) of the magnetic field on magnets somewhat more powerful using the sensor of the smartphone and a potential adjustment of the experimental measures (—) for the following special cases we used: (a) sphere magnet and a Samsung Galaxy Ace 2 Smartphone, Magnetometer Metal Detector application and (b) ring magnet and an iPhone 5 smartphone with the Magnetometer application.

For the development of the experience, first the following equation for the x component of the magnetic field of the dipole is proposed to the students:

$$B = \frac{\mu_0 m\, x^n}{2\pi}. \tag{3}$$

They must determine the value of n from the experimental data. If the theoretical model (equation (2)) is correct, the value that is obtained for n should be approximately -3.

Figure 7 shows the graphical representation of the data taken with the magnetic sensor of the smartphone for the component x of the magnetic field B in function of the x distance, for the case of the two less powerful magnets, the typical ones which are usually attached to refrigerator doors as ornaments. This figure also shows the setting of the experimental data with EXCEL, using the option ‘potential adjustment’. You can see the curve of adjustment, the equation that adjusts the experimental data (B as a function of x), and the correlation coefficient, R, square.

Table 1. Experimental results of the value of the exponent of x and the module of the magnetic moment of the magnet after the corresponding adjustment by least squares to the four magnets used in this practice and whose graphics appear in figures 7 and 8.

	$n \pm \varepsilon_a(n)$	$m \pm \varepsilon_a(m)$ $(\mathrm{A \cdot m^2})$
Refrigerator magnet 1	-3.17 ± 0.15	0.056 ± 0.019
Refrigerator magnet 2	-3.10 ± 0.13	0.17 ± 0.05
Sphere magnet	-2.91 ± 0.09	1.6 ± 0.3
Ring magnet	-3.02 ± 0.04	1.29 ± 0.12

Figure 8 shows the same results as figure 7 but for two more powerful magnets, one spherical and the other ring shaped. For the sphere, it is necessary to previously determine where its North and South poles are.

Based on the results of figures 7 and 8, it is possible to observe that the four measurements with different smartphones have a very high square correlation close to the unit, being the lowest 0.9908 (fridge magnet) and the highest 0.9992 (ring shaped magnet), much higher than the minimum that we require in the laboratory, 0.95.

Also, we observed the values we obtained for n vary between -3.17 (fridge magnet) and -2.91 (sphere magnet), which tells us that the dependency of the magnetic field with the distance is of the form x^{-3}, in total agreement with the theoretical analysis (equation (2)).

At this point, for many students, one sufficient objective is to be aware that the exponent n is very close to -3. However, there is close to 25% of the total number of students who can, wish to, and are ready to carry out more elaborate calculations and obtain new results. To these students, we proposed to treat the same experimental measures that have been used to determine the value of n in an alternative way, through the adjustment of a straight line using the least squares method. For this, we must linearize the results obtained in figures 7 and 8, taking decimal logarithms in equation (3), in which it is obtained:

$$\log B = \log\left(\frac{\mu_0 m}{2\pi}\right) + n \log(x), \tag{4}$$

where n is the exponent of x and whose theoretical value, as we know, must be -3. In this way, we already have a linear equation with which we can work through the method of least squares. If we represent log (B) versus log (x), we can obtain information on both the exponent of x and the module of the magnetic moment as well as their absolute errors, through the slope and intercept at the origin, respectively, as shown in table 1. As we can observe, the magnetic moment, m, of each magnet is different, but the exponent of x, that is, n, in all cases except the refrigerator magnet 1, is compatible with the expected theoretically (a value near to -3), being the discrepancy of only 0.6%.

Another observation we could make is that refrigerator magnets have a magnetic moment between 3% and 10% of the magnetic moment of the two most powerful magnets that we considered, the sphere and the ring.

6. Conclusions

A simple and very inexpensive laboratory practice has been designed for the laboratory of an introductory physics course for any grade of sciences and engineering study. With the help of the magnetic sensor of smartphones and a suitable app, the students are capable of determining the dependency with the distance of the magnetic field, produced by different magnets.

Students can also make a graph and deduce from the experimental information in a relatively simple form that the magnetic field is inversely proportional to the distance to the cube. Also, through an adjustment by least squares, it is possible to deduce the magnetic moment of every magnet with a good precision.

Using the magnetic sensor of smartphones, it is possible to determine how the magnetic field of the small magnets changes with the distance. The experiment was conducted by freshmen in the Computer Engineering major at the University of Castilla-La Mancha. Before the achievement of the experiment, the theoretical concepts related to the magnetic field produced by a magnet were studied. The experiment allowed the students to understand the importance of the distance in measuring the magnetic field and to be comfortable with experimental designs. As has been demonstrated, the results are completely in agreement with the theoretical prediction. Finally, and with the help of the suitable app, we think that smartphones could be used for the achievement of laboratory practices in other fields of physics.

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