Notes about Experimental Reports

These notes are intended as guidelines as to how to process results from experiments and how to write the results up, in a standard and clear form. Experiment is the basis of scientific research, and it is important to extract the maximum ammount of usable information from the data and to present this in a form which others can understand. The notes cover 3 main areas : the form of the report, experimental error analysis, and issues relating to graphing the results.

1 Format of the report

An experimental report needs to be broken down into sections detailing specific elements of the information to be conveyed. Conventionally a lab report will contain the following :

- Title
- Outline
- Theory
- Method
- Results
- Analysis
- Conclusions

although the exact names given to the various sections may vary. *Title* is fairly explanatory – it should contain the names of the experimentors and probably also the date. The *Outline* section is a brief (2-3 sentences) description of what the experiment is to be and what it is supposed to achieve. The *Theory* section should be a description of the theoretical concepts that will be involved, either in processing the results or (often) theoretical concepts that are to be tested in the experiment. It should be consise, and may well reference outside sources (see below for details about referencing). The *Method* is also fairly self-explanatory – this section contains a description of *what was done* by the experimentors. It should be written in the past passive tense – i.e. 'The apparatus was switched on and left for 10 minutes to warm up', rather than 'We switched the apparatus on and left it for ...'.

The next section, *Results* contains the raw data plus preliminary processing – in essence, the output from the experiment. It will probably include tables of data (unless so much data was measured in the experiment in which case this should be provided as an appendix) and probably graphs of the data. The other thing it should contain is an analysis of the experimental errors (see below). The 'Analysis' section contains further

analysis of the data gathered. Obviously there is a judgement call as to what belongs in which section, and some material could probably go in either. But for example, suppose you were writing a report comparing methods for measuring flow rates. Such an experiment might use methods such as timed volumetric collection, weirs and flumes. The *Results* section would contain the raw data, such as volume collected in measured time periods, and process this as far as calculating the volumetric flow rate, whilst the *Analysis* section would compare the results from the different measurement techniques. Finally there are the *Conclusions*, a short (1-2 paragraphs) section summarising the outcome of the experiment. The way to look at this is, if your reader only has time to read one section of the report, the conclusions should tell him/her what the outcome of the experiment was.

Reports should of course conform to the usual rules of spelling and grammar – spellcheck your document, but do not rely on this to pick up everything (a spellchecker will knot pick up certain types of error!) Some points to ponder :

- Figures, graphs and diagrams should be numbered and captioned.
- Most measured values will have some kind of units associated – make sure you include them.
- External work should be clearly referenced. There are several ways of doing this, but they all basically involve some form of marker in the text : '[1]' or '(Tabor, 2002)', and a list at the end of the document listing the references in some order. The important point to remember about references is that the information you give should allow your reader to track down the reference without too much effort. Book references should include title, author or editor, publisher and date of publication [1] (plus possibly a page or section number) : journal papers should give title, author(s), journal name, volume and page, and year of publication [2]. Web pages are more difficult to reference, as they tend to be transitory (one reason why web sources are not highly regarded), but should contain the url at the least.
- It is not plagiarism to include information from other sources, provided you make it clear that you are doing so.
- Contractions (doesn't, didn't) are not acceptable in a formal report, even though they are commonly used in everyday situations. Don't use them (sorry : that should be 'Do not use them').
- Paragraphs are your friends! A paragraph is a group of 2 or more sentences grouped together because they share a common theme. The first sentence is often indented, and subsequent sentences continue without line breaks.
  Some students seem adept at producing work where each sentence has a line break at the end.
  Something like this!
  This is ugly and difficult to read.
  Please do not do this either!

Many of these points are appropriate for other types of technical reports as well. Finally, try and avoid poor typesetting. 'Orphaned' words, such as section titles at the bottom of the page (the text of the section being on the following page) look bad. Word's equation editor is clumsy and difficult to use, but will give better results than just writing out ASCII.[1]

2 Error analysis

The proper treatment of errors seems to be the area that causes the worst problems for students. I think this is because many confuse 'error' with 'mistake'. In experimental work, the estimation and treatment of errors is as important as the measurements themselves. All measurements made in the lab have associated with them a degree of uncertainty in value. Timing an interval using a stopwatch introduces a degree of uncertainty in the human reaction time – but a fully electronic system (say involving light gates) will also introduce a measurement error, although hopefully a smaller one. (How much of the light gate needs to be obstructed to trigger it? If the obstructing object is not exactly following the same trajectory each time the gate may not trigger at exactly the same point each time – an error). What we need to do is to find ways of estimating the error in the various measurements, because this gives us an understanding of the confidence that we can place in the measurement. Say our theory suggests that the value $X = 2.51$. We measure this value experimentally, and discover $X = 2.74$. Is this a significant departure from theory? Well, if the error in the measurement is ± 0.01, then we would say that the two numbers are very different. On the other hand if the error is ± 0.5, then there is no reason to suggest that the measured value is in disagreement with theory. Either way we would quote the result of our experiment as

$$X = 2.74 \pm 0.01 \quad \text{or} \quad X = 2.74 \pm 0.5$$

So how do we arrive at these estimates of error?

2.1 Different types of error

In fact there are two distinct types of error to be considered : *random* and *systematic*. Let us denote the 'true' value of the variable X to be X_t. Although we will never actually know what this is, we know that X will never be exactly the same as X_t, because of the measurement errors. However if we take successive readings of X they are likely to distribute themselves in some pattern around X_t. If X is equally likely to be bigger than X_t as to be smaller, i.e. the measurements are randomly distributed around X_t, then we have a *random* error. On the other hand the readings may all be offset from the true value by some constant ammount. In this case we have a *systematic* error. As

[1] Word is, IMHO, a poor choice for writing technical documents, but it seems to be one commonly used, so a lot of this document is discussing its shortcomings. Me, I use LaTeX!

an example, consider measuring people's heights by getting them to stand up against a ruler on the wall. The exact value recorded will depend on where the experimentor's eye is in relation to the subject's head and the ruler; there will be a parallax error in the resulting measurement, which will be different for each measurement (the experimentor is very unlikely to place their head in the same place each time). However this error is just as likely to make the reading too large as too small – a random error. On the other hand, if everybody being measured is wearing shoes with 2 cm soles. In this case each measurement will be 2 cm too large – a systematic error.

Clearly, since X_t is and will remain unknown, we have no absolute way of distinguishing random and systematic errors, other than looking at the experimental setup. Systematic errors should be detected and eliminated if possible (if you can work out the systematic error then you can at least subtract this from the measurements afterwards). Random errors are more difficult : a better experiment might reduce them, and taking several measurements and averaging will also reduce them. However they can never be eliminated altogether, and all results from the experiment should be quoted with an estimate of the associated error – which we will denote ΔX – thus :

$$X \pm \Delta X$$

Estimating the size of the likely errors is important, and can usually be done by thinking about the experiment in detail – how much is the needle on the voltmeter fluctuating, what is my response time likely to be, how accurately can I measure the position of this meniscus, what is the effect of parallax error.[2]

Linked to this are the concepts of *precision* and *accuracy*. A reading is accurate if the true value is thought to be likely to lie within the error estimate $\pm\Delta X$. A reading is precise if the error estimate ΔX is small. Thus, in measuring the heights of the subjects, if your ruler is calibrated in decimetres (i.e. intervals of 10 cm, the best you may be able to do is to measure a height as 1.8 m – which may be accurate but is not very precise. On the other hand if your ruler is ruled in mm you may be able to read the height as 1.783 m. Although this is more precise, it may not necessarily be more accurate – don't confuse the two.[3] The precision of a result is reflected in the number of significant figures, or sig.figs, that the result is quoted to. The result 1.783 m is quoted to 4 sig.figs, and this suggests that you are claiming that your experiment is measuring to 1 part

[2]There is quite a lot of associated theory about errors. Random errors can be expected to distribute themselves in a pattern around X_t known as a *normal distribution*, whose mean value should be the true value (assuming no systematic errors). The width of this distribution is the *standard deviation* σ, and error estimates are conventionally quoted $\pm 3\sigma$. Averaging readings reduces this in ways which are well understood. However for most undergraduate experiments this level of sophistication is probably not needed, and the estimating techniques suggested here are probably adequate.

[3]The Hubble space telescope was launched with a duff mirror because of such a confusion. The mirror curvature was measured with two techniques – an older method which gave a low-precision result, and a modern technique using lasers which gave a high-precision result. The two results disagreed, and the engineers building this subsystem just threw away the low precision result and used the laser-based result. Unfortunately it turned out that the laser rig had been incorrectly assembled, leading to a systematic error. The results were precise, but inaccurate.

in 1000. The number of sig.figs quoted for a value should always reflect the precision of the measurement. (Note that this goes for calculations as well – your final answer from a calculation should reflect the likely precision of the calculation, not the number of digits on your calculator). This is also different from the number of decimal places, which is not a very relevant concept (1.783 m is the same as 178.3 cm, different number of decimal places, same number of sig. figs).

2.2 Combining errors

Suppose you are measuring flow rates by timed volumetric collection. You estimate the error in the timing to be ± 0.5 s, and the volume measurement to be ± 5 ml. The volumetric flow rate is of course

$$Q = \frac{V}{t}$$

What is the measurement error ΔQ resulting from the errors Δt and ΔV? More generally, how do we combine errors when processing our raw results.

To answer this, we need to introduce two further concepts, *absolute* and *relative* errors. An estimate of $\Delta t = 0.5$ s is an absolute error. However it may be important to consider how this compares with the size of the quantity being measured. 0.5 s is a very significant error if you are trying to measure a time interval of 10 s, less so in one of 10 mins. Thus, the *relative* error

$$\frac{\Delta X}{X}$$

may also be important to consider.

Now, combining errors. If we wish to add X and Y, then we add the absolute errors :

$$Z = X + Y, \qquad \Delta Z = \Delta X + \Delta Y$$

On the other hand, if we multiply X and y,

$$Z = X \times Y$$

then we add *relative* errors

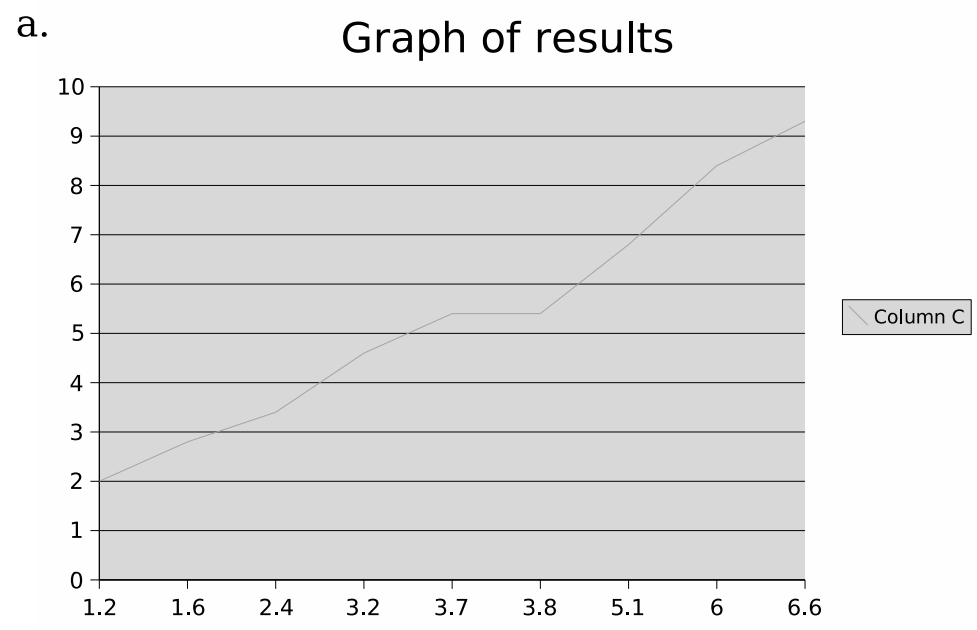
$$\frac{\Delta Z}{Z} = \frac{\Delta X}{X} + \frac{\Delta Y}{Y}$$

Simple, huh!

3 Graphs

Most students use Microsoft products for writing up their work, and thus use Excel as a way of generating graphs from their data. Whilst Excel is a good spreadsheet, with numerous useful features for presenting data such as company profits, sales and so forth, that does not make it good for presenting scientific results. I frequently find myself

a.



b.

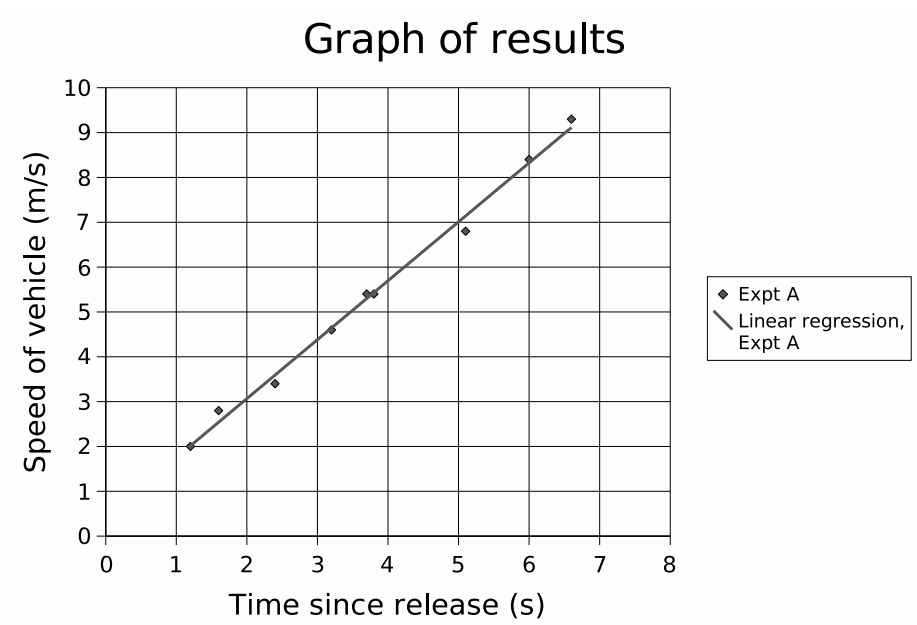


Figure 1: a. (top) an example of a very poor graph produced with the default settings in Excel. b. (bottom) a much better version of the same graph.

confronted by graphs such as figure 1a. This was produced with the default settings (very largely) of Excel's Chart feature.

So what is wrong with this? Quite a lot, although I do admit this is a composite of a lot of errors (I have seen a few graphs this bad though). Some obvious points : the axes have no captions describing what they represent or what units they are measured in, and the x-axis scale is non-linear – the points are equally spaced, so the space between 3.7 and 3.8 is the same as between 5.1 and 6. Also, I dislike graphs drawn on grey backgrounds.

There are some more subtle points to note with this as well. The graph is drawn as a solid line, without the experimental datapoints on it. This gives a misleading impression of what the graph is showing. On this graph you cannot locate the actual datapoints or distinguish them. There are in fact no experimental measurements between $x = 4$ and $x = 5$, but you would never know that. For an experimental dataset, the datapoints should be marked clearly, and if the measurement errors are large enough, *error bars* may be placed on the points to indicate the range of values covered by the measurement. Moreover, although the points are joined with straight lines here, Excel can also use a technique called spline fitting to produce a smoothed curve through (or sometimes not) the datapoints. This gives a totally false impression of the data being presented and could be very dangerous. So when should you include lines on the data? Sometimes joining the points with lines can be helpful if there are a lot of different datasets on the graph that need to be distinguished – but the actual physical datapoints themselves need to be clearly marked, as stated. Another reason would be if you were comparing your results with some known theoretical result. This would be an equation relating x and y, such as $y = 5 \sin x$, which is true for *every* value of x. In this case there is no reason to single out any particular value of x for special treatment, so the theoretical curve should be a line without points being distinguished (even though you will probably generate it by creating a table of x and y values). There is a third reason for putting lines on the graph; regression analysis, which is discussed below.

Figure 1b. shows a much improved version of the same data. Axes have captions and units, as do the datasets; the experimental data is presented as discrete points, and the scales are linear. The resulting graph – produced from a few minutes altering the options in Excel – is both more professional-looking, and also conveys the necessary information more faithfully.

3.1 Regression Analysis

Figure 1b. also includes a trend line or regression curve. Sometimes we have reason to believe that our data should fit some particular type of equation, and wish to determine the coefficients. Here, for example, we believe that the vehicle is accelerating linearly, and so the velocity should obey the law

$$v = mt + c$$

where we wish to evaluate m and c from the data. In general a straight line has the equation

$$y = mx + c$$

where m is the slope of the line and c the value at which it intercepts the y-axis. How can we find m and c? If $c = 0$, you could calculate y/x for every point and average. Alternatively, you can draw the line on by hand, judging it to pass as close as possible to all the points. Or ou can make use of a branch of statistics called *regression analysis* to basically do the same thing, using sophisticated mathematics to find a line that passes 'as close as possible' to all the datapoints, for some definition of 'as close as possible'. Luckly this is already programmed into Excel, and so it is possible to generate regression analyses for your datasets using straight lines, and more sophisticated curves such as polynomials or exponentials, if these seem more appropriate for the data. You notice that the regression line does not pass through the datapoints, in fact there is a spread of data around the line, which is probably indicative of the random error in the measurements. This is a good technique for extracting some valuable data from the measurements. You should of course state in the report exactly what you are doing ('Regression analysis was used to fit the straight line $y = mx + c$ to the data').

4 Conclusions

The objective of this document is to provide a synopsis of the characteristics of a good experimental report and to correct some of the more annoying errors that students tend to come up with. Obviously if you are making errors in taking the data I cannot help with that, but if you take heed of these notes when preparing the writeup the result should look professional and be clear to read – as well as getting a good mark (from me at least!) Further information can of course be found from a number of sources [1]. All rules are made to be broken, and these guidelines are not intended to be completely prescriptive – but if you do decide to ignore an element of this, you should have a good reason for doing so.

Gavin Tabor. Jan 2006.

References

1. 'Practical Physics', G.L. Squires, 4th Edn. CUP (2001).

2. 'Teaching CFD using Spreadsheets', G. Tabor, Int.J.Mech.Eng.Ed. **32#1** pp. 31-53 (2004).