Chapter 7

Low-Cost Physics Home Laboratory

FAROOK AL-SHAMALI AND MARTIN CONNORS

Introduction

Distance Education (DE) is the presentation of an educational curriculum through self-study materials, often supplemented by regular contact with an instructor. DE is suitable for offering educational opportunities to students in widely dispersed locations. This form of education is gaining momentum and is becoming an increasingly popular form of learning in post-secondary education. Many traditional face-to-face courses have been revised and adjusted to create correspondence (or online) versions. However, due to the pedagogical differences between various subjects and disciplines, it is not always easy to develop correspondence courses that are convincingly equivalent to their face-to-face counterparts. This is particularly evident in science courses with experimental laboratory components. Our focus in this chapter will be on first year undergraduate physics courses and the development of alternative hands-on home lab experiments suitable for DE.

The lab work is an important part of the introductory physics class. It provides the students with a medium to practice their experimental and analytical skills and helps them understand the basis of knowledge and the relation between theoretical and empirical work in physics (American Association of Physics Teachers, 1998). However, a perception exists among students, and also among many instructors, that highly quantitative experiments can only be done in supervised physics laboratories and using specialized and costly equipment. This restrictive view poses an obstacle for the development of correspondence/online physics courses. Therefore, this is currently an open subject for debate, research, and innovation.

Many attempts have been made in the past to develop correspondence physics courses, with a noticeable acceleration in this direction during the past decade. These early efforts can be distinguished and characterized by their delivery of the lab component. One of the pioneering projects was at the UK Open University, which involved a mix of onsite laboratory-based Saturday schools, home experiments with lab kits, and demonstration experiments using purpose-made audiovisual material (Ioannides, 1987). Athabasca University has a rich experience in this regard which will be discussed in detail in Section 4.

Real versus virtual & to-stay versus to-go labs

"Educational studies indicate that students accept all knowledge as facts, without understanding how it was constructed." (Etkina, 1999). This lack of understanding of how scientific knowledge is constructed and organized creates a fuzzy, and sometimes distorted, picture of the physical world. It is very important for students to understand that theory and experiment are interlocked and cannot be separated. An observation can lead to a theory, which may or may not stand experimental testing. Therefore, properly constructed lab experiments become essential components of an introductory physics course.

With the advancement of personal computers and the wide availability of the Internet, new forms of the physics lab started to emerge, which involve interactive computer simulations (Perkins et al., 2006). Such virtual lab environments are still debatable, with some giving them full support (Finkelstein et al., 2005) while others remain skeptical (Dillon, 2006). We will not enter here into the debate as to whether or not virtual labs have learning outcomes that warrant their use as a replacement of the traditional lab sessions. However, it is important to note that the physical world around us is the reality we try to understand and that physical laws are human attempts to describe this reality. Computer simulations, on the other hand, describe a virtual world as predicted by human-made physical laws. Therefore, we are concerned that the overuse of simulations combined with the underuse of real experiments will add to the existing misconceptions among students about how scientific knowledge is constructed. Nonetheless, this will not be our main concern in this chapter, in which we concentrate on real hands-on home lab experiments.

There are obvious challenges in doing actual hands-on experiments in correspondence courses. In particular, requiring students to come (or even travel) to a central location to do the lab part of a physics course is in conflict with the overall DE concept. One of the attractions of DE is the ability to do courses at home or from a place of the student's choice. Besides, such onsite labs are normally squeezed into a relatively short time period (usually a few days), which might result in a cognitive overdose, thus undermining the benefits of the whole lab experience.

This naturally leads to the next idea: If the student cannot come to the lab, why don't we then send the lab to the student? This is the concept of the home lab, which involves providing students with the necessary equipment, in the form of a lab kit, which allows them to perform real experiments in the convenience of their homes. It should be noted here that such lab kits must have a relatively low cost in order for the whole concept to be financially feasible. Also, due to the nature of DE, the lab kit components must be transportable and allow students to perform the experiments safely with very limited (or even no) supervision. However, this raises a concern about the practicality of this whole idea and also about the level and the quality of such home experiments. It is very important for the devised system not to compromise lab quality.

The idea of science kits is not new. They were previously suggested "as remedies for problems of school science equipment" (Announcements, 1964). However, with the advent of DE, such kits are being looked at as portable mini-laboratories that can substitute for the traditional brick-and-mortar labs located on campuses. We have mentioned the early experience of the UK Open University in this regard. Athabasca University started using lab kits in 1997 (Connors, 2004), as will be elaborated on later. More recently, there is the interesting experience at the North Carolina Community College of developing a very low-cost lab kit to be used in laboratory exercises suitable for a conceptual physics course (McAlexander, 2003). Another example is the apparently successful experience at Murdoch University in Australia (Jennings, 2005). The recent increase in the popularity of lab kits in distance education has even encouraged producing them commercially (Jeschofnig, 2004), which allows some institutions to outsource the handling of the lab material.

In comparing home labs with on-campus labs we should also note that each form of the lab experience has possible advantages and disadvantages. In a regular lab, for example, the student can seek immediate help and advice when it is needed, which can be provided by the instructor, the technician, or even the lab partner. In the home lab, on the other hand, students work almost independently, from the experimental setup to the writing of the lab report. This is normally reflected in the number of trials and the time spent by the student to complete an experiment (Misanchuk & Hunt, 2005). For this particular issue, arguments can be made on both sides. This is because while the lack of immediate guidance in home labs might be perceived as a disadvantage, the increased effort to make the experiment work, and the cognitive process accompanying that, can be argued to be an important part of active learning.

The lab bill

Traditional laboratories can be equipped with bulky, sophisticated, and costly equipment, whereas home lab kits tend to be far less expensive and very limited in size. The big question, however, is: Can home lab kits substitute for the presumably more specialized equipment found in traditional physics labs?

We do not believe that there is a general consensus regarding an answer to this question. This is because the whole experience of home labs and the use of lab kits is relatively new and limited. Standards have not been laid down yet and the whole idea is still under investigation and requires much more serious research. However, based on our experience at Athabasca University during the past 10 years, we believe that the answer to this question is "yes." Basically, this is because physical phenomena are all around us and are not confined inside a lab room in the physics department on campus. Whether you are adding an ice cube to your drink or going down the slope in a ski resort, you are actually involved in physical phenomena. Besides, many of the important experiments and great discoveries in the early days of physics were conducted at home and using simple tools and equipment. Therefore, we believe that it is time to get away from the stereotyped images of the physics lab and start thinking outside the box.

It is important at this point to differentiate between qualitative demonstrations which are normally used as teaching aids in classrooms and the more genuine highly quantitative experiments that are typically conducted in physics labs. The common belief is that such experiments are costly and require special support and supervision. This also leads to the perception that low-cost home lab experiments are inferior and cannot be considered genuine. This, in our opinion, is a premature judgment. It is not fair at this time to compare a practice that has been developing for more than a century with the alternative that started to develop, in a serious manner, only about a decade ago. Also, we should indicate that most of the cost involved in traditional labs goes toward providing the overhead and support. This is discussed in Chapter 10. When you eat in an expensive restaurant, you mainly pay for the place and the service and only a small fraction of the bill goes toward the food on the plate. This analogy applies, to a great extent, to the traditional physics lab. Therefore, isolating the physical phenomenon from the laboratory apparatus is a first step toward finding cheaper alternatives for observing the same physics. This is especially true in modern homes, which are full of household items (including high-tech devices) that can be used for quantitative physics experiments with sufficient accuracy.

Therefore, we propose that with enough research and imagination, low-cost, high-quality experiments can be designed for the introductory physics courses. We claim to have already developed a wide range of such experiments, which are currently in use. We continue to be active in this direction, and the novelty of home labs noted above suggests that there is plenty of room for improvement. In the next section, we provide examples of home lab experiments that are currently being used in the introductory physics courses at Athabasca University.

The AU experience

Athabasca University (AU) primarily operates as an asynchronous home-study distance education institution. This means that students can start and progress through courses based on their own schedule (subject to time limits), and do so without the need to travel or commute to a specific location. In the case of physics this includes the ability to do laboratory exercises at a place of the student's choice. AU has an open admission policy so that anyone may enter introductory level courses.

The University started offering its first physics course in 1992. Although the course was based on home study, labs were contracted to be taught on-campus at another institution in Edmonton, and students were required to attend the lab session during the summer.

Enrolment remained low through 1996. In that year, the courses were taught in-house at the Edmonton Learning Centre of Athabasca University, and the lab materials purchased to enable this were used to make the first home lab kits, introduced in early 1997. The courses have subsequently grown dramatically, and now incorporate home lab kits and, increasingly, web technology. Now AU has over 300 physics students, representing over a tenfold increase in a decade.

The three physics courses currently offered at AU are junior, algebra-based courses that cover standard topics in introductory general physics (Connors, 2004). These include classical mechanics, waves, thermodynamics, electricity, magnetism, optics, and the early quantum theory. All three courses are currently based on the widely used textbook (Giancoli, 2005), with a custom-produced study guide detailing learning steps, including readings and solutions to selected problems.

Each of the three courses has an obligatory lab component, done by students using a lab kit. Even though home labs were implemented at some other institutions at least a decade earlier, our kits were independently developed at AU to be an important feature of the physics courses. Since the lab materials are reused, the lab kits are loaned as a library item. The distribution mechanism, through our distance education library, has functioned extremely well. Kits are mailed at no cost to students, and a postal reply coupon pays for return of the kit from within Canada. Our rate of return on the kits is very high, and upon return the kits are checked and refurbished in our Science Lab. Each lab kit is accompanied by a lab manual explaining how the labs work and giving some background information. Vernier Software's Graphical Analysis program (www.vernier.com/soft/ga.html) is also supplied and the students are required to have access to a PC type computer, a requirement which no longer appears restrictive.

The initial PHYS 200 (mechanics) lab kits cost about $800 each, and were largely based on Texas Instruments' Calculator-Based Laboratory (CBL) technology and TI-83 calculators (Taylor, 1995). These were used to obtain data which could be downloaded to a home computer. Later, a second group of kits were developed at a cost of about $410 each and were based on the more restricted Calculator-Based Ranger (CBR) technology, but still with a calculator needed. More information, including photos, are given by Connors (2004). The latest generation of the commercially available motion sensors allowed direct and more convenient connection to the computer (desktop or laptop). This improvement in technology pushed down the lab kit's cost to about $190 each.

Similarly, the laboratory portions of the PHYS 201 (waves, thermodynamics, electricity) and PHYS 202 (magnetism, optics, early quantum theory) courses were initially based on CBL technology. However, due to the relatively high cost, new lab kits were developed with less expensive components. These mainly were constructed based on inexpensive digital multimeters and on sensors developed locally at the AU Science Lab (Connors, 2002). The new PHYS 201 lab kit includes a temperature probe and a circuit board from Vernier Software & Technology (www.vernier.com). This is in addition to a digital multimeter and several other items with a marginal cost. In PHYS 202 the lab kit contains a light sensor and a magnetic field sensor, from the same equipment provider, plus other cheaper items like lenses, diffraction grating, laser pointer, and a LED flash light. Students are also required to supply additional common household lab items in all courses.

The lab manual of the latest generation of PHYS 201 home lab is now available in online mode only. Students in the PHYS 201 course are able to browse the lab website and click on the various sections of each experiment. This format allows coloured pictures and video clips to be easily included and integrated with the rest of the manual. It also allows for including and updating other resources and learning objects related to the content of each experiment. Timely corrections and changes to online material are easily made. Certain parts of the lab manual, such as experimental procedures, are available in Portable Document Format (PDF) to be more printer-friendly.

In addition, the new PHYS 201 manual uses some aspects of the Investigative Science Learning Environment, which is based on physics education research (Etkina, 1999). At the beginning of each experiment, a physics law is introduced. However, for the purpose of the lab the student should not take it as a fact, but rather as a proposed theory (or claim) that may or may not be correct. The student's goal then is to perform a testing experiment and (based on his/her results) to argue and discuss the validity of the theory. A suggested testing procedure is outlined for each experiment, with the major equipment being available in the lab kit. Also, a suggested analysis of the results is given. However, students will have some freedom to follow an alternative procedure and analysis if their proposed new method is correct, rigorous, and addresses the proposed theory. This structure is expected to add more flexibility to the lab and encourages creative ideas which might be useful for future improvement and development of the lab.

Below, we present an outline of three selected experiments from recent versions of our lab manuals.

Example 1: The simple pendulum

This is a standard experiment on simple harmonic motion. It is also the first experiment in the manual and is designed such that the student can perform it using common household items even before receiving the lab kit. Here are some excerpts from the Student's Manual about this experiment.

Theory: In section 11-4 in the textbook (Giancoli, 2005), a theory is introduced to describe the oscillation of a simple pendulum. It is mentioned that "for small displacements, the motion is essentially simple harmonic" and the period of oscillation is given by

$$T = 2\pi\sqrt{\frac{L}{g}}$$

For the purpose of the lab, we will assume that this is just a theory that may or may not be a correct representation of real pendulums. Therefore, like any other physics theory, it has to pass experimental testing before it is validated. This is your goal in this lab.

Equipment: To do this experiment, you need to supply a strong, but relatively light, string about 1 m in length. A regular dental floss should work well for this purpose. You also need about 6 coins of the same type, preferably loonies or toonies, to be used as masses. To hold the coins, a medium size binder clip is included in the lab kit. Also, in the lab kit, you will find a protractor and a stopwatch for angle and time measurements. For making length measurements, you need to provide a measuring tape or a meter stick.

Procedure: Construct a pendulum by attaching one end of the string to the binder clip and the other end to a fixed support. In the first part of the experiment, you will keep the mass and length of the pendulum fixed and only change the oscillation angle (or amplitude). The purpose is to investigate the relation between the oscillation period and the oscillation amplitude. In the second part of the experiment, you will keep the oscillation angle and pendulum length fixed and only change the mass of the suspended object in order to investigate the relation between the oscillation period and the mass of the pendulum. In the third part, you will keep the oscillation angle and pendulum mass fixed and only change the pendulum length.

Analysis: A quick glance at your first data table may give you a feel of how much your data agree with the proposed theory. However, scientifically speaking this cannot be accepted as an appropriate analysis of your results, and more rigorous analysis procedures should be followed. In particular, do the values predicted by the theory agree with the measured values within the estimated uncertainties in your measurements? This is the question that you need to answer in any testing experiment.

Example 2: Charles's Law

This new experiment was recently developed at AU as a low-cost experiment to be used in the newest, online lab manual. The basic idea behind the experiment is very simple. A disposable plastic dropper is taped (bulb up) to the inside of a clear plastic container, such as a large slurpee cup. The container is then filled with salty water, resulting in the air being trapped inside the dropper. After that the whole container is placed inside the home freezer. As it cools down, the air trapped inside the dropper will shrink. Since the dropper pipet comes with volume marks on it, the volume of the air will be known once the water level reaches one of the marks. This will give the volume of the air inside as a function of temperature.

The only costly device in this experiment is the temperature probe from Vernier. However, there is no reason for the experiment not to work as well using a regular thermometer, which would bring the total cost of the experiment to under $10. Here are some excerpts from the Student's Manual.

Theory: In the textbook (section 13-6) it is mentioned that if the pressure "is kept constant, the volume of a gas increases with temperature at a nearly constant rate." It also says that the volume-versus-temperature graph "is essentially a straight line and if projected to lower temperatures E it crosses the (*x*) axis at about -273°C." Assume that this is just a theory and perform an experiment (as suggested in the procedure) to test its validity.

Equipment: For this experiment you need three items from the lab kit: plastic dropper, graduated cylinder, and the temperature sensor "Go! Temp". In addition, you need to supply about 200 g of table salt, a clear scotch tape, a juice straw, and a clear plastic container. Note that the plastic container should be at least 3 cm longer than the dropper. A computer with a USB port is also necessary for this experiment.

Analysis: In this experiment you measured the volume (V_w) of the water that entered the dropper as the temperature decreased. However, since you are investigating the thermal expansion of gasses, you need to determine the volume (V_a) of the trapped air inside. E Enter your data into the Graphical Analysis Program and plot V_a versus T. Perform a linear fit to the data and extrapolate to show the temperature at which the volume shrinks to zero. Print the resulting graph. E Based on your experimental results do you support the proposed theory? Provide a detailed discussion (about 400 words) in this regard. In your discussion, make sure that you indicate the limitations of your experiment and the possible sources of error. For example, note that the change in the water column is due to the combined change of the volume of air inside the dropper and the volume of the plastic dropper itself. Also, we know that air contains water vapour which condenses in cold temperatures. Can you estimate the significance of this condensation on your measurements?

Example 3: Ohm's Law

In this experiment, the student performs two tests of Ohm's law. In the first test he/she measures the voltage drop across a standard resistor versus the current flowing through the resistor. In the second test the student repeats the same measurements using a small light bulb. Since the temperature of the light bulb filament varies significantly, depending on the current flowing in the circuit, the student should notice that Ohm's law does not apply in this case. The experiment described below is the most recent version of an experiment used successfully for many years with parts previously assembled on a push-in breadboard. The current use of a commercial pre-assembled circuit (the Vernier Circuit Board) makes it more convenient for the students and also cuts down the checking and circulation process of returned kits in the Science Lab.

Theory: In the textbook (section 18-3) it says: "Exactly how large the current is in a wire depends not only on the voltage, but also on the resistance the wire offers to the flow of electrons E The higher this resistance, the less the current for a given voltage.” This is described by Ohm’s Law

$V = IR$

“where R is the resistance of a wire or other device, V is the potential difference applied across the wire or device, and I is the current through it.”

Equipment: All the equipment you need for this experiment are provided in the lab kit. These include the Vernier circuit board, the digital multimeter and their accessories.

Analysis: In the first part of the experiment, you measured the voltage drop across a 68 Ω resistor versus the current flowing through the resistor. Generate a graphical representation of your data. Describe (in about 100 words) your observation and the data collected. E In the second part of the experiment, you measured the voltage drop across a small light bulb. Generate a graphical representation of your data. Describe (in about 100 words) your observation and the trend of your data. E Do your data for the standard resistor support the predictions of Ohm’s Law? Do your data for the light bulb support the predictions of Ohm’s Law? Provide a detailed discussion (about 400 words) in this regard. In your discussion, make sure that you indicate the limitations of your experiment and the possible sources of error.

Conclusion

The lab is an essential constituent of an introductory physics course. Students should understand the important relation between theory and experiment in physics. However, the tradition has been to perform physics experiments in especially equipped laboratories and under the direct supervision of a lab instructor. Many of these labs involve standard experiments and use special apparatus purchased from certain lab equipment providers. As a result, there is a general impression that in order to do an experiment you must go to the lab and use the special equipment found there.

We argue that this does not have to be the case. We believe that, with good imagination and adequate research, many high-quality physics experiments can be designed and performed safely by the students at their homes using low-cost materials and devices. As discussed in Section 4, we were able to design home lab experiments for the physics courses at AU using inexpensive equipment, common household items and recycled material. The quality of the results exceeded expectations and is comparable to what is achieved in traditional labs.

While the numbers are hard to come by for other modes of provision of lab experiences, it is likely that home labs are by far the most cost-efficient. This is especially true if the capital cost of construction of on-campus labs is taken into account. We are not advocating here for the closure of traditional labs and the mass conversion to home labs. However, we are observing the rise of an alternative experience that may have at least equivalent (but not exactly the same) learning outcomes as conventional lab sessions in undergraduate physics courses.

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