1B40 Practical Skills

Introduction

The components of 1B40 are:

Basic Experimental Skills
Data Analysis Lectures
Set Experiments
Formal Reports
Computer Skills

The module seeks to

1. teach physical principles and underpin lecture material,
2. teach basics of experimental physics,
3. hone experimental skills,
4. enhance communications skills by recording observations and procedures clearly and concisely and then communicating them intelligibly (by a formal report).

Aims and Objectives

Aims:

The data analysis lectures are intended to provide you with a basic understanding of how uncertainties and errors can arise when measurements are made. The aim is to enable you to improve your experimental skills, recognise the difference between ***random*** and ***systematic*** errors in an experiment and to undertake an analysis of the uncertainty (error) in your experimental measurements.

Exercises on the application of the material of these lectures will be carried out in the Excel exercise. You will be **expected** to apply the results to your laboratory work.

Objectives

At the end of the course you should understand and be able to deal with the basic elements of the following topics:

1. How to do experimental Physics.
2. ***Accuracy*** and ***precision*** in measurement.
3. ***Systematic*** and ***random*** errors (uncertainties).
4. Treatment of "suspect" results.
5. Statistics of random variables.
6. Standard deviation and standard error (uncertainty) on the mean and their estimation.
7. The normal (Gaussian) and Poisson distributions and precision of errors (uncertainties).
8. Combining errors on many variables.
9. Correlated and uncorrelated errors (uncertainties).

10. Fitting a straight line to results.

Experimental method

All experiments in Physics and Astronomy start with a specified ***objective*** and proceed via some ***method*** to make some ***measurements*** to which are applied some form of ***data analysis*** to arrive at ***results*** from which are drawn ***conclusions*** relevant to the original ***objective.*** We have the sequence

- **Objective**
- **Method**
- **Measurements**
- **Data Analysis**
- **Results**
- **Conclusions**

Your work will be lost unless you *record* it.

In more detail, we have to….

(A) Specify the objective e.g.

- to find the value for an alleged constant,
- to investigate the relationship between some variables,
- to test an existing theory.

It is essential to know the accuracy and precision needed to achieve the required ***objective.***

(B) Devise an appropriate experimental method to obtain suitable measurements (i.e. design apparatus). Such an experiment will give the required result ***directly*** or make measurements which give the answer ***indirectly.***

An experimenter must consider how the desired accuracy specified in the ***objective*** in **(A)** can be achieved. This involves a consideration and comparison of the ***systematic*** and ***random*** uncertainties likely to arise in alternative designs of the apparatus.

(C) Determine an appropriate experimental ***procedure*** using the apparatus designed in (B). This will involve deciding how to reduce systematic and random errors (uncertainties) and deciding which measurements to spend most time over.

(D) Carry out the experiment recording not only all measurements but also all relevant details of the experimental techniques used, any difficulties encountered and the ways in which they were circumvented etc., so that, at a later date you *or* ***someone else*** could

- return to your record, understand what you did and re-analyse your data,
- write a suitably detailed report or publication from your record,
- repeat the experiment using the same techniques to check your results.

(E) ***Analyse*** the measurements made in (D) to arrive at any numerical estimates required by the ***objective***, i.e. obtain the ***results***.
These will be of little value unless the ***systematic*** and ***random uncertainties (errors)*** inherent in your method (considered in (C) above) are propagated through your analysis to the final result (an error analysis).

(F) From a study of your results and your estimates of the uncertainties (errors) to be associated with them you will draw some ***conclusions***. If you have not achieved your objective then there will follow a discussion concerning the reasons for this and how the experiment could be modified to achieve the ***objective***.

(G) All of the above work **must** be recorded in a Laboratory Notebook, which is essentially a diary of your work as it proceeds.
In 1B40 steps (A) and (B) have been done for you, later in your degree you will need to consider every step.

Recording Your Work

The Laboratory Notebook (see Laboratory Handbook)

This contains detailed records of work carried out. It is NOT a repetition of the script, but key points will need to be summarised.
It should, therefore, include

- A brief statement of the objective of the experiment and the method you intend to use.
- Diagram(s) indicating how the apparatus was assembled and used.
- Notes on peculiarities found in the apparatus.
- An outline of the experimental procedure adopted including dates and times.
- A record of all measurements taken and observations made. You must record any calculations including any other remarks on results or behaviour of apparatus which you feel may be relevant.
- Clear notes on the technique used to make your deductions from the above results, together with estimation and propagation of uncertainties (errors) to your final result.
- A statement summarising your final results and conclusions.

N.B. Remember that what goes in your Lab Notebook is dictated by the criteria in (D) and so will be marked accordingly.

Uncertainties in experimental measurements

Although physics is an “exact” science all measurements in physics are inaccurate to some degree so that what is termed the “actual” value of a quantity cannot be found. It is reasonable to assume, however, that the “actual” value does exist and the aim of the experiment is to estimate the values between which it lies. The smaller this range, the better is deemed the result. However the aim of every measurement is not necessarily to make this spread as small as possible. There is little to be gained in striving to measure one quantity to a precision of 1 in 1000 if another quantity, which equally affects the final result, cannot be measured to a precision of better than 1 in 100.

In experimental Physics the word ERROR frequently does not have its usual meaning of mistake - it is often used to express the degree of uncertainty in a measurement or result. A consideration of uncertainties is a fundamental part of any experiment because results have almost no value without knowledge of their degree of ***accuracy*** and ***precision*.** The difference between the observed value of any physical quantity and the “actual” value is called the error of observation. Such errors follow no simple law and arise from many causes. Errors of observation are usually grouped as accidental (random) and systematic, though it is sometimes difficult to distinguish between them and errors are often a combination of the two types.

Accuracy and precision are different (and need to be considered separately). There is a correspondence between accuracy and systematic error and between precision and random error.

In this course we study the numerical techniques available to estimate the systematic error and random uncertainties in our results in order to estimate their accuracy and precision.

However accuracy and precision can also affected by “avoidable errors” resulting from poor experimental technique which produces either “inadequate data” or “mistakes”.

Accuracy, Precision, Systematic & Random Uncertainties (or Errors)

A distinction should be made between **accuracy** and **precision**. Accuracy refers to the closeness of the measurements to the actual value of the physical quantity, whereas precision indicates the closeness with which the measurements agree with each other. Accuracy therefore includes precision but the converse is not necessarily true.

In experiment P2, the compound pendulum, you measure the time period of a pendulum in order to arrive at a value for g [i.e. you made an ***indirect*** measurement of g]. Suppose that you took a hundred measurements which varied in the range…
maximum = 17.071 sec, minimum = 17.048 sec, Average = 17.059 sec.

If you repeated the hundred measurements, you would expect to find that the spread of values and their average would only be slightly different. You can be fairly sure that the spread in measured values was caused by random factors, and that the result is very *precise* as the spread in values was very small. Thus random errors (uncertainties) affect the precision of an experiment. They are assumed to arise from the random combination of infinitesimally small perturbations each of random sign i.e. equally positive or negative. This assumption allows a mathematical treatment of the errors.

However, suppose that you measured the length of the pendulum with a rule with a scale wrongly marked as 9 instead of 10. You might then record measurements of 10.0, 10.1, 10.0, 10.0, 10.1, … The reading may be very precise, i.e. agreeing well with themselves, but there would be a systematic error of 1.0. (This example is not as absurd as you may think. All instruments record m when the real value is M). The answer is precise but ***not*** accurate.

Systematic errors may in principle be corrected for once you are aware of their presence and have determined their effect. The source of them is, however, often hard to identify and there is a strong temptation to assume that they are smaller than the random errors so that they are neglected. This is not always true. Systematic errors are often the most serious source of uncertainty in experimental work and, in high quality work, much time and effort is expended in identifying them, trying to eliminate them or estimating their magnitude.

A random uncertainty or error on the other hand may be merely estimated in magnitude, but never corrected for. It may be reduced by appropriate experimental technique.

Reporting results

A result must always be quoted together with an estimate of its random uncertainty (error), e.g. acceleration due to gravity at the Earth's surface, $g = 9.55 \pm 0.05\ ms^{-2}$.

Note that the random uncertainty is usually an estimate of either the standard deviation or the uncertainty on the mean. Later lectures will define these two quantities.
The estimation of the magnitude of uncertainties is usually rather imprecise and usually only warrants quoting to one significant figure. Thus the there is no point in writing, say $9.55 \pm 0.0533718\ ms^{-2}$. Equally there would be no point in writing $g = 9.55269735 \pm 0.0533718\ ms^{-2}$ or $g = 9.5519726 \pm 0.05\ ms^{-2}$.

Never quote uncertainties to different powers of ten than the quantity to which they refer, e.g. never write $g = 955 \times 10^{-2}\ ms^{-2} \pm 0.05\ ms^{-2}$.
Having decided on the magnitude of the uncertainty figure, quote the result to the same number of decimal places. Thus you should write:
$g = 9.55 \pm 0.05\ ms^{-2}$.

Poor Experimental Technique Resulting in Avoidable Errors or Mistakes

(1) Mistakes, A simple form of mistake would, in the example of the pendulum experiment, be a mis-reading of the stopwatch for one or more readings. There are two things that can be done about such mistakes:

- Take care!!
- Check that your results are reasonable AS YOU TAKE THEM. This may well involve plotting graphs as you go. NEVER wait until the end of your data taking to plot the data.

(2) Misleading or Inadequate Data, Poor experimental technique, such as too few data points, can result in **inadequate data**, leading to a **mistake**, not necessarily in the measurements but in the analysis and conclusions drawn from them.

ALWAYS PLOT ANY GRAPHS AS YOU TAKE THE DATA!!

Omission is often a cause of poor technique. Suppose you measure the viscosity of a liquid at 25°C obtain and obtain a precise result but forget to record the temperature - viscosity shows a strong temperature dependence. You have an uncorrectable uncertainty in your result as you do not know the temperature at which the experiment was performed at. The best you can do is to say you know the viscosity between say 15 and 30°C.

Accuracy & Precision, Summary

In principle you may correct for systematic errors.

IF YOU REPEAT AN EXPERIMENT UNDER IDENTICAL CONDITIONS THE SYSTEMATIC ERRORS WILL BE IDENTICAL

Random errors may not be corrected for. Their effect upon the results depends upon unpredictable random events.

IF YOU REPEAT AN EXPERIMENT UNDER IDENTICAL CONDITIONS, THE RANDOM UNCERTAINTIES WILL NOT BE IDENTICAL.

i.e. you get different results! However in principle their magnitude may be reduced infinitely small.

If a value obtained from an experiment is:	Then it is
Accurate	close to the true value
Precise	has a small uncertainty, but this does not necessarily mean that it is close to the true value
Precise & Accurate	close to the true value AND with a small uncertainty. We would like data to fall into this category

Uncertainty is our (human) assessment of the unreliability of the data, and is usually attributed to *random* or *systematic* errors.

Systematic errors are constant throughout a set of readings, or are in some way proportional to one or more of the variables.

Random errors vary from reading to reading and are equally likely to be positive or negative.