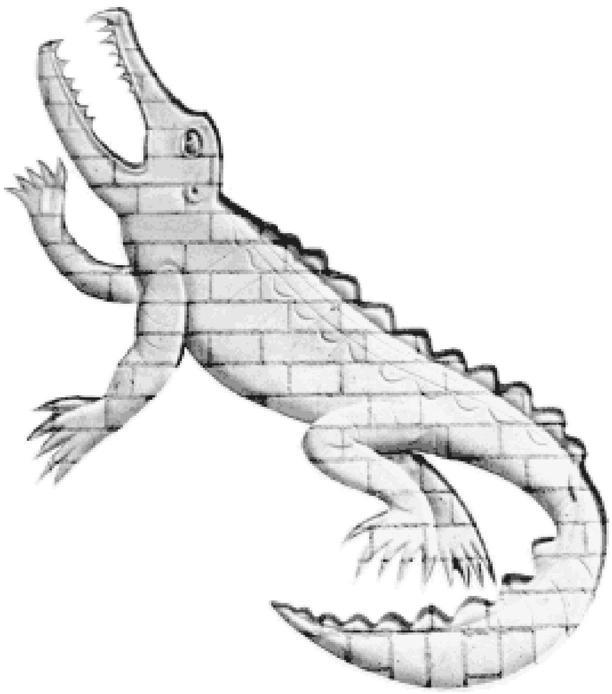
Department of Physics
University of Cambridge

Keeping Laboratory Notes and Writing Formal Reports



Cavendish Laboratory

Why a crocodile? See http://www.phy.cam.ac.uk/history/years/croc.php

Keeping Laboratory Notes and Writing Formal Reports

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1 Introduction

These notes are intended to help you with two related tasks that you will encounter throughout your time in Cambridge. These are: firstly, how to keep a good record when you perform an experiment, and secondly, how to write a formal report of a class experiment or project.

Part of the aim of the practical classes in Years 1 and 2 is to teach you these skills. These notes provide some general guidance, but you will find it very helpful to look at some of the references in section 5, as well as looking at journals to see scientific writing in action.

All the formal reports you write are assessed. However, this is as much a part of the learning exercise as a way of accumulating credit for the Tripos. In the first two years, comparatively little credit (in terms of percentage of your final mark in Part IA and Part IB) is associated with your reports since you are learning the skills of good scientific writing and communication. In Part II and Part III the reports you write will determine a significant proportion of your final mark. Learning the skills of communicating the work you have done is, however, far more important than just gaining examination credit because the production of clearly written reports is central to most professions.

2 Writing lab notes

2.1 Introduction

The purpose of a scientist's lab notes is to record what was done in an experiment, together with the results. They need not be particularly tidy, but they should be understandable by the writer or somebody else at a later date, for example when analysing the results in detail, or writing them up for publication or a formal report. Any information that might conceivably be relevant should be recorded even if it is not going to be used in the short term. The notes should also enable you to recreate accurately the experiment at a later date if more results are needed.

As you progress through the Physics course you will find it necessary to record more complete information because the experiments become less standard. However, even in the first year, you should make and record a quick estimate of errors each time you start taking a new type of measurement. This will enable you to carry out an error analysis later should it be required, without guessing at scales and resolutions. When you take precautions to guard against certain problems, note them down.

2.2 Specific guidance

Your notebook must be A4 in size and hard-bound. A suitable book can be bought from the laboratory technician.

When you start an experiment, record its title and the date. As you do each part of your experiment you should:

- make *notes* of your experimental routine, particularly of points not in the class manual. You do not need to copy out the aims, methods and diagrams given in the class manual, but you should record references to it (e.g. "for details, see section E1.3 of IA Class Manual, p.10") so that you can look up the details later;
- record all the experimental data you will need, putting it *directly* into your notebook as you make the measurements. This must include the units and a quick estimate of the error in each type of measurement, plus a note of the cause of the error and of how you assessed it. For sets of data, a table is usually best, with the error noted beside the first entry in each column;
- sketch your experimental setup or oscilloscope traces, etc., quickly but neatly. You should learn to make tidy and helpful diagrams. Include indications of scale, or the distances between important features;
- ideally you should plot graphs as you go along, not after completing the experiment, though in practice this is not always possible. It can save a considerable amount of time as you will see if certain points are spurious, or if the value is changing so rapidly in a certain region that more points are needed (or conversely if the line is so straight that fewer points are needed). If possible, scan the x-axis parameter quickly over the whole range, looking for interesting regions rather than working doggedly from one end of the graph — this will help you decide what ranges to use on the axes, and what spacing to use between points. It is straightforward to do this if you are just turning a dial (e.g. to set the frequency), but it is not possible if you are changing something (like the temperature) that takes a significant time to stabilize;
- record answers to specific questions asked in the class manual;
- make notes of your interpretation and conclusions, and highlight important features.

Do all this as you go along. This helps you to think about the experiment. For example, it helps you decide whether a rough measurement of some quantity is appropriate or whether it has to be known accurately, or whether a particular strategy is needed to check for a systematic error so that you can then reduce its effect or eliminate it altogether.

Remember that in Parts IA and IB your notes need to be read and marked by the demonstrator. He or she will not consider work that is scrappy or illegible to be acceptable. When you realize you've written down rubbish, just put a line through it. Remember too that your notebook (read in conjunction with the class manual, if any) should contain all the information you need to write a formal report. On the other hand, padding wastes time and long sentences are usually not needed.

3 The formal report

3.1 Introduction

A very important aspect of any scientific work, both experimental and theoretical, is the communication of the results and conclusions to other scientists and occasionally a wider audience. Most reports of scientific work are published in scientific journals and, associated with these publications, a style of writing has been developed which is intended to make it as easy as possible for other scientists to appreciate what has been done.

Throughout all years of the physics course you will be required to produce reports:

- Years 1 and 2: Reports on practicals you have performed as class experiments;
- Years 3 and 4: Reports on project work, experimental investigations, research reviews and computing projects.

The reason for asking you to write such reports is two-fold: firstly to present a record of work you have undertaken as part of course assessment, and secondly to teach you the skills of technical writing which you will use in your future career. The aim of this booklet is to give you some guidance in writing such an account. Aspects of the material presented here are considered in more detail in one of the lectures in the Part IB Experimental Methods course.

3.2 Overview of writing a report

The major characteristic of good technical writing is that it is strongly focused. Writing is an important form of communication, and before you start you must be absolutely clear about two things — with whom you are trying to communicate and what you are trying to tell them. Keep in mind who will be reading your work and what level of knowledge your readers possess. In almost all of the reports that you will write the intended audience is other physicists. However, you may well have more detailed technical knowledge of particular aspects of the work you are writing about than your target reader. As a good guide, write for a physics student who is at the same stage as yourself but who has not seen the particular experiment or material.

The following gives a quick guide to the contents of a formal report of a class experiment: very similar considerations apply (with just change of terminology) to a report on a computing or theoretical project.

Apart from references, the report must be self-contained. In particular, the target reader cannot be expected to have to turn to the class manual for relevant diagrams or pieces of description; note also that the class manuals are written for users who have the kit in front of them, whereas the target reader has not.

The report should make clear what has been measured, discuss experimental techniques (and difficulties where appropriate), include results, make clear what calculations have been done, and what conclusions you have reached. You should not include tables of numbers from your lab notebook unless these data help to make a point more strongly, or you consider a table the best method of presenting your results.

A good report should contain a discussion of potential errors and you may also wish to suggest further measurements or improvements to the technique or equipment employed in the experiment.

The report itself should demonstrate that you have carried out the experiment, that you understand its point, its background, why you did it the way you did, the significance of the results, and the reasons why any bits of the experiment didn't work as expected. You should especially note any results that are not in agreement with theoretical discussions given in lectures or textbooks.

3.3 The structure of a scientific report

The report should have a very clear and obvious structure. The meaning of what you write should be clear and unadorned.

Such a report may carry an account of some new theory or the results of calculations with existing theory, it may describe an experiment, or it may give an account of an observation of a natural phenomenon. Quite often, especially in physics, it will have a substantial element that is quantitative. Much of what needs to be communicated is essentially objective; what theory is to be verified, how to do an experiment, what the results are, what the results of a calculation might be.

However, a scientific paper also contains subjective elements. The writer has to explain why what has been done is felt to be important, how this work fits in with other work which has been done in the area, what is concluded from the work, and what he or she thinks needs to be done next. The difference between the subjective part and the objective part is that while a reader has a perfect right to disagree with the conclusions drawn from a particular experiment, the description of the experimental procedure is a matter of record. A convention has grown up which allows the two elements to coexist but keeps them separate by surrounding an objective description of the method and results by a subjective introduction, discussion and conclusion.

This leads to the conventional Abstract / Introduction / Theory / Method / Results / Discussion / Conclusions / References structure of a paper. Of course the exact format will be dependent on the nature of the work being reported, but it is probably not a good idea to deviate too markedly from the following structure:

- Title
- Abstract
- Introduction
- Theoretical Background (where appropriate)
- Method
- Results
- Discussion
- Conclusions
- References
- Appendices (where appropriate)

In some cases, however — depending on the experiment — it may be much easier to read if you deal with methods and results (and perhaps discussion) material first for the first part of an experiment, then for the next part, etc. You will certainly *always* want a title, an abstract, and a structure with numbered headings for the rest (the Abstract should not be numbered).

For your first reports stick closely to the structure given above. As you gain experience and become more practised you can adapt the structure for each report.

3.3.1 Title and Abstract

The Title should be very brief but allow a potential reader to judge whether the subject of the report is likely to be of interest to him/her. The Abstract is a summary of the paper, usually in less than 200 words, used largely for reference purposes so that a potential reader can decide whether the content is relevant to his/her interests. It should therefore incorporate information on what was done, the results and conclusions. Give **quantitative** results if these are an important outcome of the experiment. Do not use undefined acronyms or undefined symbols in the Abstract.

3.3.2 Introduction

Here the reader needs to understand why the work was done. What was the context of the work? What work had been done previously in this area? In short, why should the reader, no doubt very busy, spend further precious time reading on? Help the target reader by starting with the general context then moving on to focus on the goals of the work described in the report — it is also a good idea to give a brief indication of the structure of the rest of the report. The Introduction is one of the most important parts of a paper and should be clear and concise; if it is muddled or confused it is very likely that a reader will stop and read something else.

3.3.3 Theoretical Background

You should present in a concise form the main points of any theory that an experiment is attempting to verify. If this section is very short, consider incorporating it into the Introduction.

3.3.4 Method

You need to describe the experimental (or computational or theoretical) method. In describing the method, there are two aims. Firstly, having read the account, a reader should be able to repeat the procedure described. This is essential for the integrity of the science. Secondly, it must allow the reader to judge whether the conclusions you later reach are justified. Thus, for an experiment, it should include details of how the measurements were made, the precautions taken to get reliable results, preliminary checks on the apparatus, discussion of the steps taken to overcome systematic errors etc.

3.3.5 Results

Here you should present your experimental results, the results of relevant calculations and error analysis. Your description of the results has two purposes. You will use your results to formulate your own conclusions, but it must also be possible for other people to read your results and maybe reinterpret them in other ways.

In a formal report, when deducing numerical results from your data, you should usually only give the initial expression and the final result. There is no need to show the detailed working from your lab notebook except when the numerical (or algebraic) steps taken, or the assumptions made, are not obvious and require additional explanation.

3.3.6 Discussion

Here you deal with the interpretation of your results and explain what lessons you draw from them. Most often you will not have been able to prove some new theory beyond doubt, and you may worry that your results are ambiguous or incomplete. Nonetheless, important things are likely to have been learnt from the experiment or other work, so you should explain clearly what firm deductions you can make, and perhaps consider other possible interpretations of your data.

In the Discussion you should consider potential errors and any shortcomings in the experimental procedure or analysis of the data. You may also wish to suggest improvements to the work, and quite possibly what further experiments or theoretical developments you feel might need to be done.

3.3.7 Conclusions

You should wrap things up with the Conclusions section. This should indicate — both qualitatively and, where appropriate, quantitatively — how far the experiment goes towards answering the questions posed in the Introduction, summarizing what you have learnt from the experiment and if relevant, what you still do not know. If the value of a quantity has been determined, which is sufficiently well known to appear elsewhere, a comparison should be given. As always, be as clear, concise and quantitative as possible; remember busy people (but not your assessors!) will often do no more than scan the Abstract and/or Conclusions.

3.3.8 References

The body of the report should contain a more or less self-contained account of the work undertaken. References are included so as to give the reader an opportunity to find out more about the background to your work or other ancillary information. It should not be necessary for the reader to consult the references to obtain crucial information about your experiment, e.g. they are not used as an excuse to avoid drawing a crucial circuit diagram; however, verbatim transcriptions from the manual, textbooks or other references must not appear and are best dealt with by referring to the relevant manual, textbook or paper in the text. The list of references should only include items referred to in the report.

There are a number of different ways in which references can be given in a report. Two possibilities are:

- to identify each reference by a number which appears in the text either as a superscript (i.e. ^{2}) or, for example, in square brackets (i.e. [2]) at the point at which the reference is relevant. In the reference section a consecutive list of numbers appears followed, on the same line, by the reference;

- to give the name(s) of the author(s) and the year of publication at the relevant point in the text. In the reference section the names are then given in alphabetical order.

3.3.9 Appendices

Appendices are used to present material that is not pertinent to a first read but which may be useful to the reader. Appendices will rarely be needed for Part IA reports; they are often needed in Part IB reports and in the various project reports in Parts II and III.

3.4 Scientific writing style

Scientific English is not the same as literary English; the emphasis must be on clarity, not on elegance. Avoid sounding pompous and self-important. On the other hand avoid a trivializing what-I-did-next style like "....then I connected the battery, then I read the meter". Then there are issues of voice (passive or active) and tense (past or present). Passive + past is the safest approach but it can lead to extremely boring text. If you are up to it, it is better to vary tense, for example by using the present tense to describe how things are and the past tense to say what you did, and to vary voice.

3.4.1 Graphs and tables

A central part of the message of a scientific paper is quantitative, thus graphs or data tables play a central part and the strictures about clarity and economy apply just as strongly. How much data should be included? Distinguish between the results you need to refer to in your conclusions and those intermediate numerical values that you use to calculate the results but which are not really the results themselves.

When should you draw a graph, and when should you make a table? You should very rarely do both; it is a waste of paper to tabulate the same data that appears in your graphs. The general rule is that, unless the amount of data is so small that it can be appreciated almost at a glance in a tabular form, it should be presented as a graph. Only very small sets of data, which are not expected to show any strong functional relationships, should be presented as tables. Most readers just cannot be bothered to plough through masses of numbers.

The importance of graphs is that, properly used, they can convey an immense amount of information in a clear and easy-to-grasp way. There are some simple rules about graphs that you should follow. It is conventional to plot the independent variable (the variable that you control) along the x-axis, and the dependent variable (typically the variable that you measure) along the y-axis. Be sure to choose an appropriate range for the axes — do not produce a graph with all the points in one corner. Graphs should carry a figure number (in the same sequence as the numbering of the diagrams — see below) and title in the form of a caption. All graphs should be referred to within the text.

3.4.2 Diagrams

Schematic drawings can often convey information much more clearly than text. All diagrams should have the individual elements clearly labelled and the diagram itself should carry a figure number and title in the form of a caption. As with graphs all diagrams should be referred to within the text.

3.4.3 Word processing and format

You are expected to write your formal reports using a word processor. The following hints will improve the style of your document.

- Use a reasonable font size (e.g. no smaller than 12 point).
- Indent the start of a new paragraph or insert a blank line between paragraphs, or follow your package's in-built "style".
- There should be no space before a comma or full stop. Put one space after a comma and two spaces after a full stop. There should be no space inside parentheses before the first word or after the last, e.g. (this is wrong) and (this is right).
- Keep backups of older versions of your document in case of computer or disc crashes. Note that such crashes will not be accepted as legitimate reasons for the late handing-in of work.

3.4.4 Final points on English and presentation

Do not use acronyms or jargon unless you describe them in full the first time they appear in the text (following the Abstract). The following methods are acceptable: "....resonant circuit consisting of an inductor, capacitor and resistor (LCR) was" or "....an image was formed in a Scanning Electron Microscope (SEM)", etc.

- Each sentence should make one point only. Do not ramble on using long sentences with multiple commas.
- Do not use nondescript words or throw-away phrases like: "nice, about, obviously, poorer, thing, somewhere between, if you like, the impedance drops off..".
- "It's" is an abbreviation of "it is". "its" indicates possession, e.g. "its meaning should be obvious from this phrase".
- Write the numbers 1 to 9 in words, and higher numbers as figures, e.g. two multimeters, 20 readings. Try not to start a sentence with figures.
- Commonly misspelled or misused words: accommodation, dependence, dependent (e.g. on temperature); in principle, principal axes; (computer) program, programme (for any other type); phenomenon (singular), phenomena (plural); criterion (singular), criteria (plural); datum (singular), data (plural).

4 Specific points for each year of the Cambridge physics course

4.1 Introduction

Here we give a brief outline of the reports that you may expect to have to write in each year of the course. For a given report, detailed instructions (including length, deadlines etc.) are included in the relevant class manual, or in additional material provided during the term, and provide definitive instructions and information which may replace details given below. As you will see, the importance of formal reports and other forms of communication becomes greater throughout the course; the skills you learn in the early years will help you greatly in the later years of your course.

4.2 Part IA Physics

You write one brief formal report over the Christmas vacation, on an experiment carried out during the Michaelmas term, and one full report over the Easter vacation on a Lent term experiment. Feedback is via detailed marksheets.

4.3 Part IB Physics A and Physics B

If you are taking either Physics A or Physics B you write one formal report, from either the Michaelmas term or the Lent term experiments. If you are taking both, you write one report in Michaelmas and one in Lent. You must also hand in your laboratory notebooks although these are not used in the assessment. Feedback is via an interview with your head of class. This interview does not normally change your mark.

4.4 Part II (A and B) Experimental & Theoretical Physics

Formal reports are required on a number of pieces of work, including the experimental investigations, the computer project and also the research review. For the latter the structure will have to be modified from that of an experiment depending on the nature of the review, and you will also be asked to prepare an oral presentation. If you do Part IIA, the Physics in Action course also involves an oral presentation of project work together with the preparation of a poster, another important form of communication used in the scientific (as well as commercial) world.

Your reports will be more sophisticated than in Part IB, but the same rules apply. Re-read the lecture handout on writing reports from the Part IB Experimental Methods course (note that this also contains basic advice on giving an oral presentation).

In addition:

- before you start writing, make lists of the experimental/theory points you want to make, and of the explanatory additions for the target reader. Then start putting them in order: don't forget that a limited amount of forward and backward referencing (e.g. "this is discussed in section 3.4") can be very useful to break a logjam of interdependent points;

- get extra ideas for style and structure by looking at publications in the Rayleigh library. Looking at, say, Review of Modern Physics and Scientific American may help with writing a research review;
- if appropriate, do be constructively critical of your work or that of others, but do not dwell on this;
- you will find it essential to repeatedly iterate your content for clarity and for lack of ambiguity; it is helpful to get someone else to read your text and comment;
- for each of the experiments and the computer project there is an assessed viva (i.e. the mark you get for the work depends in part on your performance in the viva) with a staff member. The research review has an assessed viva with two members of staff.

4.5 Part III Experimental & Theoretical Physics

The project in Part III is a central element of your work and assessment: the project counts for one-third of the final Tripos mark. For the project you must write a report and there is also an assessed viva with two members of staff. The main text of the report should be concise (5,000 words maximum), with programs etc. being including as appendices.

Writing this report is a substantial undertaking that you must be planning and thinking about while you carry out your project — the requirements of your report may influence your project work. All the advice given above for Part II applies.

In addition, you may get ideas on how to structure your report by looking at the latest copies of the research journals on the display shelves of the Raleigh library. (Note that writing up your project in the style used in review journals or magazines such as New Scientist, Scientific American or Nature is not appropriate.)

5 Further reading

- An Introduction to Experimental Physics, Cooke C., UCL Press, 1996
- Practical Physics (4th edn), Squires, G. L., Cambridge University Press, 2001
- Experimental Methods, Kirkup L., Wiley, 1994

Errors — summary and key results

- The mean of n measurements is given by

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i = \frac{1}{n}(x_1 + x_2 + \ldots + x_n).$$

- The standard deviation σ of n measurements is given by

$$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2 = \frac{1}{n-1}\left[(x_1-\bar{x})^2 + (x_2-\bar{x})^2 + \ldots + (x_n-\bar{x})^2\right].$$

- The standard error in the mean of n measurements is given by

$$\sigma_{\mathrm{m}} = \frac{\sigma}{\sqrt{n}}.$$

- If Z is a function of the directly measured *independent* quantities A, B, C etc. the general formula for the error in Z is

$$\sigma_Z^2 = \left(\frac{\partial Z}{\partial A}\sigma_A\right)^2 + \left(\frac{\partial Z}{\partial B}\sigma_B\right)^2 + \ldots$$

- If $Z = A + B$ or $A - B$, then

$$(\sigma_Z)^2 = (\sigma_A)^2 + (\sigma_B)^2.$$

- If $Z = A \times B$ or A/B, then

$$\left(\frac{\sigma_Z}{Z}\right)^2 = \left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_B}{B}\right)^2.$$

- If $Z = A^m$, then

$$\left(\frac{\sigma_Z}{Z}\right)^2 = \left(\frac{m\sigma_A}{A}\right)^2.$$

  For example, if $Z = A^2 = A \cdot A$, then

$$\left(\frac{\sigma_Z}{Z}\right)^2 = \left(\frac{2\sigma_A}{A}\right)^2.$$

- If $Z = \ln(A)$, then

$$\sigma_Z^2 = \left(\frac{\sigma_A}{A}\right)^2.$$