Writing a Laboratory Report

1. *What is a laboratory report?*

Scientific results are of little value if they are known only to the experimenter: even commercially sensitive research has to be documented for use by, for example, the patents office or the workforce who are going to build your wonderful new invention. As scientists, therefore, we must develop the ability to communicate our results clearly and effectively to other people.

A laboratory report is the basic form of scientific communication. The aim of a laboratory report is to explain the purpose, methods and results of an experiment *clearly and concisely* to a *non-specialist scientific reader* who is *completely unfamiliar with the experiment*. The model for a laboratory report is an experimental or observational paper in a scientific journal such as *Physics Letters* or the *Astrophysical Journal*.

Note the important points in the above paragraph: the report should be:

- complete (because you are writing for a reader unfamiliar with the experiment), but concise (do not include extraneous detail or waffle);

- logically structured (to communicate your results clearly);

- quantitative (your reader is scientifically trained).

Because you are writing for an outside audience, your report should also be written in good, formal English: errors in spelling and grammar are acceptable in a lab diary, but they *will be penalised* in a laboratory report.

2. *Basic structure*

A laboratory report will normally have the following structure:

(i) *Title*
Should be brief (typically 5–15 words) but informative: *Determination of g using a simple pendulum* is better than *Determination of g*; *Selection effects in the Hertzsprung-Russell Diagram* is more helpful to the reader than *The Hertzsprung-Russell Diagram*.

(ii) *Abstract*
A paragraph (50–150 words) summarising the purpose, method and principal results of the experiment. It is usually best to write the abstract last: it is easier to summarise something if you know what it is you're summarising!

(iii) *Introduction*
This should describe the purpose and scientific context of the experiment, and point out any special features; in other words, it should answer the questions, "Why do this experiment?" and "Why do it this way?" It should be fairly short: typically somewhere between a paragraph and a page, and certainly not more than say 20% of the total length of the report.

(iv) *Theory*
Most experiments set out to test a theory, or rely on theory for their interpretation (e.g. deducing an object's effective temperature from its luminosity requires Stefan's law). It is usually best to lay out the theory, and define any specialist terms, before describing the experiment itself. Important equations should be numbered, so that they can be referred to later in the report.

(v)   *Method*
In a typical experiment in the general physics laboratory, this section describes how the experiment was performed: the equipment and other materials that you used, the measurements that you made, and any special precautions that had to be taken (for example, restricting the swing of a pendulum to small angles). It should normally include a labelled sketch of the apparatus.

In most experiments in the astronomy lab, this section relates to work that you did not do yourself—for example, taking photographs of the Moon, determining the masses of a set of binary stars, etc. In this case, this section should nonetheless include a short paragraph noting the important features of the experimental method (e.g. the types of binary system from which stellar masses can be determined) and giving a reference to the *original* source of the data, not just to the lab script. (The original source should be cited in the script; if it is not, ask a demonstrator.)

(vi)   *Analysis*
This should include the measurements that you make, with a discussion of the associated uncertainties, the analysis that you do to convert these raw data into the desired physical quantity, and the final results. The data should be presented in enough detail to justify the results: in particular, it is often necessary to show the raw data (before conversions or manipulation) in order to justify the values of the numerical uncertainties. Particular points to note are:

- data should be presented graphically if possible (it is easier to assimilate information graphically);

- if you do present data graphically, you should *not* also present them in tabulated form (e.g. if a report of an experiment to measure g includes a graph of d against t^2, it should not also have a long table of values of d and t);

- if long tables of data *are* necessary (which should hardly ever be the case), they should be relegated to an appendix;

- numerical values should be presented with their associated uncertainty, rounded to the appropriate number of decimal places (e.g. 12.34±0.16 s, $(1.28±0.06) \times 10^4$ W m^{-2}, 5.7±0.3 mm).

For more detail on presenting data, see section 3 below.

(vii)   *Discussion of results*
This section should start with a summary of the results obtained, if possible compared to textbook values or theoretical predictions. If the same physical quantity has been obtained by two or more methods (e.g. measurements of g made by pendulum timing, by sliding an object down a slope, and by timing a falling body), then the results of the different methods should also be compared.

If there are discrepancies between your measurements and the textbook values, these should be discussed: see section 3 for a guide to what constitutes a "discrepancy". Note that blaming any discrepancy on "inaccurate measurements" is *not* a good move: your experimental uncertainty should include the effect of inaccuracies in the measurement, since that's what it's intended to describe! Possible *valid* reasons for discrepancies include breakdown of the theoretical assumptions (e.g. a pendulum swinging with too wide an arc to be described by small-angle approximations), calibration errors (e.g. miscalculating the image scale on an astronomical photograph), and problems with the apparatus (e.g. an unexpected resistance in an electrical circuit caused by a bad connection).

Any possible improvements to the apparatus or technique could also be included in this section (e.g. "the largest uncertainty in this result comes from the length of the pendulum wire, which was found to stretch significantly when the bob was attached; the precision of the result might therefore be improved by using stiffer wire"). One should not be too unrealistic when suggesting such improvements: if air resistance is a problem, suggest a more streamlined projectile, not moving the experiment to Earth orbit!

(viii) *Conclusions*

This section summarises the extent to which the aims of the experiment (as laid out in the Introduction) have been achieved, what you have learned from the results, and how the results fit into a broader context (e.g., if you have shown that the Sun is approximately a blackbody, you may conclude that the laws of blackbody radiation can usefully be applied to other stars). It is often combined with the previous section (as *Results and Conclusions*), especially if the experiment worked well and there are no serious discrepancies or potential improvements to discuss.

(ix) *Acknowledgments*

If anyone has helped you particularly, either in doing the experiment or in writing the report, they should be acknowledged, e.g. "I thank my lab partner, Jane Bloggs, for her help in obtaining these results, and my tutor, Dr Smith, for reading and commenting on a draft of this report."

(x) *References*

You will probably have had to look up standard values in textbooks or data books, and you may also have had to consult a textbook or lecture notes for help with the theory. Places where you have done this should be indicated in the text (e.g. "… where the value of the astronomical unit is 1.4960×10^{11} m (Carroll and Ostlie, 1996)") and the full reference (in this case, B.W. Carroll and D.A. Ostlie, *An Introduction to Modern Astrophysics*, Addison Wesley, 1996) given in this section. You can either use the authors' names and year of publication in the text, as here, or indicate references by a number, e.g. [1] or [1], and then number the items in your reference list.

This structure is a *general guide*. Individual experiments may require slight changes: for example, an experiment which produces only one numerical result, in good agreement with theory, may not need a separate "discussion of results" section: just go straight from "analysis" to "results and conclusions". Conversely, experiments which have several rather disconnected parts may work better if the results are quoted immediately after the relevant method, so that the reader does not have to keep skipping back and forth:

- Introduction

- Theory

- Methods

  - Method 1
  - Analysis and Result 1

  - Method 2
  - Analysis and Result 2

  - Method 3
  - Analysis and Result 3

- Summary of Results

- Conclusions

> *Note that the section titles of a real report should be more helpful than this. For example, a report on the determination of g might have sections entitled*
>
> *Method 1: Timing a falling body*
>   *Analysis*
>   *Results*
> *Method 2: Motion down an inclined plane*
>   *Analysis*
>   *Results*
> *Method 3: The simple pendulum*
>   *Analysis*
>   *Results*

This is even more likely to be true if the later parts of the experiment rely on the results obtained earlier: for example, if you first determine the viscosity of a fluid, and later do several calculations which depend on this, it would be crazy to wait several pages before divulging the measured value of the viscosity!

The over-riding criterion is that the report should be *logically ordered* and *easy to read*. If the standard structure imposes an illogical ordering, or makes the report difficult to read, then you should not be afraid to change it. But it is worth pointing out that this structure has developed over many years of presenting scientific material *because* it is usually the most logical approach—so do think carefully before abandoning it.

3. *Presenting data*

The heart of a laboratory report (or a scientific paper reporting experimental or observational work) is the actual data—including, of course, the associated uncertainties. You should think carefully about how to present your data as clearly and effectively as possible.

3.1 *Graphs, tables and figures*

Your report will almost certainly include graphs or tables of results, and may well have other pictorial material, e.g. a diagram of the apparatus. These should be numbered, so that they can be referred to in the text. It is usual to number graphs and other pictures sequentially as *Figure N*, and tables separately as *Table N*: thus a report might contain Figure 1: diagram of the apparatus; Table 1: calibration constants for the thermocouple; Figure 2: graph of length against temperature for different materials; Table 2: measured expansion coefficients compared with textbook values.

- *Graphs* should have *clearly labelled axes* (name of quantity and units, e.g. temperature (K), resistance (kΩ), etc.). If there is more than one line, or more than one type of point, on the graph, a *key* or *legend* should be included *on the graph* (not just in the text: many readers will look at the graphs first, before reading the text!). There should be a *title* or *figure caption* making it clear what is being graphed. Points on graphs should normally have *error bars* corresponding to the estimated uncertainty of the point; if the error bars are too small to show on the plot, say so in the figure caption or in the key.

  You will often need to fit a straight line to points on a graph in order to obtain the physically important quantity (for example, you might get g from the gradient of a graph of d against t^2). Remember that you must also determine the *error* on this gradient (see section 3.2): if you are using Excel, the function `linest` will do this for you, but `Add Trendline` will not.

  Minor note: a plot of d against t^2 has t^2 on the x-axis, whereas a plot of t^2 against d has d on the x-axis. If fitting a straight line, you should be aware that the standard formula used by Excel assumes (i) that all the points have similar-sized errors and (ii) that the quantity on the y-axis has larger errors than the one on the x-axis.

- *Tables* should be *clearly laid out* with column headings giving name of quantity and units, as with graphs. As a general rule, do not include a table if you have presented the same data graphically. As with graphs, the uncertainties should always be quoted along with the numerical values, and the table caption should indicate what is being tabulated.

- *Figures* should be clear and well laid out. In diagrams of the apparatus, important parts should be labelled, and it is usually best if the diagram is at least approximately to scale (if it is not to scale, this should be stated). You should also consider adding figures to your theory section: they are often helpful in defining terms and clarifying relationships between objects. For example, a

force diagram would be useful in explaining how to determine *g* by sliding an object down an inclined plane.

3.2 *Uncertainties*

As you know, all numerical values in your report should have an associated uncertainty or experimental error. You determine this error in two steps:

(i) *Estimate the error in the raw data*: for example, you may feel that you can measure the length of a simple pendulum to ±0.5 mm.

(ii) *Manipulate this error mathematically to derive the error in the final result*: for example, a simple pendulum of length *l* has period $2\pi\sqrt{l/g}$, so $g = 4\pi^2 l/T^2$, where *T* is the period. Using the standard formulae, we find that the error on *g* is given by

$$\frac{\Delta g}{g} = \sqrt{\left(\frac{\Delta l}{l}\right)^2 + \left(\frac{2\Delta T}{T}\right)^2}$$

(we add relative errors because we are dividing *l* by T^2, and the 2 comes from the fact that *T* is raised to the power 2).

In your lab diary, you may well have devoted much more space to step (ii) than to step (i). But in the report, you must reverse this. Your scientifically trained readers know the standard formulae: they will *expect* you to calculate the relative error on T^2 by doubling the relative error on *T*. But they do *not* know how accurately you could measure the length of the pendulum: this depends, for example, on how easy it is to estimate where the centre of the bob is, whether the string stretches, etc. So you must explain carefully how you arrived at your estimate of ±0.5 mm, and what evidence you have that your estimate is reasonable (for example, you and your lab partner measured the string independently, and your measurements agreed to within 0.5 mm).

3.3 *Comparing your results with textbook values*

Once you have your result with its uncertainty, you can compare it with standard values. For example, suppose that you have a simple pendulum with a length of 996±2 mm, and you find that its period is 1.99±0.02 s. Your value of *g* is then 9.93±0.20 m s^{-2}. Comparing this with the standard value (at sea level) of 9.81 m s^{-2}, you see that it is about half an error bar off. This is good agreement (in quoting an error of ±0.20 m s^{-2}, you are in effect saying that the true value of *g* most probably lies between 9.73 and 10.13 m s^{-2}, which it does).

What if you had measured *T* = 1.98±0.02 s, giving *g* = 10.03±0.20 m s^{-2}? The true value is not quite included within your error range of 9.83 to 10.23 m s^{-2}—should you therefore conclude that your experiment is wrong? No, because your error bar only says that the true value *most probably* lies in that range: for example, if the true value of *l* is 994 mm (within your uncertainty) and the true value of *T* is 2.00 s (also within your uncertainty) you do indeed get *g* = 9.81 m s^{-2}. This outcome is improbable, because it requires that both of your measured quantities are a whole error bar away from the true value, in opposite directions—but it is clearly not impossible. As a general rule,

- if the difference between your value and the true value is *less than one error bar*, the two values are in *good agreement*;

- if the difference is *between one and two error bars*, the two values are still *consistent*: there is a reasonable probability that a discrepancy this large is just due to bad luck (though it would be worth looking for an alternative explanation, such as misjudging the location of the centre of mass of the pendulum bob);

- if it's *between two and three error bars*, it is likely that you have a problem: the probability of this happening by chance is less than 1 in 20. After rechecking your error calculation to make

sure you have not just made a mistake, look for flaws in the design of the experiment, or in your measurements (perhaps you set the pendulum swinging with too large an amplitude, so that the small-angle assumption made when deriving the formula for the period is not valid; perhaps you meant to measure 100 swings, but in fact measured 99).

- Finally, if the difference is *more than 3 error bars*, you definitely have a problem: the probability of this being simply bad luck is minute ($<<1\%$). You *must* discuss this carefully in your report—don't simply try to ignore it.

Note that these issues are best considered when you're actually doing the experiment, since you can then repeat the suspect measurement, examine the apparatus for problems, and so on. If you have kept your lab diary conscientiously, you will have logged any problems of this type and the steps you took to investigate them.

What about the textbook value itself? Does it have an error? In some cases, the answer is "no": the speed of light in a vacuum is *defined* to be 299 792 458 m s^{-1} *exactly* (this, together with the definition of the second, is the formal SI definition of the metre). Good professional reference sources will quote the error on experimentally determined values: for example, the 1994 *Review of Particle Properties* gives G as $(6.67259\pm0.00085)\times10^{-11}$ m^3 kg^{-1} s^{-2}. If the error is not quoted, it is best to assume that the value has been given to an appropriate number of significant figures: Carroll and Ostlie give the mass of the Sun as 1.989×10^{30} kg, implying that the error is not more than 0.0005×10^{30} kg (in fact the *Review of Particle Properties* gives $(1.98892\pm0.00025)\times10^{30}$ kg). Generally, of course, the error on a textbook value will be much less than your experimental error—but beware of textbooks which give too few significant figures: for example, if you have determined g to be 9.82 ± 0.02 m s^{-2}, a textbook which just gives "9.8 m s^{-2}" is not good enough, because while 9.8 *could* represent 9.80 (in good agreement with your value), it could also represent 9.76 (three error bars away, and therefore in serious disagreement).

3.3 *Calculations, algebra and arithmetic*

Your lab diary is probably full of calculations. However, if you look at a scientific paper, you will see that most papers contain very few calculations: they are mostly text. This is because we assume that the readers are scientifically trained, and capable of reproducing your arithmetic without having to have it all laid out for them. Thus, if your theory section defined equation (2) to be the relationship between apparent and absolute magnitude, $m - M = 5 \log_{10}(d/10 \text{ pc})$, you might say, "Using equation (2), it can be seen that a class K main sequence star of absolute magnitude 8.0 would appear in the bright star sample ($m \leq 2.6$) only if its distance were less than 0.83 pc." In your lab diary, this statement came after a couple of lines of algebra and arithmetic—but these should *not* be included in the report.

Note that the same applies to the theory section: if you need to derive any equations, you should show the minimum number of steps necessary to do the derivation. For example, the previous equation might be derived like this:

The basic equation relating two magnitudes m_1 and m_2 is
$$m_1 - m_2 = -2.5 \log_{10}(f_1/f_2), \tag{1}$$
where f_1 is the flux received from star 1 and f_2 from star 2.

If m_1 and m_2 represent the apparent magnitudes of the same star at distances d_1 and d_2, the fluxes can be related using the fact that
$$f = L/4\pi d^2,$$
where L is the luminosity of the star. Substituting for f_1 and f_2 in equation (1) gives
$$m_1 - m_2 = -2.5 \log_{10}(d_2/d_1)^2 = 5 \log_{10}(d_1/d_2).$$

For the absolute magnitude M, $d = 10$ pc by definition, so for a star of apparent magnitude m and distance d,
$$m - M = 5 \log_{10}(d/10 \text{ pc}). \tag{2}$$

Note that you should *explain* what you are doing to the reader, not simply present a list of equations!

4. *Language and style*

A lab report is a piece of formal writing: you *will* be penalised for spelling mistakes, bad grammar and poor style. There are two reasons for this. First, bad English often makes it difficult for your readers to understand what you mean: in some cases, a few grammatical errors can actually result in your sentence saying the exact opposite of what you intended it to say. More often, the meaning is simply unclear—but given that our aim in writing a report is to communicate the results clearly and effectively, even an ambiguous meaning is unsatisfactory.

The second reason for avoiding poor English is perhaps unfair, but is nonetheless a fact of life: if the paper is not well written, readers have a tendency to assume that the experiment was not well done ("if he doesn't take the time to proof-read his report, he probably doesn't take the time to check his results").

4.1 *Planning*

The first essential is to *plan* your report. Even immaculate English cannot rescue something that is badly structured, disorganised and confused: conversely, a well organised report written in poor English can usually be salvaged fairly easily with help from your tutor or a friend with better writing skills.

You should base your plan on the structure set out in section 2. For each section, note down the points you want to include, and list any diagrams, tables or graphs that are needed. Remember that your readers are unfamiliar with the experiment and certainly haven't read the lab script, so don't assume that they already know what you're talking about! Think about the order in which the material should logically be presented: this may not be the same as the order in the lab script. When you have written your draft report, go through your plan again and check that you have included all the points you listed.

4.2 *Style*

Scientific reports are usually written in impersonal language: "the resistance was measured", not "we measured the resistance"; "figure 2 shows that" or "it can be seen from figure 2 that", not "you can see from figure 2 that". This is probably not a style you are used to using (and the grammar checker in Word will complain like mad), but it is the standard approach and we will penalise you if you do not use it. The reason for it is probably that it focuses attention on the results themselves, and not on the person who did the work: the implication is that these are results that *anybody* can reproduce by repeating the experiment as described. This is a cornerstone of scientific enquiry, and is one reason why experimental papers contain details of the experimental method ("here's how we did it—go ahead and try it yourself if you don't trust us").

Tense in scientific reports is a bit confused: normally you use the *past* tense when describing *what you did* ("the resistance *was* measured"), so the methods and analysis sections should be in the past tense. On the other hand, the background information and the theory are presumably still true, so they are normally in the present tense ("the measurement of stellar masses *is* a key factor in understanding stellar structure and evolution"): thus the theory, and probably the first half of the introduction (explaining why the experiment is interesting and important) should be in the present tense. Likewise, comparisons of results and descriptions of features of the data should be in the present tense ("the results *are* shown in figure 2"; "the points in figure 2 *lie* on a straight line"; "the measured value *is* in good agreement with the prediction"). Basically, do what seems right: if you are describing something that happened in the past, use the past; if you're talking about something that still exists, use the present.

4.3 *Spelling and grammar*

As mentioned above, you *will* be penalised for spelling and grammatical errors. If you are word-processing (which we would normally expect), do use the spell-checker, but remember that it is not foolproof: it will not help you if you confuse 'there' and 'their', or misspell proper names such as Kepler or Hertzsprung. In some cases, it will even make things worse: for example, Word's spell-checker refuses to believe that 'luminosity' has a plural, and will therefore ask you to change the perfectly correct "stellar luminosities range from 10^{-4} to 10^6 times that of the Sun" to the nonsensical "stellar luminosity's…".

If you really can't spell, your best bet is to ask someone who *can* spell to proof-read a draft of your report for you. If all your friends are in the same boat, try your tutor, or the Writing Advisory Service of the English Language Teaching Centre, which is intended for precisely this purpose (for booking details, visit http://www.shef.ac.uk/eltc/was.html).

While spelling errors are embarrassing (they make you look uneducated and/or lazy), grammatical errors are potentially more serious: they can change the sense of what you've written so that it no longer means what you intended it to mean. Software is not much help here: Word's grammar checker is easily confused by anything more complicated than "the cat sat on the mat", and is likely to object to perfectly good sentences while missing obvious mistakes. If you are not confident of your syntax, the only solution is to get help: your friend doing modern languages, your tutor, or the Writing Advisory Service.

4.4 *Proof-reading*

Before you hand your report in, *read it carefully and critically*, checking for spelling mistakes, typos and formatting errors. It is just plain daft to hand in a report with a crucial graph missing altogether, a figure appearing on the wrong page and blotting out half a paragraph of text, all the superscripts or Greek letters left out, or program error messages appearing in the middle of the text (we have had all of these). You should *never* get yourself into the position where you grab your output off the printer and run straight to the office to hand it in.

5. *Assessment*

Your report will be marked for content, presentation and style. The relative weights are as follows:

Content	30%	Does the report include all the necessary material? Is the balance between sections right? Is there any unwanted material (waffle in the introduction, unnecessary tables of data, algebra, or arithmetic)?
Data presentation	30%	Have the data been presented in the most appropriate way? Are graphs and tables clearly set out, with axis labels, keys to symbols, etc.? Are the uncertainties or experimental errors properly presented, including discussion of sources of error and estimation of size of error? Are numerical results quoted to the proper precision, taking account of the estimated error?
Language and style	30%	Is the report logically organised and well structured? Is it written in good English, without errors in spelling or grammar, and in the correct scientific style?
Abstract	10%	Does the abstract provide a clear summary of the report, including aims, methods and principal results? Is it of a reasonable length (typically 50–150 words)?

Feedback emphasising the strengths and weaknesses of your work will be provided. You should take this seriously: it is intended to help you. If you are not sure why you have been criticised on a particular point, ask to speak to the person who marked it.

6. *Examples and further reading*

Example reports are provided in the first year physics Laboratory Handbook and in the astronomy Lab Resource Pack. Chapter 7 of *Experimental Methods* by Les Kirkup discusses report writing and includes a short example: it is useful to compare Chapter 7, describing a report, with Section 1.3, describing a lab diary.

Useful reference books for comparison values are:

- Kaye and Laby's Tables of Physical and Chemical Constants (Longman; the most recent edition is the 16th, 1995)

- Kenneth Lang, *Astrophysical Data: Planets and Stars* (Springer, 1993)

- C.W. Allen, *Astrophysical Quantities*