Shoestring Practicals and the Teaching of Problem Solving

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Abstract. Traditional “recipe-based” practical exercises may have a high degree of outcome predictability, but, because they absolve the student of a great deal of thinking, such exercises have a low degree of value as learning experiences. Practical exercises could instead become problem solving activities, where the student must devise a method as well as generate an answer to a question. The student is given prior warning only of the broad outcome of the task. A common objection to this sort of exercises is that realistically, it can only be performed by students after the relevant ‘theory’ has been covered. This can present a difficulty for service courses where prohibitively large groups of students would have to perform the same practical exercise simultaneously. In addition economic and logistic obstacles, such as the cost of purchasing large quantities of laboratory equipment, and problems of storage can be seen as prohibitive. In this paper, two exercises are presented that are potentially good learning experiences and can easily be performed by first year Physics students without detailed procedural instructions as problem solving activities compared to traditional ‘cookbook’ practical exercises. Furthermore the apparatus for these exercises is cheap to acquire and relatively easy to store, hence the objection mentioned above becomes invalid.

1. Introduction

Practical work is something of a ‘sacred cow’ in science education – its necessity is taken as axiomatic, its efficacy as guaranteed. A closer look at laboratory programmes might, however, reveal something less than optimal. The American Association of Physics Teachers [1] recognises five goals of the introductory physics practical:

I. **The Art of Experimentation**: The introductory laboratory should engage each student in significant experiences with experimental processes, including some experience designing investigations.

II. **Experimental and Analytical Skills**: The laboratory should help the student develop a broad array of basic skills and tools of experimental physics and data analysis.

III. **Conceptual learning**: The laboratory should help students master basic physics concepts.

IV. **Understanding the Basis of Knowledge in Physics**: The laboratory should help students to understand the role of direct observation in physics and to distinguish between inferences based on theory and on the outcomes of experiments.

V. **Developing Collaborative Learning Skills**: The laboratory should help students develop collaborative learning skills that are vital to success in many lifelong endeavors.

It is difficult to see how the traditional 'cookbook' practical can achieve any of these goals as they effectively absolve the student of the necessity to think. For example, in order for students to learn to design an investigation they reason, ponder, reason, reflect and apply themselves – the cookbook exercise requires none of these - all the student has to do is follow a set of instructions. Students find this type of exercise not only unchallenging [2, 3] but also unedifying: according to constructivist wisdom, "conceptual understanding is not so much an outcome of experimental work as a prerequisite for its successful operation" [4].

The first-year practical programme at the School of Physics, University of the Witwatersrand is a case in point. For reasons that have more to do with logistics than with good instructional practice, in any one week a student will perform a practical exercise which is allocated according to a roster. In the following week, the next exercise will be performed and so on. There is seldom any connection between the practical exercise being performed and the physics theory being taught at any given time of the year except by coincidence. The practical programme becomes essentially independent of the theoretical programme. This makes it absolutely necessary that students are given detailed instructions - literally a recipe to follow – as they may not necessarily have any relevant theoretical background when performing a given exercise. In some cases they perform a practical at the beginning of the year and only deal with the relevant theory at the end. In other cases, the converse will apply and students will be performing exercises at the end of the year where the theory is covered at the beginning and is for all intents and purposes long forgotten.

The given reason for this state of affairs is that in order to guarantee that all students perform any practical exercise shortly after the theory has been dealt with, they would of necessity need to all be doing the same exercise at the same time. As some of our service courses cater for large groups of students (approaching 1000 in some years in the case of engineering) - the sheer quantity of equipment needed; the expense of acquisition and the space needed for its storage are both regarded as prohibitive. Hence, the roster system currently and historically in force. The problem here is that didactic considerations are being knowingly sacrificed for logistic considerations – there is no claim of any didactic advantage to be gained from the roster system, merely that there is no other economic way of doing it.

In this paper we argue that this may not necessarily be the case. There exist several practical exercises – perhaps enough for an entire curriculum and if not, for at least part of one – that require apparatus that is so cheap and compact that all students, even in large groups, *can* do them simultaneously. Acquisition and storage of the apparatus is not a problem – in fact a significant portion of it is generic equipment that would be in stock anyway, such as metre sticks, retort stands, clamps etc. We present here two of these exercises as examples. Each of these exercises has what we like to call a high '*didactic payload'* – in other words, they have good potential as learning activities. In particular, there is good potential for these exercises to achieve the goals of practical work according to the American Association of Physics Teachers [1]. In addition, the added possibility exists of using the practical exercise as a way of teaching problem-solving which is not possible with the 'cookbook' exercise.

2. General considerations

When a practical exercise is performed in the absence of a recipe – i.e. where the devising of a method is part of what the student has to *do* – two things are essential: The students must be *au fait* with the relevant theory and students *must* prepare for the exercise. In the absence of these two requirements, the exercise becomes worse than a cookbook practical. Most university lecturers would probably maintain that any student not *au fait* with theory already covered and unwilling to do preparation should not be at university anyway.

Exercise 1: The measurement of the track separation of a laser disc.
Suitability: Any first year physics courses involving physical optics.

In this exercise the student is faced with the instruction to measure the track separation of a laser disc. Most students are familiar with CD's and DVD's and should have an idea that the track separation is very small and might wonder what sort of instrument they will be using to measure such a small separation. Provided that diffraction and the diffraction grating has been dealt with in lectures and in tutorials, the student - with luck and some judiciously dropped hints from the lecturer and maybe some creative *'googling'* – should come across the idea that the laser disc is in fact a diffraction grating. At this point the student can figure out that measuring the separation of the interference maxima can lead to the calculation of the line separation of any diffraction grating and hence the track separation of the laser disc. Hereafter all that remains is the logistics of actually taking the measurements.

The procedure is as follows: First the student needs to 'calibrate' the laser – i.e. establish the wavelength of the laser light. This is necessary as the lasers being used are likely to be laser pointers and the wavelength is unlikely to be obtainable from a label. For this purpose, a standard diffraction grating, the laser to be used and some metre sticks – as well as sundry stands and clamps are all that's required.

The laser is shone through the diffraction grating as shown – note that the metre stick is actually used as a screen to make measuring separations between maxima more convenient:

Once the diffraction angle is known, the wavelength of the laser light can be calculated:

$$m\lambda = d\sin\theta \Rightarrow \lambda = \frac{m\lambda}{d}$$

where d is the line separation of the diffraction grating and m is the order number of the interference maxima.

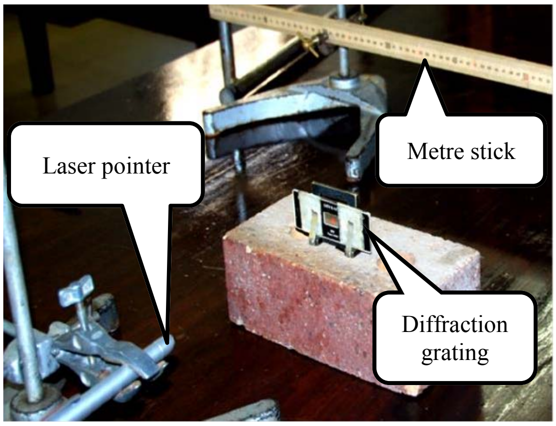

Figure 1. Laser disc track separation experiment – measuring the laser light wavelength.

At this point the diffraction grating is replaced with the laser disc. Here, the student is faced with a problem to solve: the disc is backed with a reflective layer and will not transmit the laser light. There are two solutions to this problem: either remove the reflective layer or place the metre stick acting as the screen just behind the laser. The latter is preferable as you can re-use the laser disc several times.

In the photograph shown in Figure 2, the bright spot above the '50' on the metre stick is the central maximum of the pattern reflected back onto the stick.

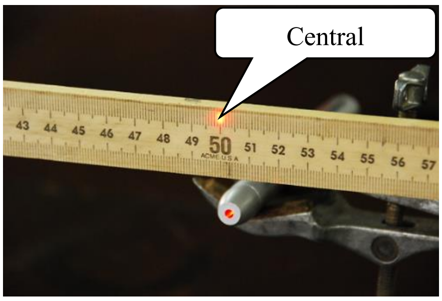

Figure 2. Laser experiment – diffraction pattern central maximum.

Once again, the diffraction angle is determined as before using the measured separation between two interference maxima (again sensibly zero and one), and the distance between the laser disc and the metre stick and then the track separation is determined from:

$$m\lambda = d\sin\theta \Rightarrow d = \frac{m\lambda}{\sin\theta}.$$

The value typically obtained by first year students, working in the complete absence of a recipe, is close to the 'book' value of 1.6 μm [5].

The cost of the apparatus is minimal: most of the items needed are already in stock in a properly equipped physics laboratory – the only item not usually part of standard stock would be the laser discs. We have never had any problem obtaining enough of these at no cost at all. The existing stock of lasers might need to be increased, but laser pointers can be bought for as little as R35.00. Better quality laser pointers will cost about R200.00 but even this is hardly prohibitive. Storage of the items between exercises is also no problem as they are compact and take up very little space.

Exercise 2: The collision apparatus.
Suitability: any first year physics course involving two dimensional projectile motion and conservation of momentum.

A curved ramp is clamped to a laboratory bench so that a ball bearing rolling down the ramp leaves its lower end horizontally – see photograph:

A plumb bob hangs from the end of the ramp so that the point vertically below the end can be marked on a sheet of paper on the floor.

The simplest exercise is to roll a ball bearing down the ramp and determine the speed with which it leaves the end of the ramp. As before, the student would be faced with the instruction to do so and no recipe to follow. The only measurements needed are the height through which the ball falls and the horizontal distance between the point directly below the end of the ramp and the point of impact of the ball on the floor. This point of impact is marked by placing carbon paper over the sheet of paper on the floor, business side down. The impact of the ball on the carbon paper will make a dot on the sheet of paper. Both of these distances can be measured with sufficient accuracy with a metre stick. The time in flight is calculated from the (vertical) height (h) through which the ball falls:

$$h = \tfrac{1}{2}gt^2 \Rightarrow t = \sqrt{\frac{2h}{g}}$$

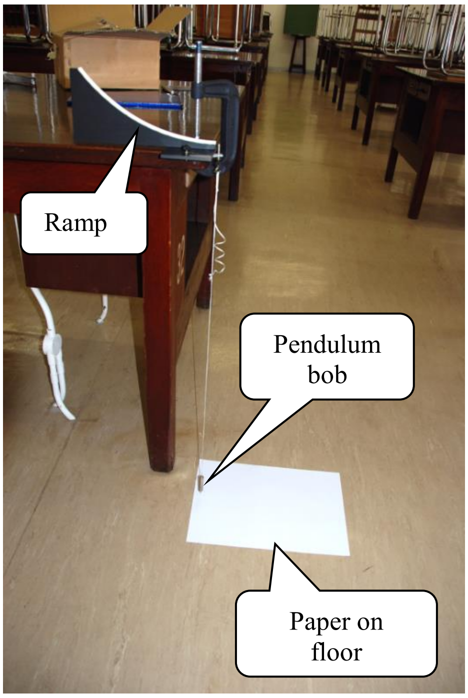

Figure 3. Collision experiment apparatus.

Assuming negligible air resistance, the horizontal acceleration can be assumed to be zero and hence the initial horizontal speed can now be calculated from the time in flight and the range (s) of the ball using: $v_o = s/t$.

A more ambitious (and follow-up) exercise would be to demonstrate conservation of linear momentum in two dimensions. For this a second ball bearing is placed on a special holder at the end of the ramp. – see figure 4 below. The apparatus can be set so that the rolling ball strikes the stationary ball a glancing blow, after which the two balls fall to the paper below. The landing points of the two balls are marked using carbon paper as described before. An example of a typical result is shown in figures 4 and 5 below:

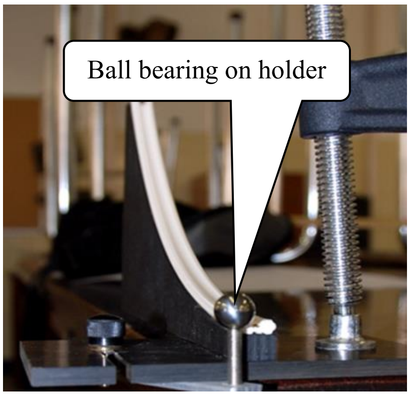

Figure 4. Second ball-bearing on holder.

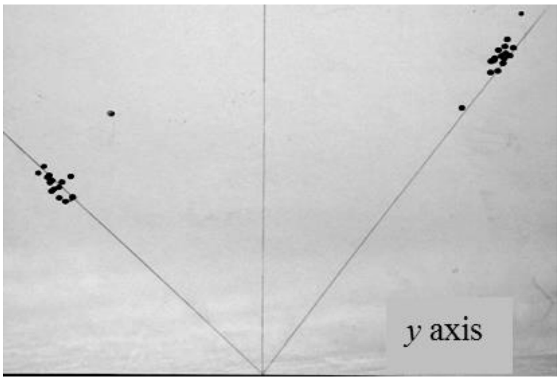

Figure 5. Collision experiment; ball bearing landing points on the floor.

If the bottom edge of the sheet is regarded as the *y* axis, then the line up the centre of the sheet is the *x* axis. The *x* and *y* components of the ranges of the two balls can now be measured on the paper and hence their initial horizontal velocities – and hence their momenta immediately after the collision. The *y*-components of the momenta can be summed and shown to equal zero, and the *x* components can be summed and compared to the momentum of the moving ball just prior to the collision – its velocity having been determined in the earlier phase of the exercise. Another possibility would be to compare the loss of gravitational potential energy as the ball rolls from the top to the bottom of the ramp with the gain in mechanical kinetic energy. There will be a mismatch between these quantities as some of the lost potential energy becomes rotational kinetic energy. Reconciling the gain in rotational kinetic energy with the mismatch could be tricky as there is no guarantee that the ball does not slip at any point as it rolls down the ramp. There is also a question of precisely where the ramp, which is 'U' shaped in cross section, supports the ball. These problems can be minimised by judicious design and construction of the apparatus – or choice of ball bearing. Whatever the case, this could be a very nice introduction to rotational kinetic energy. The ramp – which is essentially the major part of the apparatus not normally resident in any laboratory – can be easily and cheaply constructed. They can also be bought from a laboratory supply, but the whole point is to cut costs so that large quantities can be procured. The workshop staff at The Wits School of Physics estimate that the cost of making one ramp, ready to use is less than R50.00.

3. Conclusion

With these two exercises it becomes possible to require the students to do two things not usually required in a practical exercise: firstly, the students must figure out for themselves how to perform the required procedure. This forces them literally to solve a problem as they are not simply following instructions that somebody else has provided. Secondly, they can be required as part of the exercise to write a description of their procedure in the form of a set of instructions that somebody else could follow in replicating their exercise – i.e. they can be made to construct an algorithm for performing the exercise. As these two requirements are the essence of problem-solving, this changes the practical exercise from a 'cookbook' exercise into a problem-solving exercise.

Faced with the limited didactic efficacy of 'cookbook' practicals, we should be looking for better alternatives for our first (and other) year programmes. Some exercises do exist which are not prohibitively expensive and could therefore be done by all students of even quite large groups simultaneously. With some effort it should be possible to devise a large enough collection of such 'shoestring experiments' that at least a portion of a first year practical programme could be run as problem solving exercises that were directly linked to the theoretical programme. A question we need to address is 'what stops us?' One answer to this could be that there is a shortage of research data to support what we are proposing here. Three issues arise from this: the first is that a logical next step would be a proper evaluation of this type of practical exercise. The second is that supporting research data *does* exist – Allie *et al.* [6], report that this form of practical is used at the Physics Department of the University of Cape Town and '*has greatly enhanced the overall learning experience of our students*.' Thirdly, it may not be useful to take the attitude that in the absence of 'hard' data, we should not proceed. After all, given a programme to train runners that effectively absolved the trainees of the need to run – would we *really* insist on hard research data before we started looking for a better option?

Another – potentially unpopular - answer to the question that must be considered very carefully: perhaps we don't want to change existing programmes for purely emotional reasons. All the effort and expense that went into creating them in the first place – and the fact that they now allow teaching staff to operate in something of a comfort zone that they will be understandably reluctant to leave. If there is any validity in this answer, we need to think very carefully about what we are doing and about possibly making some changes.

Although these simple experiments do place student in "real" problem-solving situations, they may not however be easily acceptable by teaching staff. For example, during a tea room discussion, a colleague suggested that there is a danger that the 'shoestring' practical would, because of its low budget image, reduce the motivation of students to perform properly during practical exercises. Our answer to this is twofold:

- There is no necessity to tout these exercises as being in any way inferior to the more conventional exercises involving 'big-budget' equipment.
- Historically, the performance of students during conventional practical exercises has in fact sometimes been 'suboptimal' – an example being the widespread use of '*recycled'* measurements during laboratory exercises in the first author's own first year of physics in 1971.

References:

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