Chapter 28

A Sequence of Experiments

In Part I of the course, we present a theoretical treatment of classical mechanics. Physics theory was the work of a number of great physicists, included Isaac Newton, James Clerk Maxwell, Josiah Willard Gibbs, Albert Einstein, Erwin Schroedinger, Werner Karl Heisenberg, Paul Adrien Maurice Dirac, and moderns to numerous to mention. There is also experiment, in which we study nature to see how it behaves. We've already mentioned Tycho Brahe, Chien-Shiung Wu, and Rainer Weiss, but there are a vast number of other people who did important experiments.

All these theorists and experimenters when successful generate new results. Newton presented his results, his Laws of Motion, by writing a book, but under modern circumstances results are reported to the scientific world in the form of short papers (typically 4-20 pages) in scientific journals. There are then a very few people whose specialty is reading all those papers, summarizing them, and presenting them to the scientific world in the form of review articles (indeed, there is a journal, *Reviews of Modern Physics*, that only publishes these review articles). As we have mentioned great theorists, and great experimentalists, it would only do to mention a great reviewer, Virginia Louise Trimble, whose reviews on the Solar neutrino problem forced recognition that there was indeed a problem.

The purpose of this experimental sequence is to give you some experience in doing real experiments. A real experiment is an experiment in which you do not know the answer in advance. Real experimental work has important parts that are not often discussed in physics courses. These experiments will introduce you to some of those parts. I therefore do not give detailed instructions as to exactly how to do your experiments. Indeed, an important part of experimental work is to realize that there may well be several different methods of measuring the same quantity, and that experiment may be needed in order to determine which experimental approach gives the best results. Real experiments have errors, some of whose sizes can be determined experimentally.

These experiments are very much not like the experiments you will encounter in some freshman physics courses, where the objective is to confirm with experiment that I was telling the truth about, e.g., the period of a pendulum, and if your experiment fails to confirm theory, you are required to go back to the lab and do the experiment again and again until it confirms the theory. (No, I did not make that up.) The experiments here are meant to show you, with very little equipment and some basic mechanics, how you would go about designing an experiment. Yes, the results are known in advance, but that's not the point of what you are doing.

You may have been told about a "scientific method" in which the sole purpose of an experiment is to test a hypothesis. In this method, before you do an experiment, you are required to make a guess (a "hypothesis") as to the correct answer. The objective of the experiment is to determine if your guess is true or false. If the experiment disagrees with your guess, your guess is wrong and must be rejected. That approach to science is not always correct. You may find it interesting to read a history of the solar neutrino problem, in which measurements of solar neutrino emissions were made, two-thirds of the neutrinos were missing, and the neutrino instrumentation, solar modeling, and nuclear physics people could each think the fault was not theirs.

Much real science does not resemble this supposed 'scientific method'. For example, when the United States set out to sequence the human genome, it was already extremely well established that *homo sapiens* had chromosomes with DNA sequences. In principle, you could have guessed the DNA sequence, and then done experiments to see if your guess was right. However, the number of possible human DNA sequences is somewhat large, say four to the 3.2 billion power, so the likelihood that any guess would be correct is exceedingly small. What was actually done was exploratory. We did not know what was there, so we set out to measure it. That's real science.

These laboratories will require a very modest amount of equipment. You are going to study a conventional pendulum, a physical pendulum, and an Atwood machine. You will also use your pendulum make a quantitative test of Newton's Three Laws for a special case.

A reasonable school laboratory will supply the equipment you need. If you are doing self-study or home schooling, you will need to create your own apparatus, just like many real scientists do. You will need a precision timer and a precision scale, but these are now incredibly inexpensive.

For the conventional pendulum, you need some strong thread and some heavy nuts from a set of nuts and bolts. The nuts will serve as the pendulum bob, the heavy mass at the bottom of the pendulum. The pendulums need to hang from something. For the conventional pendulum, a traditional chemical laboratory support stand is a good choice. The longer the support rod is, so long as it is solidly braced, the better the experiment will work. A support clamp lets you hang the pendulum a distance out from the vertical support rod, so that the pendulum does not collide with its vertical support. Some years ago, some of my cleverer students taped a plastic ruler – the sort with holes in it – to the top of a door. Some inches of the ruler stuck out beyond the end of the door. The pendulum was hung from the ruler, giving a pendulum with more-than-six-feet of swing. For the pendulums, the bottom end of the pendulum bob needs to clear the table top or floor by a small distance. The length of the string needs to be varied over a considerable range. Some ingenuity is needed here. A vertical piece of pipe, rigidly mounted, and some clamps will work. Some children's construction toys will solve the problem. Finally, at one point in these experiments a laser pointer will be convenient.

For the physical pendulum, you will need a wooden yard or meter stick, a wood drill, and some reasonably large bolts with their nuts. Many yard and meter sticks have a hanger hole, typically brass-lined, close to one end. You will also need to drill some holes in your meter stick, carefully centered relative to the width of the stick, through which you will during the experiment place some heavy nuts and bolts. A thin nail serves as a good, relatively frictionless hanger for the meter stick. Where you put the nail may require some creativity to solve.

To build a good Atwood machine you need a low-friction arrangement for the top pulley or pulleys, some thread, and some reasonably heavy weights.

Several measuring instruments are needed. To weigh pendulum bobs, a scale is required. Electronic scales good for up to 300 or 500 g with a precision of 0.01 g are now remarkably cheap, much cheaper than the older triple-beam balances. The sort of balance used to weigh jewelry, that will weigh 300 or 500 g with a precision of 0.001 g, 1 mg, is readily found on the internet. You will need a digital stopwatch. These are readily available with an accuracy of 0.01 s, but for almost the same price you can probably find a stopwatch that reports with an accuracy of 0.001 s. The more accurate watch is preferred. If someone tells you that you do not need the extra accuracy, because human reflexes are not that accurate, they are missing the point of the experiment.

[Minor aside: Particularly if you are doing this experiment in a university setting, you might very well be using a triple beam balance to measure the weight of your nuts and bolts. There is a right way to make a measurement with a triple beam balance, and a completely wrong way. A remarkable number of people will tell you to use the completely wrong method. In using a triple beam balance, you adjust the weights on the balance until they are correct. However, you have two basic choices. The balance may be swinging up and down, or it may be parked and level. In the correct approach, the balance is swinging up and down. When it is balanced, the swings have the same height up as down. If the balance is just sitting there, the static friction between the knife edge of the balance and its arm may well hold the balance in position so that it appears to be properly balanced, even though it isn't. In that case, the measured weight will be incorrect. The *parked and level* method is **wrong**.]

Finally, you will need some arrangement for recording your work. If you at school, you will be told how to do this. Otherwise, the reasonable choices are: a wire-bound large notebook, three-hole paper and a ring binder, or if all else fails a computer. The computer is dangerous. It is much easier to erase a computer file than to lose a notebook. When I taught the course, students were issued two-part carbonless paper. At the end of the lab, the student kept a copy and the TA kept a copy.

The virtue of the wire-bound notebooks is that it makes it very difficult to lose any pages...until you lose the entire notebook. Some schools, however, are very fond of this approach to recording data. If you are working on several things, with a wirebound notebook it is impossible to reorder pages to keep together results on the same topic. With a ring binder, rearranging pages is not an issue. Inserting large graphs in a wirebound notebook may also be challenging.

No matter where the page is to lurk, in a permanent notebook or a ring binder, the format of the page starts out the same. At the top, right hand corner is traditional, you place the date. Then each of the people using the page initials it. When you are done with the page, you put a line below your last written remarks, and then you initial below the line.

[Aside: In some fields of science, people are extremely picky about using either ring binders or permanently bound recording books. Other fields want the data to be recorded electronically in a computer. As you advance from this course, you will simply have to find out which method is expected in each laboratory cycle and accommodate to what you are told to do.]

To be honest: Some parts of these labs are a bit tedious. To determine statistical properties of your measurements, you need to repeat the same measurement many times. In Laboratory 2, do you really need to test all those different ways of measuring the period of a pendulum? After all, I could have told you exactly how to measure the period. Yes, the tests are needed. You are seeing real science in action, where a major part of the experiment is tuning the apparatus until it works as well as possible. With real science, you can spend weeks or months or years getting the experiment to work. Finally, you get to the point where you are taking real data. The actual data may then show up very quickly. In the experiments here, pendulums are fairly foolproof. Building a decent Atwood machine may be more challenging.

An important part of scientific experiments is determining the accuracy with which your measurements have been made. Some measurements are very crude. Some measurements are extremely accurate. You will do several straightforward experiments that demonstrate how to measure accuracy, leading to discussions of random error and statistical analysis. We then advance to experimental design. You will study different methods for measuring the period of a pendulum. You will do some physics experiments: you will study how the period of a pendulum depends on the pendulum's properties. Finally, you will try to duplicate two experiments that test Newton's Laws, namely the Atwood machine and the force balance.

This space reserved for your notes.