Experimental Physics

2019/2020 **Year 2** [WL] M&P & Nat Sci

S1 PH20060/67 & S2 PH20061/63
Lab Coordinator: Dr Sloan

Data or it didn't happen

In brief, how this ‘With labs’ [WL] course works

- In year 2 we combine the Maths and Physics students with the Natural Science students and then randomly assign you to one of two groups, either ‘Group 1’, or ‘Group 2’. See time-table for details. Please check on moodle to find your group.
- Much of the content and assessment in the Year 2 [WL] is identical or near identical to the Year 1 [WL] course you did last year.
- **Semester 1**: You will work in a pair and do 2 experiments, each experiment will take two 3 hours session on a Thursday morning.
- For each experiment you will be randomly assigned your partner and should not work with the same partner twice.
- As in year 1, each experiment has a script that walks you through the apparatus you'll use and the underlying physics. These are all on moodle and available in the laboratory.
- The identity of your particular experiment will be released week by week on moodle.
- You will write up one experiment as a report.
- **Semester 2**: You will work in pairs on a single project. These will run for 3 normal Thursday sessions. Assessment will allow some iteration. You will submit a complete report after those 3 sessions. Your report will be assessed for [S+P] ‘Structure and Presentation’. You will then have one more session in the lab before re-submitting your report (amend and edit as you wish) to be assessed for [C+P] ‘Clarity and Physics’.
- You will be assessed on how well you prepare for the labs, how you perform in the labs, and how you present you work in a written report.

You are not expected to know everything and be perfect. This is a training course of how to approach experimental science. Your own inherent enthusiasm and engaging with the course will get you far. This [WL] experimental course is designed to allow you to become competent or even good and excellent experimentalists, statisticians and report writers, over four semesters over two years. Each semester is counts to 15 % of two units. So overall all it is worth just over one whole unit. The fact that this is a fairly long booklet reflects what we expect you to be able to do and understand by the end of the two years.

Your timetable: Semester 1

	Year 2 **Semester 1**					
	Group 1			**Group 2**		
Session Week Beginning	**Thursday** Nat Science + M&Phys	**Submission** Deadline	**Feedback** & Return	**Thursday** Nat Science + M&Phys	**Submission** Deadline	**Feedback** & Return
Week 1 1/10/2018	Experiment Yr2 #1 Day 1 in lab	Summary: Wed 23:59	Summary: In lab	-	-	-
Week 2 8/10/2018	Experiment Yr2 #1 Day 2 in lab	-	-	–	-	-
Week 3 15/10/2018	-	-	-	Experiment Yr2 #1 Day 1 in lab	Summary: Wed 23:59	Summary: In lab
Week 4 22/10/2018	Report Peer Review 3W4.3	-	-	Experiment Yr2 #1 Day 2 in lab	-	-
Week 5 29/10/2018	Experiment Yr2 #2 Day 1 in lab	Summary: Wed 23:59	Summary: In lab	-	-	-
Week 6 5/11/2018	Experiment Yr2 #2 Day 2 in lab	-	-	Report Peer Review 3W4.3	-	-
Week 7 12/11/2018	-	-	-	Experiment Yr2 #2 Day 1 in lab	Summary: Wed 23:59	Summary: In lab
Week 8 19/11/2018	-	Report: for [S+P] & [C+P] Mon 14:30 Log-book: Mon 14:30	-	Experiment Yr2 #2 Day 2 in lab	-	-
Week 9 26/11/2018	-	-	-	-	-	-
Week 10 3/12/2018	Report feedback tutorials for [C+P] in lab	-	Report: for [S+P] & [C+P] Wed AM on moodle Log-book: Thur in lab	-	Report: for [S+P] & [C+P] Mon 14:30 Log-book: Mon 14:30	-
Week 11 10/12/2018	-	-	-	Report feedback tutorials for [C+P] in lab	-	Report: Wed AM on moodle Log-book: Thur in lab

- The identity of the experiment you will do will be released on the prior Thursday.

Your timetable: Semester 2

	Year 2 **Semester 2**					
	Group 1			**Group 2**		
Session Week Beginning	**Thursday** Nat Science + M&Phys	**Submission** Deadline	**Feedback** & Return	**Thursday** Nat Science + M&Phys	**Submission** Deadline	**Feedback** & Return
Week 1 4/2/2019	Intro to Projects	-	-	Intro to Projects	-	-
Week 2 11/2/2019	Project Day 1	Summary: Wed 23:59	Summary: In lab	-	-	-
Week 3 18/2/2019	Project Day 2	-	-	-	-	-
Week 4 25/2/2019	Project Day 3	-	-	-	-	-
Week 5 4/3/2019	-	-	-	Project Day 1	Summary: Wed 23:59	Summary: In lab
Week 6 11/3/2019	-	Report: [S+P] Mon 14:30	-	Project Day 2	-	-
Week 7 18/3/2019	-	-	-	Project Day 3	-	-
Week 8 25/3/2019	Project Day 4	Summary*: See section 4.3 Wed 23:59	Report: Wed AM on moodle Summary: In lab	-	-	-
Week 9 1/4/2019	-	Report: [C+P] Mon 14:30	-	-	Report: [S+P] Mon 14:30	-
Week 10 8/4/2019	-	-	-	Project Day 4	Summary*: See section 4.3 Wed 23:59	Report: Wed AM on moodle Summary: In lab
Week 11 15/4/2019	-	-	-	-	Report: [C+P] Mon 14:30	-
Not much later	-	-	Report	-	-	Report

Contents

Part A: Framework

Section 1

Purpose of Experimental Physics

The following excerpts are from ref [1].

1.1 What is science?

Science is complex and multi-faceted, but the most important characteristics of science are straightforward:

- Science focuses exclusively on the natural world, and does not deal with supernatural explanations.
- Science is a way of learning about what is in the natural world, how the natural world works, and how the natural world got to be the way it is. It is not simply a collection of facts; rather it is a path to understanding.
- Scientists work in many different ways, but **all science relies on testing ideas by figuring out what expectations are generated by an idea and making observations to find out whether those expectations hold true.**
- Accepted scientific ideas are reliable because they have been subjected to rigorous testing, but as new evidence is acquired and new perspectives emerge these ideas can be revised.

1.2 Some Sloan philosophy

Science is a bit like taking a journey into the **unknown**, you have to make best **educated** guesses, and then when you find a junction, you have to have a **reason** for choosing the way you go. Only then will you **convince** anyone of your new findings. And at all steps, and I really can't emphasise this enough, **data or it didn't fucking happen.**

1.3 Science relies on evidence

Ultimately, scientific ideas must not only be testable, but must actually be tested - preferably with many different lines of evidence by many different people. This characteristic is at the heart of all science. Scientists actively seek evidence to test their ideas - even if the test is difficult and means, for example, spending years working on a single experiment, travelling to Antarctica to measure carbon dioxide levels in an ice core, or collecting DNA samples from thousands of volunteers all over the world. Performing such tests is so important to science because in science, the acceptance or rejection of a scientific idea depends upon the evidence relevant to it - not upon dogma, popular opinion, or tradition. In science, ideas that are not supported by evidence are ultimately rejected. And ideas that are protected from testing or are only allowed to be tested by one group with a vested interest in the outcome are not a part of good science.

1.4 Observing the natural world

We typically think of observations as having been seen 'with our own eyes', but in science, observations can take many forms. Of course, we can make observations directly by seeing, feeling, hearing, and smelling, but we can also extend and refine our basic senses with tools: thermometers, microscopes, telescopes, radar, radiation sensors, X-ray crystallography, mass spectroscopy, etc., and these tools do a better job of observing than we can! Further, humans cannot directly sense many of the phenomena that science investigates (no amount of staring at this computer screen will ever let you see the atoms that make it up or the UV radiation that it emits), and in such cases, we must rely on indirect observations facilitated by tools. Through these tools, we can make many more observations much more precisely than those our basic senses are equipped to handle.

Observations yield data. Whether the observation is an experimental result, radiation measurements taken from an orbiting satellite, an infrared recording of a volcanic eruption, or just noticing that a certain bird species always thumps the ground with its foot while foraging - they're all data. Scientists analyse and interpret data in order to figure out how those data inform their hypotheses and theories. Do they support one idea over others, help refute an idea, or suggest an entirely new explanation? Though data may seem complex and be represented by detailed graphs or complex statistical analyses, it's important to remember that, at the most basic level, they are simply observations.

Observations inspire, lend support to, and help refute scientific hypotheses and theories. However, theories and hypotheses (the fundamental structures of scientific knowledge) cannot be directly read off of nature. A falling ball (no matter how detailed our observations of it may be) does not directly tell us how gravity works, and collecting observations of all the different finch species of the Galapagos Islands does not directly tell us how their beaks evolved. Scientific knowledge is built as people come up with hypotheses and theories, repeatedly test them against observations of the natural world, and continue to refine those explanations based on new ideas and observations. Observation is essential to the process of science, but it is only half the picture.

1.5 Purpose of your [WL] 'With Lab' unit

During lectures you learn about scientific theories. But real science involves making measurements of nature. The purpose of this lab portion of your 'With Lab' unit is to teach you how to approach measurement: how to plan it; how to think about it; how to analyse it; how to determine if it means anything; how to report it. Just about all these skills will be new to you, and all take time and effort to master (I'm still trying).

1.6 Some background and context for the [WL] course

- These labs and their accompanying assessments were radically re-designed for 2017/2018, in reaction to student feedback. Specifically through the 2016/2017 Staff Student Liaison Committee (SSLC), and Online Unit Evaluations (OUE) feedback comments. I have been careful not to create more work for students to do for this experimental course. For each new item I have tried to balance this with the removal of something, or have it only within the laboratory or skills hours. Nearly everything in this course is aimed at helping you efficiently and effectively learn the skills of a scientist. The skills you learn are transferable, in the first instance, to other laboratories courses you may do, and definitely to any projects you undertake in latter years.

  Overall the lab and this re-written lab-manual have several aims.

  ⇒ To be a near step-by-step guide to undergraduate labs.

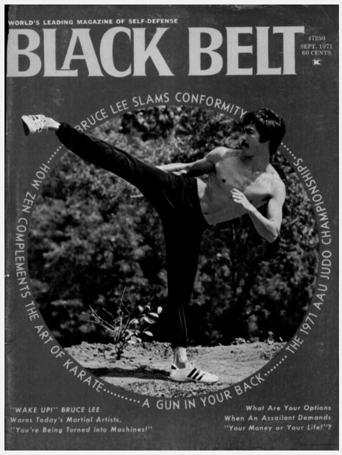
  ⇒ To test you on the key skills required, not only for lab-based work, but for any work in which you have to communicate complex ideas and results.

  ⇒ To be an effective and useful exercise in learning physics, experimental physics and the scientific method.

  ⇒ To reward good work and good thinking.

Bruce Lee

Learning is definitely not mere imitation, nor is it the ability to accumulate and regurgitate fixed knowledge. Learning is a constant process of discovery, a process without end. In JKD we begin not by accumulation but by discovering the cause of our ignorance, a discovery that involves a shedding process.



Unfortunately, most students in the martial arts are conformists. Instead of learning to depend on themselves for expression, they blindly follow their instructors, no longer feeling alone, and finding security in mass imitation. The product of this imitation is a dependent mind. Independent inquiry, which is essential to genuine understanding, is sacrificed. Look around the martial arts and witness the assortment of routine performances, trick artists, desensitized robots, glorifiers of the past and so on - all followers or exponents of organised despair.

How often are we told by different 'sensi' or 'masters' that the martial arts are life itself? But how many of them truly understand what they are saying? Life is a constant movement - rhythmic as well as random; life is constant change and not stagnation. Instead of choicelessly flowing with this process of change, many of these 'masters', past and present, have built an illusion of fixed forms, rigidly subscribing to tradition concepts and techniques of the art, solidifying the ever-flowing, dissecting the totality.

The most pitiful sight is to see sincere students earnestly repeating those imitative drills, listening to their own screams and spiritual yells. In most cases, the means these 'sensi' offer their students are so elaborate that the student must give tremendous attention to them, until gradually they lose sight of the end. The students end up performing their methodical routines as a mere conditioned response, rather than **responding to** 'what is'. They no longer 'listen' to circumstances; they 'recite' their circumstances. These poor souls have unwittingly become trapped in the miasma of classical martial arts training.

A teacher, a really good 'sensi', is never a **giver of truth** they are a guide; a **pointer** to the truth that the student must discover for themselves. A good teacher, therefore, studies each student individually and encourages the student to explore themselves, both internally and externally, until, ultimately, the student is integrated with their being. For example, a skilful teacher might spur their student's growth by confronting them with certain frustration. A good teacher is a catalyst.

Excerpts from ref [2]. Some language has been updated.

Section 2

Laboratory information

2.1 Safety in the teaching laboratories

2.1.1 Summary of Health and Safety at Work Act, 1974

- Each employee of the University and each student working in the University has responsibility to take care of his or her own safety and the safety of others.
- By good example and training, staff and students should be encouraged to adopt high safety standards in their work as a routine.
- The University is to ensure so far as is reasonably practical the safety of its employees and other people working in or visiting the University.
- The Act places the duty on all persons that they shall not intentionally or recklessly interfere with or misuse anything provided for health and safety.

2.1.2 Laboratory Regulations

- Eating, drinking and playing music are not permitted in the laboratories.
- Please switch off mobile phones before entering and leave the laboratories before making any calls. This is not only out of courtesy for other workers: mobile phones interfere with some of the most sensitive equipment and music reduces concentration and compromises safety.
- Do not place your bags or coats on the desks.
- No undergraduate may work in the laboratories outside the hours of 09.15 -17.15, except with the direct permission of a member of academic staff teaching in the laboratory course, and in no circumstances alone.
- All laboratory work must be carried out in the spirit of section 2.1.1.
- Details of any special hazards will be given in the instructions issued for individual activities.

2.1.3 Summoning Emergency Assistance

- **In case of fire**, break the glass in the nearest fire alarm point. This will sound the alarm in the building and automatically summon the fire brigade. If trapped in a room, close the door, open the window and summon assistance using internal phones (dial 666) or attract attention.
- **In case of an accident** requiring urgent medical attention
  - ⇒ dial 666 from any University telephone. One is located on the landing of each floor.
  - ⇒ Or 01225 383 999 form your mobile.
  - ⇒ Give the operator your name, extension number, the location of the injured person and the nature of the injury if possible.
  - ⇒ Alternatively, dial 999 from a public line. Repeat the message on the University 666 number as soon as possible so that local assistance can be summoned.

2.1.4 Emergency Alarms

- On hearing the emergency **evacuation** alarm
  - ⇒ Leave the building promptly but calmly by the nearest fire exit.
  - ⇒ In the teaching labs the nearest accessible exit will usually be that at the rear of 3W or on the Parade away from the buildings.
  - ⇒ Do not use the lift.
  - ⇒ Beware of the dangers from flying glass etc. and stay away from buildings.
  - ⇒ During lectures or laboratories, follow the directions of the member of staff in charge.
- On hearing the emergency **Invacuation** siren
  - ⇒ Stay in the laboratory.
  - ⇒ Close any windows.

Framework

2.2 Logistics

2.2.1 Groups and Timetable

- Each laboratory session starts at **09:15** and finishes at **12:05**. Experiments **stop at 12:00** to allow time for log-book stamping.
- **Before** the lab session, check which experiment you are scheduled for and read it through carefully - you may have to upload a pre-session summary.
- **At the start** of the lab session, make sure to get your log-book and attendance sheet stamped. This is for safety reasons, to know how many people might need to be evacuated from the lab.
- **During** the lab session, let us know if you need to leave the lab even for a short amount of time (e.g. to drink water).
- Get your **log-book stamped** when you achieve the experimental minimum. It is up to you to know what this is, and seek out a demonstrator to get a stamp once you've achieved it.
- **When you leave** the lab session, get your log-book stamped.

2.2.2 Anonymous marking and Student Number

As much as possible we will use anonymous marking. You will use your 'Student Number' to identify the owner of the work you submit. You can find your Student Number on your library card beside the term 'Student Number'.

Do not use any other number. We only have access to your Student Number so if you use a different number we won't know whose work we have and you won't get any marks.

2.2.3 Absences and late arrival

Missing sessions will impact on your ability to become a fully formed scientist. Any absence will naturally impact on your lab partner for that session. There is, unfortunately, no easy way to catch-up with extra sessions.

- **Approved absence** If as part of your degree you are absent, for example to attend a placement interview, but not say to represent the University at hockey, the relevant mark, achievement or peer-review, will be adjusted accordingly. Please let the lab coordinator Dr Sloan know in advance.

- **Illness** If you miss a session due to illness please contact your Director Of Studies (DOS) with a doctor's note if appropriate and ask your DOS to contact the lab coordinator Dr Sloan. The relevant mark, achievement or peer-review, will be adjusted accordingly.

- **More than one absence** Since there are only 5 ± 1 sessions, absence from two constitutes too much of the Experimental Physics course to be easily adjusted for. Therefore if you are absent, for whatever reason, on two or more occasions in a semester, you will have to seek redress for those absences through the usual University IMC route.

- **Lecture clash** The NatSci and Math&Phys timetables are more complex than most. From time-to-time a clash of labs and lecture can happen, if so please contact the lab coordinator Dr Sloan as soon as you can. We usually try and resolve any such clash by asking for the lecture to be recorded.

- **Late arrival** If you arrive later than 9:25 it will be noted and your possible Achievement score for that session reduced accordingly. Because of the excessive disruption it would cause to your lab partners, late arrival after 9:40 will incur a further more dramatic reduction to your possible Achievement score.

2.2.4 Fitness for laboratory work

If you are not fit to be in labs and therefore poses a risk to either yourself, other students, staff, or lab apparatus you will be told to leave the laboratory immediately. This could be due to infectious illness or injury as well as alcohol or drug misuse.

If you are sent away from labs because of genuine illness or injury, you are advised to see the GP and obtain a medical note. The contact your DoS as outlined in section 2.2.3 above.

If you are is sent away because of alcohol misuse, the university sees this as a 'life style choice' and therefore no mitigation can be offered.

2.2.5 E-Learning and Moodle

Moodle (https://moodle.bath.ac.uk) is our generic online teaching portal with information and material for all the courses you are registered for. There is a specific page for Year 2 NatSci/M&P laboratories , on which you should be automatically registered. If it does not appear, contact your DOS. Make sure your Moodle settings include the right (University of Bath) email address for you, as Moodle will be used to send emails to the entire class (e.g. with schedule alteration or useful tips for reports).

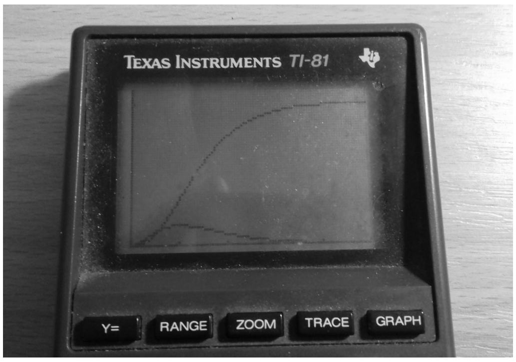
- Our Moodle page also provides
  - ⇒ experimental handouts,
  - ⇒ copies of the timetables,
  - ⇒ this guide to the labs,

- Apart from an introductory e-mail, there will be **little e-mail contact**.

  ⇒ It is your responsibility to know what's going on, turn up on time and submit work on time.

2.2.6 Things you will need every week

- This **manual**.
- Enthusiasm.
- Your own **log-book**. You can get one from the Laboratory Technical Coordinator during the first lab session, or buy one from the Union Shop (or elsewhere). Graph paper with special scales (e.g. logarithmic) will be supplied as needed.
- **Calculator**. Any scientific model is good enough. The University calculator is the Casio FX-85ES (http://www.bath.ac.uk/student-records/examinations/newunivcalc.htm), also used in exams.
- **Graphing Calculators** I wouldn't be where I am without my Texas Instruments Ti-81 graphics calculator. I can plot functions, zoom about, enter data and easily do linear fitting. It's quick, easy and fits in my pocket. I bought it in 1993 so there may well be better cheaper models. Using a computer and Python programming is just as good or better, but I can use my graphics calculator while sitting in front of the experiment. But not in an exam.



- **Data storage**. All free-access computers can access your home drive (H:) where you are encouraged to store some of the results you might acquire during the experiments. A USB stick (available from shops on campus or anywhere else) enables quick backups and can be used to share the data with other lab partners where you jointly took the data.
- Graph paper, rough paper, scissors, paper, glue, staplers, guillotine etc. are available in the teaching laboratory and will be supplied as needed.

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2.3 Staff

(a) Lab coordinator: **Dr Sloan**, Lecturer in Experimental Physics

(b) Academic Staff: **Dr Dale**, Royal Society Research Fellow

(c) Academic Staff: **Dr Stirling**, Post Doctoral Research Associate

(d) Academic Staff: **Prof Salmon**, Professor in Physics, CPhys and FinstP .

Figure 2.1: Members of Academic Staff

(a) Year 1: **Henry Etheridge**

(b) Year 1: **David Collomb**

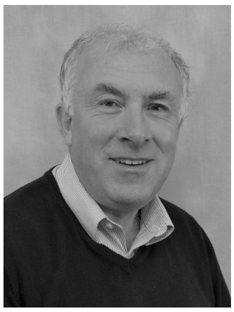
(c) Year 2: **James Arter**

(d) Year 2: **Nicola Bannister**

Figure 2.2: Postgraduate Demonstrators

(a) **Dr Jenny Williams**

(b) **Ms Isobel Wells**



(c) **Mr Martin Fullick**

(d) **Dr Chirs Shearwood**

Figure 2.3: Members of Technical Staff

Framework

2.4 Getting more information

- Read this manual again!
- Speak to a member of staff during the normal sessions.
- Check the moodle page.
- For any other enquiries, not covered by the above activities, contact the lab coordinator Dr Sloan following the convention below.

2.4.1 Contacting staff by e-mail

- I use an automated e-mail filter so you **must include exactly** the following in the subject of the e-mail

  ⇒ WLYear2

- Begin the text of the email with 'Dear Dr Sloan'. Do not begin the email 'Hi'.
- We get so many e-mails every day that unless your e-mail is correctly addressed it will probably get missed.
- Tell me who you are, name, year, degree and which unit your message is about.
- Any email should sound like a formal letter, not a text message or a demand to a customer service representative. For example, you could write:

  > Dear Dr Sloan,
  >
  > My name is Jane Quiggly, I am a 2nd year NatSci student in your PH20013 Quantum class. I cannot come to your office hours this week. Are you available at any time on Monday instead?
  >
  > Sincerely,
  >
  > Jane

  Do NOT write:

  > Hi,
  > I need to talk to you about the test. Can I come by Mon?
  > Thx Jane

- Write in complete sentences with correct spelling, grammar, and punctuation.
- Proofread your email before sending it.

Section 3

Sequence of an experiment

3.1 The natural flow of an ideal experiment

Real experimental life is not linear, but in these teaching labs we have well defined experiments and so we start you with nice experiments that will adhere to the following sequential flow. This will allow you to master the fundamentals of experimental science before you tackle real scientific questions.

- Prepare: before the laboratory session:
  - ⇒ Read the experiment script through and, if you wish, make some notes and descriptions in your log book. See section 10 for guidance.
  - ⇒ How may you determine uncertainties - including possible systematic uncertainties?
  - ⇒ Remember to date this work.
  - ⇒ **Assessment** $\boxed{\textbf{A1}}$: Use this work to help write a brief summary of your experiment.
- Execute:
  - ⇒ During the lab session:
    - ∗ On a new page put the new date in your log book.
    - ∗ Write the method you are actually using in your own words with your own emphasis etc.. You can including any setting used, particularly if the lab script is unclear or you are doing something differently.
    - ∗ Consider how you have determined any uncertainties and explain this.
    - ∗ Write down the real raw data, with absolutely no processing.
    - ∗ Write down the file location of any electronic spreadsheets etc. and what they contain.
    - ∗ Analyse as you go along, it will help you to spot mistakes.
    - ∗ **Assessment** $\boxed{\textbf{A2}}$: Achievement.
    - ∗ **Assessment** $\boxed{\textbf{A3}}$: Log-book.
  - ⇒ After the lab session:
    - ∗ On a new page put the new date in your log book.
    - ∗ Complete all your analysis and discussion.

  - * Reflect on the experimental process you have used. Would you have done things better? What else could you do or measure? etc.

  ⇒ **Assessment** $\boxed{\textbf{A3}}$: Log-book.

- Report: tell the world about your discovery

  ⇒ **Assessment** $\boxed{\textbf{A4}}$: Peer review of previous reports.

  ⇒ **Assessment** $\boxed{\textbf{A5}}$: Python-stats and LaTeX course work: Practice/refresh your practical Python based stats and your LaTeX skills.

  ⇒ **Assessment** $\boxed{\textbf{A6}}$: Report: Write a concise and near self-contained report about one of your experiments - you choose.

3.2 Assessment

Both Groups:

Assessment	What?	Semester 1	Semester 2
A1	Pre-session Summary	5 % #1 5 % #2	5 % #1 5 % #2
A2	Achievement	12 %	-
A3	Log-book	10 %	-
A4	Peer Review	6 %	-
A5	Stats and LaTeX	10 %	-
A6	Report	20 % [S+P] 32 % [C+P]	18 % [S+P] 72 % [C+P]

3.2.1 Assessment progression

There is a semester-by-semester progression of weight onto the report and on to the fraction of the report-mark that reflects the physics (Clarity and Physics mark [C+P]) rather than the technicalities of constructing a report (Structure and Presentation [S+P]).

- Weight of report overall:
  - ⇒ Year 1 Semester 1, 38 %
  - ⇒ Year 1 Semester 2, 49 %
  - ⇒ Year 2 Semester 1, 52 %
  - ⇒ Year 2 Semester 2, 90 %
- Clarity and Physics [C+P] fraction of overall report mark:
  - ⇒ Year 1 Semester 1, $= 0$
  - ⇒ Year 1 Semester 2, $\sim 1/3$
  - ⇒ Year 2 Semester 1, $\sim 2/3$
  - ⇒ Year 2 Semester 2, $\sim 4/5$

There is a corresponding decrease in the weight for the log-book component. Although don't be fooled, without a good log-book you can't produce a good report. This progression will be reflected in the skills you should acquire as the laboratory progresses and at the end of year 2 you will be well positioned to tackle the various projects you will encounter in year 3 and possibly year 4.

3.2.2 Plagiarism

Presenting work that is not your own for assessment constitutes plagiarism. Plagiarism occurs when a student 'borrows' or copies information, data, or results from an unacknowledged source, without quotation marks or any indication that the presenter is not the original author or researcher. Another form of plagiarism (and hence cheating) is auto-plagiarism or self-plagiarism. This occurs when a student submits work (whether a whole piece or part of a piece) without acknowledging that they have used this material for a previous assessment.

- If you are resitting the year you cannot re-submit your reports and assessment from the previous year. Any submission must be entirely new.

If you use someone else's pre-existing work - say, by summarising it or quoting from it - you must reference the original author. This applies to all types of material - not only text, but also diagrams, maps, tables, charts, and so on. Be sure to use quotation marks when quoting from any source (whether original or secondary). Fully reference not only quotations, but also paraphrases and summaries. Appropriate references according to the type of work or image should always be given.

All submitted work, reports and pre-session summaries, will be assessed for plagiarism. Your submission will be automatically checked against a vast repository of: University of Bath work; the lab manuals; other students' submissions; wikipedia; and reports from undergraduates at other University. Any student who is found to have used unfair means in an examination or assessment procedure will be penalised. 'Unfair means' here include:

- fabrication (for example, reporting on experiments that were never performed)
- falsification (for example, misrepresentation of the results of experimentation)
- plagiarism (as discussed above)
- self-plagiarism (duplication of one's own work, as discussed above)

The University's QA Code of Practice, QA53 Examination and Assessment Offences, sets out the consequences of committing an offence and the penalties that might be applied.

Penalties for unfair practice will be determined by the Department or by the Faculty/School Board of Studies. They may include failure of the assessment unit or part of a degree, with no provision for reassessment or retrieval of that failure. Proven cases of plagiarism or cheating can also lead to an Inquiry Hearing or disciplinary proceedings. Claims of inadvertence or ignorance will not be accepted as a basis for mitigation of a penalty.

If you are accused of an offence, the Students' Union's welfare services are available to support you when your case is being examined. Other more specific points to note:

- You cannot copy from the lab manual for the experiment, that is, you must put everything in your own words.
- Most cases of plagiarism arise through poor time management and so trying to submit an assignment on time and using a little cut-and-paste. Nonetheless, this is still plagiarism and will be treated accordingly.
- Plagiarism is covered in the Academic Skills sessions in year 1 semester 1 and the compulsory moodle based Academic Integrity Initiative: Training and Test.
- See: http://www.bath.ac.uk/library/infoskills/referencing-plagiarism/

Project reports In semester 2 you submit a report on your project work twice. You are expected to use your first submission, the feedback you get, and your own thoughts to improve your report and submit again. In this case you can use as much or as little of your first submission and it will not count as plagiarism.

3.2.3 Late submission of work

In line with the normal University regulations:

- You will be expected to hand in all assessed coursework and dissertations/projects by a specified date and time. This is to ensure fairness to all students who are submitting work.
- If there are valid circumstances preventing you from meeting a deadline, your Director of Studies may grant you an extension to the specified submission date. Forms to request an extension are available from your Department. You will need to provide a description of the circumstances which you feel support your request. Your Director of Studies may ask you to produce supporting evidence. Please ask them to then contact the lab coordinator Dr Sloan.
- If you submit a piece of work after the submission date, and no extension has been granted, the maximum mark possible will be the pass mark (40 %).
  - ⇒ For some assignments in this [WL] course, particularly the pre-lab summaries, any late submission will result in a mark of 0 (zero).
- If you submit work more than five working days after the submission date, you will normally receive a mark of 0 (zero), unless you have been granted an extension.
- It is not usually possible to mark coursework anonymously if it is submitted after the deadline.

3.2.4 Marking

We hope that overall the marking and feedback will be fair, transparent and helpful. We do not assess all the, say, graphs of your report, but may look at a specific one at random or a subset. There is, wait for it and don't tell anyone else, an uncertainty on marking, both random and systematic. A mark or grade is simply our measurement of your 'learning' (whatever that means).

We've been working hard to eliminate these uncertainties as much as possible, but they will be there to a certain amount. The random uncertainties should average to zero (see section 13.2.1 on page 75). We've worked hard to eliminate systematic uncertainties. However, if you spot one please tell us and we'll try and address the issue.

3.3 Feedback sessions

You submit a report, we mark it and give you advice on how to improve things next time - **feedback!**. Usually that is the end of the process, but to make this more effective use of your learning time and ours there are several 'feedback sessions' throughout the year. See the timetable at the front of this booklet.

- These sessions will be chance for you to ask questions about your report and the feedback you got. The more questions you have the better and the more you'll get out of it.
- We'll talk through the overall themes that all student struggle with.
- You can ask specific questions.
- You can identify any technical mistakes we may have made in the marking.

I hope these one-to-one informal sessions allow you to understand more what we are looking for and so make more efficient use of your and our time and overall enable you to produce better reports and ultimately better science. The students that really engage with this feedback and ask pointed questions during the 10 min sessions, generally do much better in the next set of reports.

Part B: Assessment

Section 4

Assessment A1 : Pre-session summary

4.1 Rationale

Experimental science is about testing ideas and answering questions. It is essential, before setting foot in a laboratory, to know what questions you're trying to solve, how you may solve them and what they may mean. You don't just get into a car and start driving, you know where you're going and you may even have a route map.

See the **'Guide to: Pre-lab' in section 10** for practical tips on how to approach an experiment and a few examples of previous student submissions and associated marks.

Moreover, the skill in reporting complex ideas neatly and concisely are precisely what you require to write a scientific abstract, or really any summary of anything, for example, why you may be the best person for a job.

4.2 Details

On selected experiments (see timetable) you will upload to moodle a maximum 120 word summary in plain text (not Word etc.) by the Wednesday at 23:59 before you perform that experiment during the normal Thursday lab session. You are advised to collect a copy of the experimental script the week before. All scripts are also available on moodle. These summaries will be marked during the Thursday session. Feedback and marking will all be based on moodle.

- No late submissions can be accommodated.

It is advisable to submit well before the deadline just in case you are taken ill etc. The pre-session summary should be in plain text, plain English and contain the following information.

- A descriptive title, see section 12.2.1.
- What it is you are going to measure.
- Why you may want to measure it.
- How you are going to measure it.
- Perhaps some steps along the way to the final measurement.

- What you intend on comparing your measurement with.
- What you think may be the main sources of uncertainty.

You should paste your summary into your log-book. Moreover, you are expected to produce such a summary in your log-books for all your experiments. This task is difficult as fitting all this information into 120 words is demanding and often needs creative thinking.

4.3 Details for session 4 of Projects

Write a new summary but based on what you wish to do having now analysed and written up your project. It is unlikely you will not spot something interesting or possibly wrong, or have a new idea. The scientific method is iterative, so we're allowing you to experience a little bit of iteration. Crudely you could write something like: "We found ... hence we're going to ... because ...". If you simply restate the initial projects purpose you won't get many marks, I want to know what and why you're going to do something based on your thinking.

Section 5

Assessment A2 : Achievement

5.1 Rationale

As part of the measuring we do to give you marks and grades and degrees, we need to differentiate between students to reward to those who earn it. We have carefully aligned the assessment scheme of these labs to reward the skills and achievement that will guide you to being a good experimentalist. Therefore instead of a standard 'attendance' mark, here we test how much of your experiment you managed to perform within the session. Those who come prepared (the pre-session summaries will help this), arrive promptly and work well and diligently will be rewarded.

5.2 Achievement for each experiment

In order to gain the Achievement mark we expect you to perform a certain amount of your experiment. These 'experimental minimums' should not be viewed as a final target. Alongside the achievement mark, the log-book and report marking includes a component that will reflect how much of the experiment, from the minimum to the complete experiment you manage. Reading ahead and writing a pre-session summary will stand you in good stead.

- Log-book stamping:
  - ⇒ Your log-book will be stamped at the beginning of the session.
  - ⇒ Once you achieve the minimum requirement find a member of staff or post-graduate demonstrator, show your achievement and get a stamp.
  - ⇒ Your log-book will also be stamped when you leave.
- You **cannot** include or analyse any data that you or your lab partner did not take. But you should compare with and reference the literature.
- Any amount of data analysis, thought, discussion can be entered outside of the lab session. Just date that work as normal. It will count towards your log-book mark.

The experiments are designed so that the 6 hours should be more than enough to complete the experiments, with built in contingency for possible time lost due to normal experimental difficulties. For example, having an incorrectly set up oscilloscope, or an item of equipment just not working. Past experience suggests the predominant reason an experiment may not be finished is where the first hour of the sessions is taken up with reading the script. Accurate and efficient experimentation is an important skill to master, as is reading ahead and planning.

If there are extenuating circumstances why you did not complete the minimum required in the session please inform a member of Academic Staff during the session and get them to make a note in your log-book. For example, time lost due to a fire-alarm, medical emergencies etc. But of course, you can complete the analysis outside the normal hours, it is just that all the data must be taken during the laboratory session.

5.2.1 Late arrival

[Taken from section 2.2.3] If you arrive later than **9:25** it will be noted and your possible Achievement score for that session adjusted accordingly. Because of the excessive disruption it would cause to your lab partners, late arrival after **9:40** will incur a further adjustment to your possible Achievement score. Because the year 2 experiments are two sessions long, after the second session I'll give out marks for each session based on whether the minimum was achieved over the two sessions.

- Minimum achieved.
  - $\Rightarrow$ $+50$ % for each session for arrival before 9:25
  - $\Rightarrow$ $+35$ % for each session for arrival before 9:40
  - $\Rightarrow$ $+30$ % for each session for arrival after 9:40
  - $\Rightarrow$ $+0$ % for each session absent
- Minimum NOT achieved.
  - $\Rightarrow$ $+15$ % for each session where the student was present
  - $\Rightarrow$ $+0$ % for each session absent
- Authorised absence or illness
  - $\Rightarrow$ See section 2.2.3
  - $\Rightarrow$ Your Achievement mark will be adjusted accordingly.

5.2.2 Experiment by experiment minimums

Code	Experiment Name	Minimum achievement
P3	Laplace's equation in heat transfer	Take all measurements and complete 4.1 : numerical method.
P4	Hall coefficient in a semiconductor	Carry out whole experiment for at least 3 field strengths.
P5	The Zeeman effect	Observe all splitting and polarisation effects. Carry out whole experiment for at least 5 field strengths.
P6	Ultrasonic waves	End of section 5 : transmission at normal incidence for a finite thickness plate.
P7	Haynes-Shockley experiment	Take all measurements and perform calculation in 3(a) and 3(b) : drift velocity and mobility and carrier transport.
P8	Fourier optics and image processing	Carry out section (v) (low pass filtering) for gauze A and one other slide.
P9	Franck-Hertz experiment	Collect and process data for at least 3 different temperatures.
P11	Polarised light	End of section 3.4 : circular polarisation.
P12	Microwave antenna	End of section 3 : the Yagi antenna. NOTE: do not do nor write-up the astrophysics section.
P15	X-rays	End of section 5 : absorption and filtering.
P16	Jamin interferometer	Measure angle v pressure for 5 pressures and process results as in section 3.2.
P17	Electron spin resonance	End of section 3.2 : determining the resonance magnetic field.
P18	Fresnel equations	Collect data for 5.2.2 (reflectivity - high to low index)
P19	Critical Potentials	End of section 3.0 : complete experiment for helium.

Assessment $\boxed{A2}$

Section 6

Assessment A3 : Log-books

6.1 Rationale

In any experiment it is essential to keep a running record of everything that is done. The record should be clear - and economical. On the one hand, you do not want to have to spend time subsequently searching pages of numbers without headings to find a particular set of results, or puzzling out from some meagre clues just what the conditions were when you made a certain set of measurements. On the other hand, to produce a record that is so clear that it may be followed with absolute ease by someone else is itself a time-consuming operation and is hardly necessary. You should aim at a record that you yourself will be able to interpret without too much difficulty after an interval of, say, a year.

Extract from ref [3].

6.2 Details

You will be assessed on the quality of your laboratory log-book and you will find examples of log-books on moodle.

- Section 11 details of how to construct your log-book: read it.
- At the end of each experiment, you must staple and fill out the 'log-book check-list' of section 6.3. Paper copies will be available in the teaching laboratory.
- You can get formative feedback on your log-books during the lab sessions by asking a demonstrator.
  - ⇒ They will not give you an informal mark.
  - ⇒ They will talk to you about your log-book and in general what they think of it. The demonstrators are an excellent learning resource, please do use them.
- You will **submit** your log-book as timetabled on page (ii) and section 3.2 for mark-weighting details. This will allow us to provide feedback to you throughout the year to help you improve your record keeping.

- One experiment in your log-book will be chosen at random to mark.
- Note, some of the log-book marking requires you to plot graphs. This could simply be a calibration curve, not necessarily a 'proper' results graph.
- Marks will be returned by moodle.
- Feedback will be by either moodle or in the log-book itself.
- We always aim to update and improve our moodle mark-scheme, so the scheme below may not quite match the present moodle scheme, but it will be close.

6.3 Log-book mark and self-assessment scheme

Administrative				
Full name on book?	No: 0 Marks	Initials only: 1 Marks	Yes: 2 Marks	
E-mail and department so it can be returned if lost?	No: 0 Marks	Missing either email or department: 1 Marks	Yes: 2 Marks	
Loose leaf paper?	Yes lots: 0 Marks	A few bits: 1 Marks	None: 2 Marks	
Contents (front or back) (pages, experiment name/number, date)?	No: 0 Marks	Incomplete: 1 Marks	Yes: 2 Marks	
Page numbers on each page?	No: 0 Marks	Incomplete or illegible: 1 Marks	Yes: 2 Marks	
Each page dated at the top?	No: 0 Marks	Incomplete or illegible: 1 Marks	Yes: 2 Marks	
New page taken at the beginning of a new day?	No: 0 Marks	Yes: 1 Marks		
Writing legible?	No: 0 Marks	Mostly illegible: 2 Marks	Can be read but sometime tricky: 4 Marks	Easy to read: 6 Marks
Each page dated at the top?	No: 0 Marks	Incomplete or illegible: 1 Marks	Yes: 2 Marks	
Completed and reasonable self-assessment?	No: 0 Marks	Many items not scored or obviously not a reasonable attempt: 2 Marks	Some items not scored: 4 Marks	Yes: 6 Marks

Some evidence of pre-session activity, e.g., similar to assessment A1. Marks for logical sense and understandability, can be cut 'n' paste from a typed document?	No: 0 Marks	A simple copy of the experimental script.: 4 Marks	Some attempt over a simple regurgitation of the experimental scrip, but not much evidence of actual thought.: 8 Marks	Nicely written summary as requested for the pre-session summaries activity.: 12 Marks
Diagrams				
Good use of diagrams/sketches?	No diagrams: 0 Marks	Perhaps a poor sketch or two: 1 Marks	Some nice sketches, but perhaps too few or too scrappy: 2 Marks	Well drawn sketches that allow easy reading of the log-book: 3 Marks
Clear diagrams?	No diagrams: 0 Marks	Poorly drawn: 1 Marks	Good attempt and may be useful to the author, but perhaps not so useful to the casual observer: 2 Marks	I look and I understand what's what: 3 Marks
Well labelled diagrams?	No diagrams: 0 Marks	Some attempt at a label, but not clear: 1 Marks	Nice label: 2 Marks	Excellent label, just like a figure caption: 3 Marks
Tables				
Good use of dimensionless heading?	No tables or no headings: 0 Marks	Some attempt, but perhaps not consistent or illegible: 1 Marks	Good effort, but some room for improvement: 2 Marks	Excellent, just as requested: 3 Marks
Clear accompanying explanation to table what is being recorded and which values are raw values?	No table or no associated explanation: 0 Marks	An effort at an explanation, but so brief as to be not useful for the reader: 2 Marks	Clear explanation, clear indication of raw values, but to the reader could be more clear: 4 Marks	Reads like a report: 6 Marks

Clear indication of where raw uncertainty arises?	No: 0 Marks	Some attempt made but on the whole not helpful to the reader: 1 Marks	Some indication, but perhaps not as clear as it could be: 2 Marks	Clear description and maths if needed: 3 Marks
Clear indication of how uncertainty on final processed number arises?	No: 0 Marks	Some attempt made but it's not clear what it entails. Perhaps illegible, or lacking textual description: 2 Marks	A decent attempt but perhaps scrappy or missing an element: 4 Marks	Yes, logical descriptions and step by step mathematics: 6 Marks
Clear link to computer file?	No link given: 0 Marks	Some evidence of a link: 1 Marks	Good but probably still insufficient for a reader to find the file: 2 Marks	Very clear and unambiguous link to University file system: 3 Marks
Graphs				
Graph included?	No graphs at all: 0 Marks	A poor graph: 2 Marks	A nice graph: 4 Marks	Has excellent graph: 6 Marks
Title or explanatory text is descriptive and concise?	No title or text: 0 Marks	Some evidence of a title etc. but not enough, or too illegible, to understand the graph: 1 Marks	Nice title or text, but still lacking some key details, but sufficient for most uses: 2 Marks	Very clear title or text, makes graph easily understandable to the reader: 3 Marks
Labelled axes?	No graph or axis not labelled: 0 Marks	Hints at a label, but not useful: 1 Marks	Axis labelled, perhaps one or two missing, or poorly written: 2 Marks	All axis appropriately labelled: 3 Marks
Correct use of dimensionless units?	No graph, or no attempt at dimensionless units: 0 Marks	Some evidence but too scrappy or incorrect to be useful: 1 Marks	Some good use of dimensionless units, but some could be better: 2 Marks	Excellent use of dimensionless units on all axis: 3 Marks

Indication of error bars?	No graphs, or no error bars: 0 Marks	Some minor attempt at error bars: 1 Marks	Nice error bars, but perhaps non-physical or a few missing or no text description: 2 Marks	Excellent error bars, with clear explanation: 3 Marks
Clarity				
Good use of space?	No, all compressed together: 0 Marks	Occasionally starts on a new page, but experiments run into each other, or hard to tell the start or end of a section: 1 Marks	Some good use of space to ensure an easily digested book, but still some room for improvement: 2 Marks	A very clear and well laid out log-book: 3 Marks
No overwrites and no tippex?	Evidence of much tippex or overwriting: 0 Marks	Some bits seem confused by overwriting of tippexing: 1 Marks	A few bits seem confused by overwriting of tippexing: 2 Marks	None observed: 3 Marks
Descriptive notes in plain English as to what's what?	No, text at all, just tables and numbers etc: 0 Marks	Evidence of patch attempts to string together some textual narrative: 3 Marks	Some description, but could be, illegible, too long, or too short: 6 Marks	Lovely descriptions, not overly verbose but enough to know what's what: 9 Marks
No pencil (except graphs and diagrams)?	Any evidence of pencil at all (except graphs and diagrams): 0 Marks		No evidence of pencil (except graphs and diagrams): 3 Marks	
Completion				
Did the student fully complete the experiment over and above the experimental minimums?	Just the minimum: 0 Marks	Some effort at analysis: 5 Marks	Good effort, nearly complete, but no conclusions: 10 Marks	A compete an experiment as can be asked for: 15 Marks

Section 7

Assessment A4 : Peer Review

7.1 Rationale

> Not everyone can write great literature, but anyone can write good, clear English - if he or she is prepared to take the trouble. Be critical of what you write. Ask yourself continually whether what you have written is logical, clear and concise. If not, try again - and again. Hard writing makes easy reading. Give your work to others to read for critical comment; read and criticize theirs. You should not regard good experimenting and good writing as separate things. There is beauty in both, and it is no accident that the greatest scientists like Galileo and Newton have produced some of the finest scientific writing.

Extract taken from ref [3].

Once in the year you will attend a 'Peer Review' session. This will give you the opportunity to review reports from students in another group. Hopefully the process of reflecting on them will, in the future, improve your report writing. This session will be run during the normal lab time slot, see your specific timetable on page (ii).

The main 'learning feedback' of this exercise will occur when you submit your next report.

7.2 Details

- You will **read, review and comment upon 2** student reports labelled A and B.
  - ⇒ The reports are real student reports written with the guidance given in this document.
  - ⇒ Paper copies of reports A and B will be handed out and collected back in at the end of the session.
  - ⇒ If you have a DAP requirement (e.g., extra time in exams, rest breaks etc.) please contact the lab coordinator Dr Sloan well in advance and appropriate adjustments will be made, e.g. earlier start time.

7.2.1 [S+P] Structure and Presentation

For each report you will complete a **moodle based quiz** with questions matching the majority of the 'Structure and Presentation' [S+P] marking scheme, see section 9.3 on page 37:

- The quiz will be open from 9:45 am to 11:00 am.
- Your responses will be **marked against** the original marks given by the staff for that report.
- **Feedback** to you will be via moodle.
- You may have your copy of this lab manual
- To ensure fairness the exercise will be run under exam conditions:
  - ⇒ no talking
  - ⇒ mobile phones and bags at the front
  - ⇒ no use of the internet except for accessing the relevant moodle page since you may have to consult the relevant experimental lab script.

7.2.2 [C+P] Clarity and Physics

You will work in small groups to discuss the 'Clarity and Physics' of the reports, see section 9.4 on page 41.

- Between 11:05 and 12:00 you will work in small groups and discuss the 'Clarity and Physics' of the reports.
- If there are white boards you will use them, if not post-it notes.
- I and one of the demonstrators will rove around asking questions and nudging you along.

Section 8

Assessment A5 : Stats and LATEX

8.1 Rationale

Since we live in the 21st century, we going to aid you in using computers to do much of the heavy lifting of the statistical analysis of your experiment and the generation of your final reports. We can show you how to do all this, but these computer skills just require practice. So this assessment will run in near identical guise in Year 1 semester 1 and semester 2, as well as in Year 2 semester 1. This will give you practice to allow you ultimately to produce better science and better scientific reports (and so get more marks!).

8.2 Details and instructions

Each student will be given a unique set of experimental data. Below are a list of statistical results you will work out and then report using the LATEX template to produce a very short report of your statistical analysis. You can find an example report on moodle. Present your answers as depicted in the moodle example and taking into account the instructions in this booklet.

Note, the LATEX template for this assessment is based on the template you will use for report writing. Also, the exmaple given at the end of this section highlights the parts you will need to modify in the LATEX document, so not much to do except type in your values, upload your figures and enter your various equations.

8.2.1 Year 1 Semester 1

Data Set 1: A set of 10,000 measurement of an electrical current and the uncertainty on each measurement. No experimental parameters were changed during these measurements. The current was flowing though a $100\ \Omega$ resistor.

- For the first 3 current measurement work out the following.
  - ⇒ Their mean.
  - ⇒ Their standard deviation σ.
  - ⇒ Their standard error of the mean s_{mean}.
- Repeat for the first 5, 10, 50, 100 and finally all the 10,000 data points.

- Report your findings in a neat table.
- Plot the values with 'error bars' of the first 50 data points.
- Report your best value and uncertainty of the electrical power dissipated in the resistor.

Data set 2: A set of 40 measurements of the restoring force of a spring as it undergoes compression and expansion.

- Perform a linear least square fit to your data.
- Report your fitting parameters of the slope and its uncertainty and the intercept and its uncertainty.
- Plot the positional dependence of the force with their associated 'error bars'. Include your best line fit.

8.2.2 Year 1 Semester 2

For your new data sets, repeat the analysis for Year 1 Semester 1 and do the following analysis:

Data Set 1:

- For the first 3 measurement work out the following.
  - ⇒ Their weighted mean.
  - ⇒ Their weighted standard error of the mean s_{mean}.
- Repeat for the first 5, 10, 50, 100 and finally all the 10,000 data points.
- Report your findings in a neat table.

Uncertainty propagation equations You will find in the Excel file the identity of two equations. Report them and also report the mathematical formula that links the uncertainty Δx on x to the uncertainty Δy on y. The equation are given here in table 8.1.

Table 8.1: The identify of the 6 possible equation for students to present and analyse.

Equation number	Equation
1	$y = \frac{a+b}{x^2}$
2	$y = (a+b)x^n$
3	$y = b \log_{10} ax$
4	$y = ae^{bx}$
5	$y = \frac{a}{b+x}$
6	$y = a \sin(b+x)$

Equilibrium Spring position Combining the spring constant k, force $F_{x=0}$ at $x = 0$ with their associated uncertainties, find and report the x position of the equilibrium spring position x_0 and its uncertainty.

8.2.3 Year 2 Semester 1

For your new data sets, repeat the analysis for Year 1 Semester 1, Year 1 Semester 2, and do the following for Data Set 3.

Data set 3 You have measured the position h of a body falling for a time t from an initially stationary position. Air drag and turbulence have modified the usual $h = \frac{1}{2}at^2$ relationship. Determine the power law dependence p of the speed on the drop time, $h \propto t^p$.

- Plot on an appropriate linear scale the data.
- Plot the same data on an appropriate logarithmic scale.
- Perform a weighted linear least squares fit and include it on your logarithmic plot.
- Report the power p and uncertainty.

Section 9

Assessment $\boxed{\text{A6}}$: Report

9.1 Rationale

Part of academic life is producing lab reports, although we academics grandly describe them as 'papers'. The skills required and indeed most of the structure of lab reports are the same required for any written means of communication. Newspaper columns have abstracts, introductions, discussions etc., they just don't label them. It is a key skill in communications and where we will also assess your level of understanding of the physics of your experiment. See section 12 for a detailed guide to the report.

You will be assessed on the Structure and Presentation [S+P] and the Clarity and Physics [C+P] of your reports. Example reports are on moodle, complete with Word and LaTeX versions.

These activities and assessments are designed to be a structured and reflective exercise allowing you to improve your report writing semester by semester. They will prepare you well for years 3 and 4 .

9.2 Details of assessment

The assessment of lab reports will take the following form:

- You will write **one** lab report per semester on an experiment of your choosing.
- You will use a **template**
  - ⇒ Either use the Word template on moodle
  - ⇒ Use the example Word report on moodle
  - ⇒ Use the LaTeX template on moodle
  - ⇒ Use the example LaTeX report on moodle
  - ⇒ Use whatever you like as long as your report looks like the example reports on moodle
- **No longer than 8 pages.**
- This will be **uploaded** as a **pdf file** to moodle
  - ⇒ The **file name** will be 'your-student-number.pdf' (see section 2.2.2 on page 8).

Assessment A6

⇒ In Word ‘save-as’ and then choose pdf or ‘Export’ to pdf.

⇒ In LaTeX use pdflatex or some-such.

⇒ It will be checked for plagiarism.

⇒ Marks and feedback will be via moodle.

9.3 Mark-scheme for [S+P] Structure and Presentation

Administrative				
Is it anonymous?	No I can identity the student, either on their paper report or on the file-name of the report: 0 Marks		Yes: 6 Marks	
Is the filename just ‘student number.pdf’?	No they used some other format for the filename: 0 Marks		Yes that was the format used: 6 Marks	
Student Number given on report?	No: 0 Marks		Yes: 3 Marks	
Overview				
Layout looks like the template?	Not at all: 0 Marks	Not really but has something, e.g. headings: 4 Marks	Follows closely, but has minor problems, e.g., wrong font, or margins, or poor figure placement etc.: 8 Marks	Perfect. It looks like an IOP article. Is of a standard to publish as is: 12 Marks
Section in order: Abstract, intro, experimental, results and specific discussion, general discussion, conclusion, references?	Not at all: 0 Marks	Roughly, but some missing or in the wrong order: 4 Marks	Yes, but perhaps, e.g., the content of all the sections don’t quite match their headings: 8 Marks	Excellent, following section order and each section does what it’s supposed to: 12 Marks
Abstract				
Good length? 125 ± 25 words?	No abstract: 0 Marks	Way too short/long: 2 Marks	Too short/long: 4 Marks	Good length: 6 Marks
Does it contain quantitative measurements?	No: 0 Marks		Yes: 3 Marks	

<table>
<tr><td>Are the quantitative measurements reported with appropriate uncertainty and units?</td><td>No:
0 Marks</td><td>Yes but with formatting issues:
3 Marks</td><td colspan="2">Excellent, e.g., (7.2 ± 0.2) kg:
6 Marks</td></tr>
<tr><td colspan="5">Experimental</td></tr>
<tr><td>Diagram presented?</td><td>No diagram in experimental section. Or copied from somewhere else:
0 Marks</td><td>A diagram, but a poor effort, e.g., scrappy, difficult to understand:
2 Marks</td><td>Nice diagram showing the main points clearly, but has some minor imperfection, e.g., size or layout:
4 Marks</td><td>Excellent diagram, nothing to improve:
6 Marks</td></tr>
<tr><td>Useful caption?</td><td>No caption:
0 Marks</td><td>Caption is only a number and title:
2 Marks</td><td>Good descriptive caption, but has minor problems, e.g., English or incomplete and diagram cannot be quite understood as standalone entity:
4 Marks</td><td>Excellent caption clearly describing all aspects of the the diagram:
6 Marks</td></tr>
<tr><td colspan="5">References</td></tr>
<tr><td>More than 3 refs? (only articles and books)?</td><td><3 could be www refs which are not allowed:
0 Marks</td><td>3 Refs:
2 Marks</td><td>4 Refs:
4 Marks</td><td>4 or more good refs:
6 Marks</td></tr>
<tr><td>Correctly formatted?</td><td>No refs:
0 Marks</td><td>Poorly:
2 Marks</td><td>Fine but still some typos/messy:
4 Marks</td><td>Perfect:
6 Marks</td></tr>
<tr><td colspan="5">Graphs</td></tr>
<tr><td>Computerised graph included?</td><td>No graphs at all!:
0 Marks</td><td>Hand drawn or poorly presented, e.g., with a bounding box:
3 Marks</td><td colspan="2">Yes:
6 Marks</td></tr>
<tr><td>Does it have a title?</td><td colspan="2">Yes there is a title, or there is just no graph:
0 Marks</td><td colspan="2">No title - this is good:
3 Marks</td></tr>
</table>

Labelled axes?	No label or no graphs: 0 Marks	Poorly: 1 Marks	Nicely but could be improved: 2 Marks	Excellent: 3 Marks
Good use of units?	No: 0 Marks	Poor: 1 Marks	Nicely but could be improved: 2 Marks	Excellent: 3 Marks
Indication of error bars?	No error bars and no mention in caption as to why: 0 Marks	Poor: 1 Marks	Nicely but could be improved: 2 Marks	Excellent indication of uncertainty: 3 Marks
Readable text on print out?	No: 0 Marks	Poor: 1 Marks	Ok but could be improved: 2 Marks	Excellent clarity: 3 Marks
Descriptive caption?	Nothing more than a title: 0 Marks	Nice description, but some item, missing, e.g., details of fit, or precise experimental parameters: 2 Marks	Excellently clear and useful: 4 Marks	Excellently clear and useful: 6 Marks
Table				
Nicely formatted table?	No: 0 Marks	Poor: 2 Marks	Nicely but could be improved: 4 Marks	Excellent formatting, just what was asked for: 6 Marks
No title on table?	Title given, or no table - bad: 0 Marks		No title - this is good: 3 Marks	
Variables and units given?	No: 0 Marks	Poor: 2 Marks	Nicely but could be improved: 4 Marks	Excellent and clear table: 6 Marks
Clear caption?	No: 0 Marks	Poor: 2 Marks	Nicely but could be improved: 4 Marks	Excellent caption, informative and clear: 6 Marks
Displaying values and mathematics				

All values given with error?	All wrong: 0 Marks	A few nice, but most wrong: 2 Marks	A few typos: 4 Marks	Yes: 6 Marks
Variables in italics?	All wrong: 0 Marks	A few nice, but most wrong: 1 Marks	A few typos: 2 Marks	Yes: 3 Marks
Units in plain text?	All wrong: 0 Marks	A few nice, but most wrong: 1 Marks	A few typos: 2 Marks	Yes: 3 Marks
Kept to a minimum without missing out key items?	There was none: 0 Marks	Way too much/too little, e.g., showing excessive arithmetic, not using English in between maths etc.: 2 Marks	Just about right, but some instances of, e.g., too much detail, or perhaps not quite enough linking maths: 4 Marks	Excellent level of mathematics: 6 Marks
All variables etc. defined?	No maths: 0 Marks	Sloppy: 2 Marks	Mostly all defined: 4 Marks	Yes: 6 Marks
All equations numbered on the right-hand-side?	No: 0 Marks		Yes: 3 Marks	
No crazy punctuation, just normal text?	No maths: 0 Marks	Poorly done, e.g., does not flow in text, or write 'as equation (1) shows, . . . ': 2 Marks	Nicely done, but a few typos: 4 Marks	Excellent integration of maths into plain text: 6 Marks
Achievement				
Did they report a fully complete experiment from the point of the experimental minimum to the complete experiment?	Just the minimum: 0 Marks	A few bits of data but not much analysis: 2 Marks	Some data, some analysis: 4 Marks	Fully complete data and analysis: 6 Marks
Did the student try anything 'off script'?	No, or at least not highlighted: 0 Marks	Mentioned something, but no data or analysis: 1 Marks	Some data and analysis: 2 Marks	A full off-script experiment presented: 3 Marks

9.4 Mark-scheme for [C+P] Clarity and Physics

All items are marked as indicated at the top of each column except for the 'Analysis and results' row which carries the higher individual marks indicated. The moodle marking scheme will also have a column for 'Not attempted, zero marks'.

You report will be assessed by a member of academic staff and on moodle you will receive you marks according to the scheme below. You will also receive feedback on moodle with suggestions on what to focus on to help improve your next lab report. You will be able to discuss marks and feedback during the tutorial sessions, see section 3.3 on page 18.

Note the mark scheme for [C+P] is derived (plagiarised!) from the scheme used to assess the MSci 4th year project that you could do in the final year of your degree. It is also similar to that used for the 3rd year Industrial Team Project report. The main difference here is that we expect less for the same mark.

	2 marks	4 marks	5 marks	6 marks	7 marks	9 marks
Overall presentation						
Writing style	Totally incoherent writing style	Clumsy or inappropriate writing style, often lapsing into colloquialisms, inappropriate tense, mixture of writing styles	Reasonably good writing style, but with some lapses into colloquialisms, inappropriate tense, mixture of writing styles	Good writing style	Very good writing style	Exemplary writing style; lively and articulate writing, showing excellent command of technical terminology and strong arguments
Description & explanations	Largely incomprehensible descriptions and explanations	Sloppy and confusing descriptions and explanations	Some descriptions and explanations are succinct, clear and precise, but some confusing/confused passages	Most descriptions and explanations are succinct, clear and precise	Nearly all descriptions and explanations are succinct, clear and precise	Entirely succinct, clear and precise descriptions and explanations
Figures & tables	Poor figures and/or tables	Adequate figures and/or tables	Reasonably well designed and relevant figures and/or tables	Generally well designed and relevant figures and/or tables	Well designed and relevant figures and/or tables	Creative use of well designed and relevant figures and/or tables
Linking text with figures and tables	Very poor or missing linkage of the text with figures, tables and equations	Text links poorly with figures, tables and equations	Satisfactory linkage of the text with figures, tables and equations	Text mostly links well with figures, tables and equations	Text links well with figures, tables and equations	Excellent linkage of the text with figures, tables and equations

	2 marks	4 marks	5 marks	6 marks	7 marks	9 marks
Motivation: background and context						
Motivation I: Aims, objectives & applications	Very weak description of the project's aims & objectives, its context and any applications of the work	Poor description of the project's aims & objectives, its context and any applications of the work	Reasonable description of the project's aims & objectives, its context and any applications of the work	Good description of the project's aims & objectives, its context and any applications of the work	Very good description of the project's aims & objectives, its context and any applications of the work	Excellent description of the project's aims & objectives, its context and any applications of the work
Motivation II: background	Very weak description of physical background to the project	Poor description of physical background to the project	Reasonable description of physical background to the project	Good description of physical background to the project	Very good description of physical background to the project	Excellent description of physical background to the project, at a level exactly appropriate for the audience
Achievement						
	Very weak experimental and/or computational skills	Weak experimental and/or computational skills	Evidence of reasonable experimental and/or computational skills	Evidence of good experimental and/or computational skills	Evidence of very strong experimental and/or computational skills	Evidence of excellent experimental and/or computational skills
	Very poor quality and quantity of results, or results presented very poorly	Poor quality and quantity of results, or results presented poorly	Satisfactory quality and quantity of results	Good quality and quantity of results, presented clearly	Very good quality and quantity of results, presented clearly	Excellent quality and quantity of results, presented clearly

	2 marks	4 marks	5 marks	6 marks	7 marks	9 marks
Analysis and scientific understanding						
Critical analysis of technique	Little or no discussion of the advantages and limitations of the techniques used	Little or no discussion of the advantages and limitations of the techniques used	Reasonable discussion of the advantages and limitations of the techniques used	Clear discussion of the advantages and limitations of the techniques used	Strong critical assessment, with a very good discussion of the advantages and limitations of the techniques used	Insightful critical assessment, with an excellent discussion of the advantages and limitations of the techniques used
Analysis & results	Very weak analysis of the results Marks 2	Weak analysis of the results Marks 6	Satisfactory analysis of the results Marks 8	Good analysis of the results, including comparisons with relevant published theoretical or experimental results Marks 12	Very good analysis of the results, including comparisons with relevant published theoretical or experimental results Marks 14	Excellent analysis of the results, including comparisons with relevant published theoretical or experimental results Marks 16
Uncertainties	Treatment of uncertainties weak, flawed or missing	Treatment of uncertainties weak or flawed	Uncertainties treated and discussed reasonably well	Good treatment and discussion of uncertainties	Very good treatment and discussion of uncertainties	Uncertainties treated and discussed entirely rigorously and appropriately
Conclusions	Very weak or missing conclusions	Weak, unclear or unjustifiable conclusions	Conclusions reasonably clear and justifiable	Clear and justifiable conclusions	Clear, justifiable and complete conclusions	Clear, justifiable and complete conclusions, with suggestions for the future development of the project

Assessment A6

Part C: Writing and experimental guides

Section 10

Guide to: Pre-lab

Things I would do before an experiment assuming I really wanted to perform an excellent experiment during the actual lab session.

- **Get** a copy of the lab script for the experiment either on moodle or during the previous session.
- If time permits have a **look** at the experiment apparatus before the session (in the previous session perhaps).
- **Read** the lab script cover to cover - this is the most important step.
  - ⇒ Highlight the items you think are critical.
  - ⇒ Highlight the items that answer the points you'll need to report in the pre-lab summary (section 4 on page 20).
  - ⇒ Highlight the items that you don't quite understand.
- **Write** up in your log-book your take on the experiment, that is, write a short summary.
- Try and be very clear on what measurements you are actually going to take.
- You can even **estimate** the number of measurements you'll take for each section of the experiment.
- From this you may be able to **identify** what the major source of uncertainty in the final answer is going to be.
  - ⇒ Will it be statistical?
  - ⇒ Systematic?
  - ⇒ How will you try and work around this problem?
  - ⇒ Mathematically how will you treat the uncertainty?
- Have a look at the reference in the script. Or have a little google on the subject, or look at the index of your large physics textbook (Knight etc.). Any notes you make can be added to your log-book.

Use your log-book to **record** any pre-session work you do, then, at the very least, you'll know where it is and you'll gain marks for it when we mark you log-book.

10.1 Student examples

10.1.1 Medium: 66%

Calculate resolution of microwave astronomy observation antennae using data collected from dipole and Yagi antennas.

Measuring the angular response of antennae at different wire segment lengths when microwaves are projected at them. This can be sued in astronomy to help observe CMB from the Milkyway.Firing microwave waves at the antenna and recording the voltage produced through the receiver and then rotating the antenna through 360 and measuring at regular intervals. Results compared to theoretical plots of the different antennae. Errors can come from changing antennae angle consistently and anechoic foam being worn over time allowing microwaves to escape.

	Disagree strongly	Disagree a bit	Agree	Strongly Agree
The title is clear and useful.			✔	
I can tell what they are going to measure.			✔	
There is a good a motivation.			✔	
They explain how they are going to do it.			✔	
They explain well the logical progression of the experiment.			✔	
They explain what they are going to compare with.				✔
It's well written.		✔		

10.1.2 Excellent: 95%

Application of microwave radiation to investigate the Angular Response of Simple Dipole and Yagi Antenna

Microwave radiation will be used to measure the angular response of a selection of antennae. The normalised angular response of simple $\lambda/2$ dipole and 2λ dipole antennae will be graphed in polar coordinates and compared with the response determined from theory. The relative response of the partial Yagi antennae will be graphed on a decibel scale to highlight the antennae's directionality. The gain of the full Yagi antenna will be determined and compared with that of the half wavelength dipole antenna. Yagi has application as a television antenna and microwave antenna have application in astrophysics, notably in the discovery of cosmic microwave background radiation.

	Disagree strongly	Disagree a bit	Agree	Strongly Agree
The title is clear and useful.				✔
I can tell what they are going to measure.				✔
There is a good a motivation.				✔
They explain how they are going to do it.				✔
They explain well the logical progression of the experiment.			✔	
They explain what they are going to compare with.				✔
It's well written.				✔

Section 11

Guide to: Log-books

This section is reproduced near verbatim from ref [3]. Copies are available in the lab, the library and online.

In this section some suggestions for keeping the record are given. The important thing is not that you should regard them as a set of rules to be followed blindly, but rather that you should understand the spirit behind them, which is to produce a record - accurate, complete, and clear - with a minimum of effort.

11.1 Bound notebook

The advantage of a single bound book is that one knows where everything is - in the book. There are no loose bits of paper to be mislaid. It is required that the pages of the notebook are numbered, and a detailed list of the contents is compiled at the beginning of the book.

11.2 Recording measurements

All measurements should be recorded immediately and directly. There is no exception to this rule. Do not perform any mental arithmetic - even the most trivial - on a reading before getting it down on paper. For example, suppose numbers appearing on an ammeter have to be divided by 2 to bring the readings to amperes. Write down the reading given by the instrument markings first. Do not divide by 2 and then write down the result. The reason for this is obvious. If you make a mistake in the mental arithmetic, you are never going to be able to correct it. In making and recording a measurement, it is a good idea to check what you have written by looking at the instrument again. So

- read,
- write,
- check.

All written work should be clearly and unambiguously dated at the top of each page.

11.3 Down with copying

An extremely bad habit of many students is to record the observations on scrap paper or in a 'rough' notebook and then to copy them into a 'neat' notebook, throwing away the originals. There are three objections to this:

- It is a gross waste of time.
- There is a possibility of a mistake in the copying.
- It is almost impossible to avoid the temptation of being selective.

The last is the most important and is worth considering further. In most experiments we do not use all the measurements. We often decide that some measurements are not very useful, or were made under the wrong conditions or are simply not relevant. In other words, we are selective. This is quite proper, provided we have objective reasons for the selection. But it is vital that all the original measurements be retained. We may subsequently wish to make a different selection. And in any case all the experimental evidence must be available, so that someone else may form an opinion on the validity of our selection, or indeed on any aspect of the original measurements.

An important part of a practical physics course is to train you to keep clear and efficient records, but this training cannot begin until you try to make direct recordings. They will probably look very messy at first and perhaps will be difficult to follow, but do not let that discourage you. You will gradually learn from experience and improve. The result will never look as pretty as the copied out version, but that is of no consequence. The important thing in a record is clarity, not beauty.

Having said that, let us add that a certain amount of copying out may well be useful. It is often a distinct aid to clarity, which in turn is desirable, not only for its own sake, but also because it reduces mistakes in working out the results. It is very often the case that at a certain point in the experiment we want to bring together various results dotted about in different parts of the account. We may want to plot a graph, do some calculations, or perhaps just look at the numbers. But, since we are retaining the original readings, this copying may be, in fact should be, highly selective and has nothing to do with the wholesale copying mentioned above.

11.4 Diagrams

'One picture is worth a thousand words' - Chinese proverb.

The importance of diagrams in a record or an account can hardly be exaggerated. Combined with a few words of explanation, a diagram is often the easiest and most effective way of explaining the principle of an experiment, describing the apparatus, and introducing notation. Consider the following alternative descriptions of a piece of apparatus for investigating the motion of a pair of coupled pendulums:

Description 1. A piece of string was fastened to a horizontal rod at two points A and B. Two spheres S_1 and S_2 were suspended by strings, the upper ends of which were attached to the original string by slip knots at the points P_1 and P_2. The lengths AB, AP_1, BP_2, P_1P_2 are denoted by a, y_1, y_2, and x respectively. The distance from P_1 to the centre of S_1 is denoted by l_1, and from P_2 to the centre of S_2 by l_2. The degree of coupling between the pendulums was

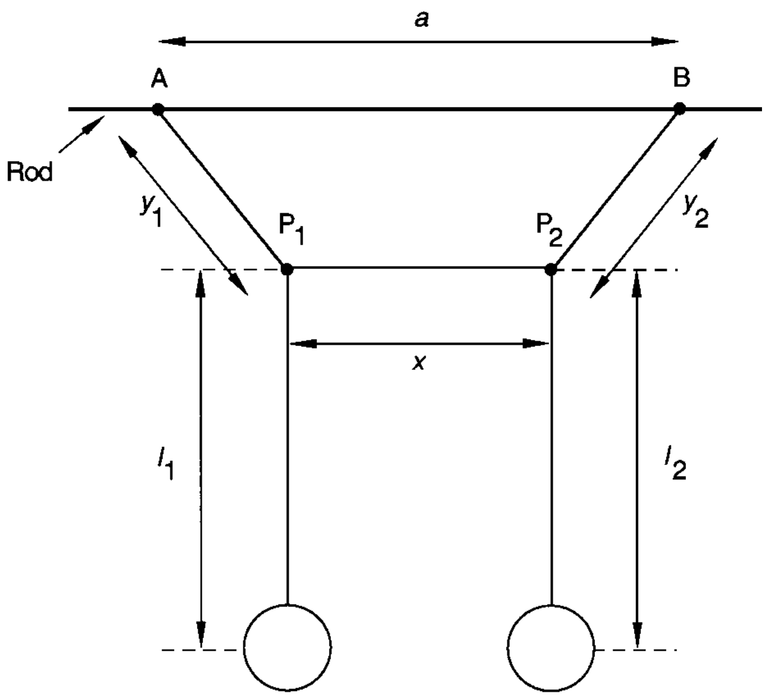


Figure 11.1: A simple diagram worth many words.

varied by varying the distance x. This was done by moving the knots P_1 and P_2 along the string AP_1P_2B, the system being kept symmetric, i.e. $y_1 = y_2$.

Description 2. The apparatus was set up as shown in Fig. 11.1. AP_1P_2B is a continuous length of string. P_1, P_2 are slip knots. Coupling varied by varying x by means of slip knots ($y_1 = y_2$ throughout).

Comment on the two descriptions is superfluous.

A diagram should not be an artistic, or even photographically true, representation of the apparatus. It should be schematic and as simple as possible, indicating only the features that are relevant to the experiment. Furthermore, although an overall sketch of the apparatus drawn roughly to scale is often helpful, you should not hesitate to distort the scale grossly in another diagram if this serves to make clear some particular point.

Suppose, to take a simple example, we are measuring the focal length of a convex lens by placing it on a plane mirror and observing when an object and its image are coincident. We wish to indicate whether a particular measurement refers to the distance from the object to the top or bottom of the lens. Figure 11.2a is to scale; Fig. 11.2b is not, but is much clearer for the purpose. A diagram is usually the best way of giving a sign convention.

11.5 Tables

When possible always record measurements in tabular form. This is both compact and easy to follow. Measurements of the same quantity should preferably be recorded vertically, because the

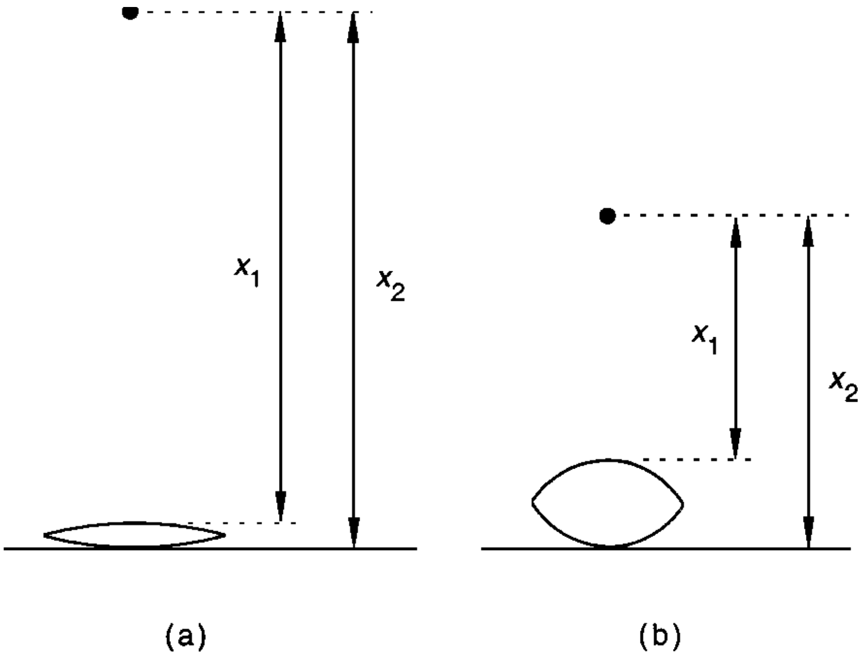


Figure 11.2: Exaggeration for clarity.

$T/$ K	10^3 K$/T$	$\gamma/$ mN m^{-1}
283	3.53	74.2
293	3.41	72.7
303	3.30	71.2

Table 11.1: Surface tension of water

eye can more readily compare a set of vertical numbers. Head each column with the name and/or symbol of the quantity, followed by the units.

For convenience, the power of 10 in the unit should be chosen so that the numbers recorded are roughly in the range 0.1 to 1000. There are several conventions for expressing units in a table. The one recommended by the Symbols Committee of the Royal Society - and used in this lab - is that the expression at the head of a column should be a dimensionless quantity. Consider Table 11.1, which gives the values of γ, the surface tension of water, at various values of the temperature T. (The values are taken from Kaye and Laby 1995, p. 60.) We have included also the values of $1/T$ as a further illustration. The quantities $T/$ K, 10^3 K$/T$, and $\gamma/$ mN m^{-1} are dimensionless, and are therefore suitable headings for the columns. The first line of numbers is interpreted thus.

$$\text{At} \quad T/\text{ K} = 283, \qquad \text{i.e.} \quad T = 283 \text{ K} \tag{11.1}$$

the value of $1/T$ is given by

$$10^3 \text{ K}/T = 3.53, \qquad \text{i.e.} \quad 1/T = 3.53 \times 10^{-3} \text{ K}^{-1}, \tag{11.2}$$

and at this temperature the value of γ is given by

$$\gamma/\text{ mN m}^{-1} = 74.2, \qquad \text{i.e.} \quad \gamma = 74.2 \text{ mN m}^{-1}. \tag{11.3}$$

Once the unit has been specified at the top of a column it is not necessary to repeat it after each measurement. If you do decide that you need to change from, say a V to a mV scale, then you should rule a line across the table and indicate the new scale for the particular column. As ever, just make it clear and unambiguous.

In general all unnecessary repetition should be avoided. It wastes time, it wastes energy, and it clutters up the record. The fewer inessentials we have, the easier it is to follow the essentials.

11.6 Aids to clarity

Diagrams and tables are two aids to clarity. But any such aid is to be welcomed. Groups of measurements of different quantities should be well separated and each should have a title. If a set of measurements leads to one value, say the mean, it is helpful if this one number is not only labelled but also underlined, or made to stand out in some way.

In general you should not be too economical with paper in keeping the record. You will often find yourself starting to record measurements without giving them a title or specifying the units. The habit of leaving a few lines of space at the top permits these items to be added tidily later on. Omitting titles to start with is not necessarily a sign of impatience, but is in fact a sensible practice. You will usually be able to add much more useful titles - often of an extended nature - after several sets of measurements have been made.

A definite hindrance to clarity is the habit of overwriting. Is 37, 27 or 37? Do not leave the reader - or yourself at a later date - to puzzle it out. Just cross out and rewrite $\cancel{27}$ 37.

11.7 Some common faults - ambiguity and vagueness

Example 1. A student is told to measure the viscosity of water at 20 °C and to compare the value obtained with that given in some table of physical constants. The following appears in his notebook:

$$\begin{array}{rl} \text{experimental value} & 1.005 \times 10^{-3}\ \mathrm{N\ s\ m^{-2}} \\ \text{correct value} & 1.002 \times 10^{-3}\ \mathrm{N\ s\ m^{-2}} \end{array}$$

Which is his value and which the one given in the tables? If we know him to be a modest person we might guess that what he calls the ‘experimental value’ is his own, and what he calls the ‘correct value’ is the one in the tables. If he is conceited it might be the other way round. But of course we ought not to have to guess, on the basis of his personality or otherwise. He should have written something like

$$\begin{array}{rl} \text{this experiment} & 1.005 \times 10^{-3}\ \mathrm{N\ s\ m^{-2}} \\ \text{Kaye \& Laby (16th ed. p. 51)} & 1.002 \times 10^{-3}\ \mathrm{N\ s\ m^{-2}} \end{array}$$

Other adjectives such as ‘actual’, ‘official’, ‘measured’, ‘true’ are equally vague in this context and should be avoided. Note that a detailed reference to the tables has been given. We might want to check the value or look at the table again.

Example 2. Consider a notebook entry such as

$$\text{Ammeter A 14} \quad \text{zero offset} \quad -0.03\ \mathrm{A}$$

Does this mean that when no current passed the instrument read -0.03 A, and therefore 0.03 should be **added** to all the instrument readings to get the correct value, or does it mean that 0.03 should be **subtracted**? Again we are left to guess.

In accordance with the rule that measurements should be written down directly, without the intervention of any mental arithmetic, what the experimenter should do is to read the instrument when no current is passing and write down the value. So the entry should be something like

$$\begin{array}{l} \text{Ammeter A 14} \\ \qquad -0.03\ \text{A} \leftarrow \text{reading when no current passed} \end{array}$$

Example 3. The following is a statement of a kind often found in a student's log-book. 'The timebase of the oscilloscope was checked with a timer-counter and found to be accurate within experimental uncertainty.' This is objectionable for its vagueness on two essential points. Firstly, an oscilloscope timebase has a number of ranges and the statement does not indicate which one or ones were checked. Secondly, the evidence for the statement has not been given, and without that evidence we have no means of knowing whether the statement is justified.

11.8 Log-book examples from Bath

You will find on moodle some examples of, log-books taken from previous year's students.

Section 12

Guide to: Reports

This section is reproduced near verbatim from ref [3]. Copies are available in the lab, the library and online.

The communication of ideas, theories, and experimental results is an important part of scientific work. Vast quantities of scientific literature are pouring out into the world, and if you take up a scientific career of any kind you are almost certain to add to the flood. If you can achieve a good standard of writing, two benefits will accrue - one to yourself when people take note of what you have to say, and the other to the rest of the world who - strange to say - prefer their reading matter to be clear and interesting rather than obscure and dull.

We are going to consider some elementary features of good scientific writing. The discussion is confined to a report on some experimental work in physics, but much of what we have to say applies to scientific writing in general. Keep in mind that your report is a logical (not chronological) description of your scientific endeavour. It's worth saying, it is not a dumping ground for data and maths, it is a piece of prose interrupted by figures and equation wherever appropriate.

- For these labs remember to use the correct template (see section 12.8).
- The maximum page limit is 8 pages, most reports will be shorter.

12.1 Plan of report

Your report will be divided into the following sections.

- Title
- Abstract
- Introduction
- Experimental
- Results and specific discussion
- General discussion
- Conclusion

- References

Some reports describing experimental work also contain theoretical material which might well constitute an additional section, coming after either Introduction or Results. Very often what you perceive as 'theory' is really just the mathematical method of extracting information from your raw results. This low-level 'theory' should fit into the relevant results section in order to interpret the results. We consider each section in turn.

12.1.1 How a report is read

In general reports are not read from first word to last. The figures play a critical role in the usefulness of your report and its ease of comprehension. Here is my normal method of reading a scientific report.

- Read title and skim abstract $\Rightarrow$ Look at figures. $\Rightarrow$ Read figure captions. $\Rightarrow$ Read conclusion. $\Rightarrow$ Actually read from top to bottom.

The point is the figures matter enormously.

12.2 Sections of report

12.2.1 Title

The title serves to identify the report. It should be brief - not more than about 10 words. You should bear in mind that the title will ultimately appear in a subject index. The compiler of an index relies heavily on the words in the title in deciding where it should appear. So if there are one or two key words which help to classify the work, try to put them in the title.

Some commonly used words:

- **Measured**: If you directly measure, say, the size of a thing and report it, then use measured.
- **Determined or derived**: If you measure a thing, then workout something else by calculation, then use determined, or derived or some other suitable word.

For example, 'Measuring . . . by . . . to determine . . . '. Health warning, the word 'calculation' in a title implies the result of a pure theoretical calculation with no input from experiment. Since this is an experimental lab, don't use it.

12.2.2 Abstract

Every report will have an abstract of 125 ± 25 words, giving positive information about its contents. The abstract serves two classes of reader. It enables those who work in the subject to decide whether they want to read the report; and it provides a summary for those who have only a general interest in the subject - they can obtain the essential results without having to read the whole report. The abstract should therefore not only indicate the general scope of the report but should contain the final numerical results and the main conclusions. Here is a sentence by sentence guide (not instruction manual) to construct an abstract [4].

> The first sentence of an abstract should clearly introduce the topic of the paper so that readers can relate it to other work they are familiar with. However, an analysis of abstracts across a range of fields show that few follow this advice, nor do they take the opportunity to summarize previous work in their second sentence. A central issue is the lack of structure in standard advice on abstract writing, so most authors don't realize the third sentence should point out the deficiencies of this existing research. To solve this problem, we describe a technique that structures the entire abstract around a set of six sentences, each of which has a specific role, so that by the end of the first four sentences you have introduced the idea fully. This structure then allows you to use the fifth sentence to elaborate a little on the research, explain how it works, and talk about the various ways that you have applied it, for example to teach generations of new graduate students how to write clearly, it should also report you main numerical findings (6.23 ± 0.07) ms^{-1}. This technique is helpful because it clarifies your thinking and leads to a final sentence that summarizes why your research matters.

12.2.3 Introduction

The introduction is an important part of the report, it laies out the aims and objectives and the outcome of the work. Most experiments are part of a general investigation of a physical problem. The introduction should make clear

- Why the problem is interesting,
- the part played by your experiment in solving or helping to solve the problem,
- the relation of your investigation to any previous work.

Many students struggle to write an introduction to their reports. The more you read around the specific subject (or google and read) the more you will be able to put your experiment into some sort of scientific context.

These points add up to you answering the question 'Why did you do the experiment or what was its object?' You may assume that the reader of the main body of the report has a certain background knowledge of the subject, but it may be that someone starting the report does not have this knowledge. The introduction should serve as a possible starting point for them You may not wish to go back to the beginning of the subject, in which case you should give references - not too many - to published work which does provide the necessary background. The introduction plus this work should bring the reader to the point where they are ready to hear about your experiment.

The **final paragraph** of the introduction should start: 'Here we show . . . '. And then you concisely tell the reader exactly what your work did - a bit like a even smaller abstract but without the need for numerical results. With the aim and objectives laid out all though the beginning of the introduction, they'll then have a good sense of how the whole report/experiment fits together. (The only time it is really acceptable to use 'we'.)

12.2.4 Example of title, abstract and introduction

Your report should look nearly exactly like this example taken form a student report. This is a good report, but is a few years old so doesn't follow all the rules of this guide to reports. Nor has the student got everything right. Don't reverse engineer this report for its content, the peer-review sessions will allow you to see and reflect on past reports.

The LaTeX .tex files and figure files for this manuscript are on moodle.

Angular response of simple dipole and Yagi microwave antennae

Student Number: xxxxxxxxx

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Abstract. Microwave radiation was used to measure the angular response of a selection of antennae. Radiation used had a wavelength of 31.9±0.2mm in free space and was generated using a Gunn oscillator. The normalized angular responses of a simple $\lambda/2$ dipole and 2λ dipole antennae were graphed in polar coordinates and compared with the response determined from theory. The relative responses of the partial configurations of the Yagi antennae were graphed in polar coordinates on a decibel scale to highlight the antennaes directionality. Yagi has application as a television antenna and microwave antenna have application in astrophysics, notably in the discovery of cosmic microwave background radiation. Due to limitation of apparatus used and time the results presented are susceptible to large random errors.

Introduction

An elementary property of antennae is their receiving pattern exactly coincides with their transmitting radiation pattern. While this experimental work employs radiation of microwave frequency all mentioned theory is applicable to an antenna designed for other frequencies of electromagnetic radiation, such as radio. The decision to perform experimental work with radiation of the microwave region was primarily motivated by limited space available for equipment; the dimensions of an antenna designed to receive radio signal would have to be comparable to a wavelength of 1-10m. Moreover, microwave antennae are vital in themselves for their application in space exploration, most notably in the discovery of cosmic microwave background radiation.

The simple dipole antenna is the most commonly used class of antenna. It has wide application in radio and telecommunications on its own and also serves a vital role as the driven element in many other types of antenna [1]. Its structure comprises of two identical conductive elements [2] that serve as a resonator for standing waves. For a receiving antenna, the split in the center of the radiating element allows a feeder to take power from the antenna. The geometry of a basic dipole antenna is shown in Figure 1. The length of the radiating element determines vital features of a dipole antenna such as impedance and operating frequency. An ideal dipole antenna will have an angular response that is described by

$$P\left(\theta, \frac{h}{\lambda}\right) \propto \left[\frac{\cos\left(\frac{2\pi h}{\lambda}\cos\theta\right) - \cos\left(\frac{2\pi h}{\lambda}\right)}{\sin\theta}\right]^2 \tag{1}$$

where P is the power received by the antenna, A is a scalar with unit of Watts and θ, h and λ are as defined in the caption of Figure 1. From equation (1) it is clear that the angular response of a given dipole antenna is dependent on orientation angle and the ratio of the dipoles length to the wavelength of incident radiation. This equation assumes that the wires constituting the antenna are of an infinitesimal width and have an infinitely high conductance. Such assumptions are not attainable outside the realms of theory. Hence, the measured angular response of a dipole antenna will deviate from this ideal plot. Advantages of the basic dipole antenna are that it is straightforward to construct and use. However, an antenna of this type is, theoretically, equally responsive in the

Guide: Reports

12.2.5 Experimental

In this section comes the description of the **apparatus**. The amount of detail here varies considerably, and you must use your own judgement, but a few general principles may serve as a guide. If the apparatus you used is of a standard kind, it is probably sufficient to say what it was and give a reference so that anyone interested can find a full description. On the other hand, if it contains some novel features, they should be described in some detail. Although you may assume that the reader of this section has a certain familiarity with the background to the work, you should not go farther than this. You should certainly not aim the report directly at other experimentalists using the same or similar apparatus. So you should not use esoteric phrases understood only by such workers. Nor should you include minute experimental details of interest only to them.

- Include at least one diagram with a caption.

Analogy: Imagine you're reporting on a nice meal you cooked. Think of this section as laying out the items you used in the kitchen (mixer, oven etc.), all the ingredients used and possibly where you bought them from.

12.2.6 Results and specific discussion

This is the most important section. Here you demonstrate with evidence the narrative of the report as laid out briefly in the introduction paragraph 'Here we show'. The main problem is jumping to some final polished set of data too soon. You must lead the reader through from your experimental apparatus, to, say, Plank's constant. The main thought, brought to you by Peter Jackson of the Lord of the Rings film fame, to keep in your head is:

Show and tell.

Well ok, he said 'show don't tell', but I want you to do both as your producing a written document, not a feature film. The report is an exercise in convincing your reader that you have fund something new, and you have done it correctly.

However, in general it is neither possible nor desirable to give all the measurements. They would only confuse and distract the reader. They would have to spend time assessing their relative importance and extracting the essential results. That is your job before writing the report. You should, therefore, give only

- a representative sample of some of the basic measurements,
- the important results.

Note the word **representative**. The sample that you present in the report should give a faithful picture of the quality, precision, and reproducibility of the measurements. So if you have fifty sets of them, you do not reproduce the second best with the caption 'Typical set'.

12.2.6.1 Figure by figure: Part 1: Intro, results and discussion

The results section may be broken down into several sub-sections, each describing and reporting an experiment or aspect of an experiment. The first figure must be associated with the experimental section. So if you're measuring a voltage (but in the end work out something else) you must first show a graph of voltage. Or it may be the trace on an oscilloscope, show the trace and explain what it is with reference to your experimental apparatus and underlying physics.

Each figure, typically 3 or 4, will have associated text. That text will:

- Introduce the figure: 'Figure 1 shows'.
- Introduce the reason of the measurement. 'To measure the ... we first measure ...'. That bit may come before the 'Figure 1 shows' bit.
- Describe the important parts of the figure. 'The time-trace clearly demonstrates the initial ramp of the voltage, leading to the application of an electric-field and the response the the magnet. Location (i) is the initial start of the ramp, (ii) the end of the ramp, (iii) the equilibrium magnetic field taken for measurement and (iv) the ramp back to zero field.
- Then to get at whatever it was we wanted, we need to probe the voltage dependence.

So the next sub-results and discussion section could have a figure with 3 or 4 sub-plots, or 3 or 4 superimposed plots to demonstrate that with different voltage ramps to demonstrate different equilibrium magnetic fields. Explain what it means, how you understand it. Here you may now want to include a model and theory. And/or detail how you extract the equilibrium value with its uncertainty.

So the next subsection maybe trying to work out of your results match the theory. Here you can be cunning. If the theory-model says a dependence should go as, say, $P = Ar^2$, then a log plot with a straight-line fit will give you the exponent with uncertainty, and the offset will give you the pre-factor A with uncertainty. See section later on how to actually do all this in practice. This is a much stronger demonstration that the model works, than just fitting the model to the data. That may come later in the general discussion section.

12.2.6.2 Figure by figure: Part 2

To reiterate, for example

Exp 1 You may measure a trace on an oscilloscope, show the trace and explain what it is, from it you may extract, say the amplitude.

Exp 2 Then plot the amplitude as a function of voltage, from this you extract a slope.

Exp 3 You plot the slope dependence on temperature which was what you were interested in in the first place.

In this sequence the logical progression of results presented is obvious. With some of the undergraduate experiments the progression is not explicitly given. It is up to you to give (invent) a logical progression for your results.

- Logical progression do not necessarily flow the order you did the experiment, or the order in the experimental script.

After introducing the precise experimental measurement, then showing the results, it is best to have a specific discussion about those results, what they mean and what they may imply. Often this specific discussion can be used to explain the motivation for the subsequent experiment, thus plainly laying out your experimental logic. You must, of course, for any value reported include its associated uncertainty and a brief description of how you reached that view.

Analogy: You cook the roast first. So you describe that method here, then talk about how great it was, you tested it for this and that. What always accompanies roasts is vegetables. So on to the next 'experiment' cooking the veg. How you did it etc. etc., so by the end of this section you are in a position to discuss the whole meal overall.

12.2.7 General discussion

Here you may discuss the underlying physics of your experiment. What is in the end showed. This will make reference back to the motivation of the introduction and explain if and why you results mater. You may keep hold of your last graph for this section. Once that's done move onto to include

- comparison with other similar measurements, if there are any,
- comparison with relevant theories,
- brief discussion of limitations.

Very often (and for reasons I don't understand) students use this section to whinge about the equipment or some-such thing. Don't do that. If by way of a systematic or random uncertainty you can not go far enough to say something useful, then by all means outline clearly why this is, or at least why you think it's the case. But mostly use this general discussion section to discuss the physics you were investigating.

12.2.8 Conclusion

Discussion of the state of the problem under investigation in the light of your results. This is the conclusion, the counterpart to the object of the experiment, given in the introduction. It's a bit like a mini-abstract and mini-'here we show' paragraph.

12.2.9 References

At any point in the text where you refer to some fact or other you should put a reference so that a reader of your work can either check this fact, or find out more about it. At the undergraduate level we do not expect you to do too much external reading, but a bit would be good. Perhaps the lab script references some items, or one of the standard physics text books (Knight, Tipler etc.) can be used. Or Wikipedia can be used as a starting point. Very often their articles have good list of references at the foot. Wikipedia by its fluid nature is a poor reference itself. (Note the numbered reference used in this booklet are the correct style of number, but the references themselves are not the style you will use in your reports.)

- You cannot reference the lab manual as this document is not available outside of the University of Bath. Therefore a reader in, say, Bristol of your work would be unable to access it and hence it is a poor reference.

  $\Rightarrow$ You may therefore have to derive results yourself from a well known starting point.

⇒ This will be a lot of fun.

- References will be indicated in the text by a number in square brackets [1].
- Numbers will increase sequentially through the text, [1] first, then [2] and so on.
- These numbers will map to a similar numbered list of references in the reference section.
- For these lab reports there will only be three types of references and we will define the style here. This will be different to the IOP reference style and perhaps others for other reports you have to write. They should include in this order:

  ⇒ initials then family names of all authors

  ⇒ titles of journal articles

  ⇒ year of publication

  ⇒ title of journal, book or other publication

  ⇒ volume number

  ⇒ editor(s), if any for books

  ⇒ town of publication and publisher for books

  ⇒ page numbers or article number

- Book

  [1] G. L. Squires, 2001, Practical Physics, 4th Edition, Cambridge, Cambridge University Press.

  [2] S. Meyer, 2007, Twilight, London, Atom.

- Scientific Articles

  [3] K. R. Rusimova, N. Bannister, P. Harrison, D. Lock, S. Crampin, R. E. Palmer, P. A. Sloan, Initiating and imaging the coherent surface dynamics of charge carriers in real space, 2016, Nature Communications, Art. 12839.

  [4] J. D. Watson, F. H. C. Crick, Molecular Structure of Nucleic Acid, 1953, Nature, Vol. 191, p737.

- In this [WL] Experimental Physics lab, for web sites, the only permissible site is NIST, no other online reference will be allowed. The Academic Skills seminars etc. will guide you as to how to reference that site correctly.
- Very often you may find an article online, but you must reference its journal, number, volume, page etc., not its web link.
- The reference formatted at the end of this document are not in the style that you will use so do not use them as a template.

The precise formatting at this stage of your University life is not too important, a stray full stop or comma is not an issue. Just as long as there is a list of not less than three items and they fit the format outlines here. If you are struggling to find references, the general introduction to the report (however you pitch it) is often a good place to put some broad and general references and hence demonstrate that you can do referencing.

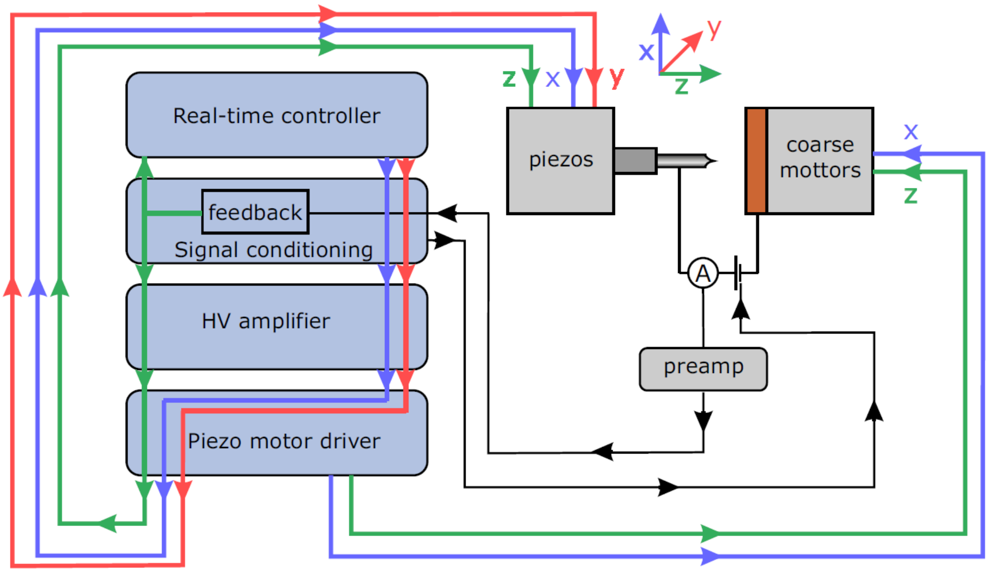

Figure 12.1: STM feedback circuit. At a set sample bias, the tunnelling current between the tip and the sample is amplified and converted to voltage using a pre-amplifier. It is then used to provide feedback for the STM tip height. Both the piezo motors and the coarse approach motors are driven with the piezo driver. Unlike your report report where you have to make the diagram and caption, I have taken the diagram and caption from ref. [5].

12.3 Diagrams, graphs, and tables

A diagram can be a great help in understanding the text. Unless the apparatus is completely standard, a diagram of it should nearly always be included. Graphs are a very convenient and common way of displaying the results. They should be kept simple; the same applies to diagrams. Tables can be used if reporting more than one or two values is deemed important, more so than showing their trend graphically.

- You **must include** at least one of each:
  - ⇒ Diagram
  - ⇒ Graph
  - ⇒ Table

12.3.1 Diagrams

A diagram should be an easily understood schematic of your apparatus indicating the important points. Sometimes it can be a scale diagram, sometime purely schematic. It should not be hand drawn, unless your drawing is remarkably precise and neat. I tend to use Microsoft PowerPoint (akin to Word) to construct my diagrams as you can use shapes and arrows etc. to make something professional looking. Some labelling on the diagram may be necessary. The caption should contain enough information to educate the reader as to what the diagram represents. See for example, figure 12.1

12.3.2 Graphs

The main way to present your data to the reader is through a graph. It shows the individual data points and quite possibly a trend and mathematical fit. Graphs should

- be clear and uncluttered.
- have well labelled axis
- have 'human' scale numbers for the axis, i.e., not 0.000001, rather put M (for mega if appropriate) and then renumber the axis as 1. See section 12.4.
- have no box surrounding it.
- have an axis border on the bottom, top, left and right.
- have inward pointing tick marks on the bottom, top, left and right.
- be understandable when printed in black-and-white
- not have a title
- not have lines connecting data points
- have an indication of the uncertainty as an error bar on the data points in both axis with an explanation in the caption. If they error bars are too small to show you must still mention that in the caption.
- if it has a fit make the fit line distinct
- have no fit parameters on the graph, put them in the caption and main text.

There are two templates you could use, either using Excel or python. Excel produces a terrible default graph, but if you work hard can produce a nice graph. Or use the programming language python. This is fairly easy and all you have to do is modify a template. It will produce high quality graphs.

- Excel: For more information see moodle for, a Panopto video of how to use Excel to produce a nice graph, and the Excel file that you could use as a template.
- Python: For more information see moodle for a Panopto video of how to use python to produce publication quality graph. This takes you through how to start python to producing a figure file. It really is quite good and I managed to learn how to use it all in about 2 hours. See fig. 12.2.
- Also see moodle for a pdf of the 'Graph' chapter from 'Practical Physics' by G. L. Squires.

12.3.3 Tables

See section 11.5 on page 51 for how to construct a nice table.

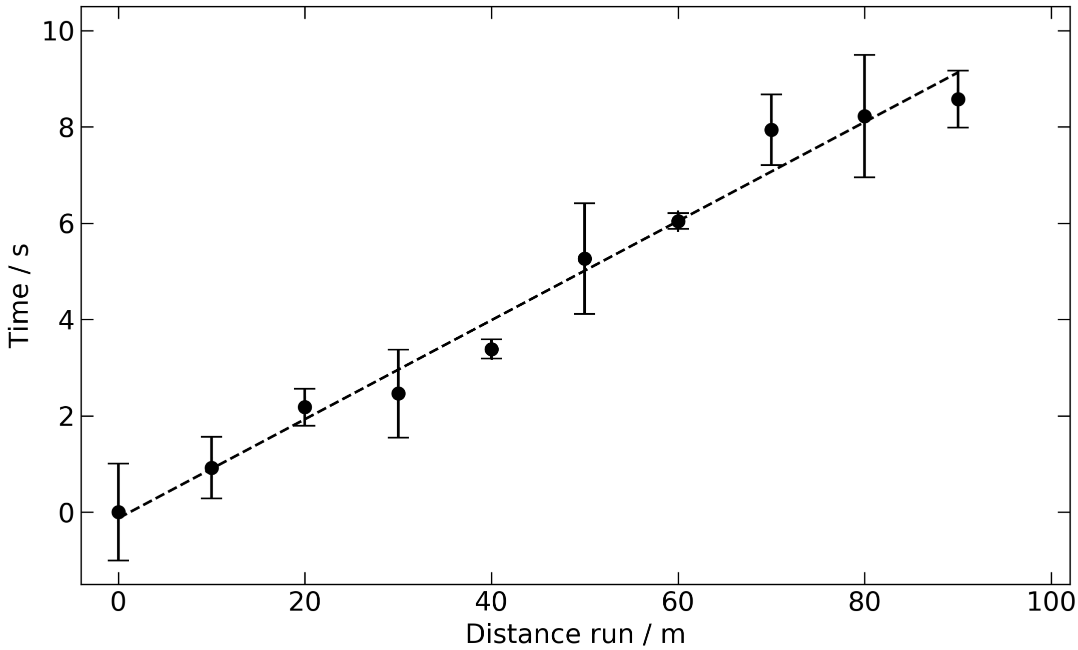

Figure 12.2: A plot produced by the python template showing measurement taken of Usain Bolt running a 100 m race (not really). Error bars are given by the precision of the measurements. Due to its small size, the uncertainty in the distance, 0.02 m, is omitted from the plot. A linear least square fit, dashed line, gives a slope of (0.103 ± 0.05) sm^{-1} and an intercept of (-0.1 ± 0.3) s.

12.3.4 Referencing graphs and tables

All items (be they tables, graphs, diagrams) must be referred to in the text in the order that they appear in the manuscript.

- Table, label as ‘Table 1’, ‘Table 2’ and so on.
- Graph, label as ‘Figure 1’, ‘Figure 2’ and so on.
- Diagram, label as ’Figure 3’, ‘Figure 4’. Graphs and diagrams share the same ‘counting’ integer.

12.4 Displaying values

There are three items to consider. (i) the uncertainty of your results, (ii) the SI prefix of your values and (iii) the formatting for presenting them.

12.4.1 The uncertainty on your result

- Display your uncertainty to 2 significant figures.

- Display your value rounded to the same digit as the second of your uncertainties significant figures (see examples below)

12.4.2 SI Prefixes

For any report of a value of a force, or distance etc., use the power of 10^3 SI Prefixes. Do not use powers of ten. See table 12.1 for the standard notion and below for examples. Pick a SI Prefix so that your value is at maximum 1000 and at minimum 1. See examples below.

Table 12.1: A range of SI prefixes that cover the main range of values used. FInd more online if you wish: https://www.npl.co.uk/si-units.

Multiplying Factor	SI Prefix	Power of 10	Multiplying Factor	SI Prefix	Power of 10
1 000 000 000 000	tera (T)	10^{12}	0.001	milli (m)	10^{-3}
1 000 000 000	giga (G)	10^{9}	0.000 001	micro (μ)	10^{-6}
1 000 000	mega (M)	10^{6}	0.000 000 001	nano (n)	10^{-9}
1 000	kilo (k)	10^{3}	0.000 000 000 001	pico (p)	10^{-12}

12.4.3 Formatting

Variables are italicised, whereas units are in normal text. This is true of tables, text and maths. For example

$$h = (2.56 \pm 0.16)\ \mathrm{km} \tag{12.1}$$

where h is the height in km of a really tall person with an uncertainty of one standard error of the mean based on 134 measurements. If the uncertainty is much lower than the reported value that quoting both becomes unwieldy, then use the alternative format of just reporting the uncertainty on the last two digits,

$$h = 2.56989(16)\ \mathrm{km} \tag{12.2}$$

which is the same as

$$h = (2.56989 \pm 0.00016)\ \mathrm{km} \tag{12.3}$$

but neater.

12.4.4 Examples

- 1.98765 m $\pm$ 0.012 m $\Rightarrow$ (1.988 ± 0.012) m
- 0.98765 m $\pm$ 0.012 m $\Rightarrow$ (988 ± 12) mm
- 98765.98 N $\pm$ 12.23 N $\Rightarrow$ (98.765 ± 0.012) kN $\Rightarrow$ $98.765(12)$ kN
- 0.0000789 K $\pm$ 0.0000100 K $\Rightarrow$ (79 ± 10) μK

12.5 Mathematics

Mathematics should be kept to a minimum. There is no need for arithmetic detail. It may be that you do want to report that 'according to Snell's law,

$$n_1 \sin \theta_1 = n_2 \sin \theta_2, \tag{12.4}$$

where n is the refractive index of a material and θ the angle as given by figure 1.' By this point it's probably easier to include a diagram rather than laboriously define in the text all the terms.

But in general for mathematics

- All equations must be numbered.
- They should be part of the text and hence punctuated by commas and fullstops.
- The equation number should be right justified.
- All symbols must be defined.
- If you wish to refer back to an equation you can 'see equation (1) for ...', but at its first use you don't have to ref it, it just appears in the text naturally.
- Equation formatting in Word is bad. However, you can trick it by using an invisible 3×1 table, with the equation in the middle box, and the equation number right-aligned in the right box. Or apparently you can define a centred tab and then a left-aligned tab and that may also work.

Maths example

differently to the injected charges. Mathematically therefore we can define the overall population time-dependence as

$$\frac{N(t)}{N_0} = \frac{N_0^A}{N_0} \exp\left(-\alpha_A \frac{It}{e}\right) + \frac{N_0^B}{N_0} \exp\left(-\alpha_B \frac{It}{e}\right), \tag{1}$$

where $N(t)$ is the total number of molecules that remain in their original position after an injection time t at a current I. N_0 is the total number of manipulated molecules from an initial population of N_0^A and N_0^B molecules ($N_0 = N_0^A + N_0^B$) with a probability of manipulation per electron given by α_A and α_B respectively and e is the charge of an electron.

12.6 Clarity

Clarity is an essential quality in scientific writing. We may distinguish two kinds.

12.6.1 Structural clarity

Writing may be said to have structural clarity when the reader can readily follow the outline of the argument - or see the wood despite the trees. Similar topics are grouped together, and the groups arranged in a logical order. You are strongly advised to construct a framework before writing the report. This is a skeleton outline in which all the ideas, arguments, experimental details and so on are represented by a word or phrase. When the items are in this form, the arrangement is seen much more clearly and, moreover, is easily changed if not satisfactory. The main sections of the scheme should correspond to the plan given in section 12.1.

12.6.2 Expositional clarity

The other type of clarity, which may be called expositional clarity, is making the reader understand exactly what you are trying to say at each stage in the discussion. Clear writing depends on clear thinking. You will not be able to produce a clear and logical report unless you do understand the physics. Just do the best you can and as you progress through the semesters you will get better and better.

12.7 Good English

We come to the final link in the chain between you and the reader - the words themselves. Good English in scientific writing is not just a matter of correct grammar - though that is not unimportant - it is choosing words and composing sentences to say exactly what you mean as concisely and pleasantly as possible. We make a few miscellaneous points here.

- On the whole, short sentences make for clarity, but variety is necessary to avoid monotony. You can be clear in long sentences, but it takes more skill.
- Paragraphs can help the reader to follow the argument. Start a new paragraph when you are starting a fresh point, or when you start discussing a point from a different angle. But do not use single-sentence paragraphs or too many short paragraphs. Some people are prone to use txt spk pargs.
- Avoid verbiage, roundabout ways of saying things, and redundant adverbs. Thus the second version should be preferred to the first in the following examples:
  - ⇒ Calculations were carried out on the basis of a comparatively rough approximation.
    - ∗ Approximate calculations were made.
  - ⇒ Similar considerations may be applied in the case of copper with a view to testing to what extent the theory is capable of providing a correct estimate of the elastic properties of this metal.
    - ∗ The elastic properties of copper may be calculated in the same way as a further test of the theory.
- Avoid qualifying a noun with a long string of adjectives - most of which are not adjectives anyhow. For example The time-of-flight inelastic thermal neutron scattering apparatus ...should be replaced by The time-of-flight apparatus for the inelastic scattering of thermal neutrons ...
- The unattached participle is a common fault in scientific writing. Sentences like 'Inserting equation (3), the expression becomes ... ' or 'Using a multimeter, the voltage was found to be ... ' occur frequently, so much so that you may not even realize what is wrong with them. Perhaps the following example taken from Fowler (1965) will show. A firm wrote to a customer 'Dear Sir, Being desirous of clearing our books, will you please send a cheque to settle your account. Yours etc.' They received the following reply: 'Sirs, you have been misinformed. I have no desire to clear your books.'

12.7.1 I, we, you - no

This next section sets quite strict rules, that even I break when I'm writing my lab-reports. However, it is best to begin with these rules and then relax them in future years where, for example, the use of 'we' can be quite powerful when used sparingly and in particular circumstances. But first you should learn to produce a standard, albeit dry, lab report.

The #1 writing no-no is to never use 1st or 2nd person. Why? In academic writing, it's important to avoid personal bias. Using 'I' or 'we' makes the report about you and your experiences, instead of research and concrete details.

Before I give examples, let's review the 1st person. 1st person uses I or We, as in 'I am upset' and 'We ran away'. Also stay away from using me, us, my, mine or ours.

Let's also take a quick look at 2nd person. Second person uses you and your. When you use 2nd person point of view, you are directly addressing the reader, kind of like I am doing right now. While this is okay when writing a personal letter, it is not okay in formal writing, especially essays or research papers. Avoid using this pronoun at all costs because you never want to communicate directly with the reader.

Instead of 'I cannot believe how much tuition has increased', try, 'Tuition has drastically increased'. Instead of 'Don't text while you drive', try, 'Don't text and drive'. Students are so used to using I, my, we, you and your, that they have a hard time weeding them out of their papers. So, here is my tip of the day: Every writing program, like Microsoft Word, has a search function. Do a simple word search for each of the ones listed here

- I
- Me
- My
- Mine
- Our
- Ours
- Us
- We
- You
- Your
- Yours

Once you see them, shift your point of view.

Extract from ref [6].

12.8 Report writing using LaTeXdocument template

All scientific journals now only allow reports to be submitted electronically. You will usually find instructions about this at the beginning of each issue. In addition, journals usually produce a pamphlet giving instructions to authors so that their reports may conform to the general style of the journal.

Here we will use a slightly modified LaTeXdocument template taken from the Americal Physical Society and specicially the 'gold standard' physics journal Physical Review Letter (known as PRL). You will find this template on moodle. You will also find on moodle an example of a real research article that used this template so you can get an idea of what a report should look like. I do not expect your reports to be quite so polished, but using this template will allow you to focus more on the content and less on the formatting. Also, I do not expect you to understand every word of the example report, but you should be able to read and determine what, for this example, each section is trying to do and how it sets about it.

Here and on moodle you will also find instruction on how to use the 'mark-up' language LaTeX. All my papers are written with LaTeX as are my lecture notes and this pamphlet. If you just want to use LaTeX to generate nice equations go to:
http://www.codecogs.com/latex/eqneditor.php.

12.8.1 LaTeX

LaTeX is mark-up language, which essentially is a bit like a computer language. In amongst the text you write you have to put in commands to get a certain output, so you can't just make something bold face by selecting and clicking the 'Bold' button, instead you just type in your text, for example, . . . '`here is some \textbf{bold} text`' produces 'here is some **bold** text'.

The key is once you tell LaTeX to use a template, see moodle, you can just fill in the title and student number and the program LaTeX will do all the had work of choosing a font, positioning the title correctly etc. and I hope produce a nice readable document. After learning a few tricks for equations etc., you can focus on your writing and content and not on the mechanics of producing a pretty document. This booklet is make using LaTeX as are all my lecture notes and all my lab-reports.

LaTeX is free and you can use online (see moodle as well) at: https://www.overleaf.com/. And, oh yes, in the Python environment you'll be using, called 'Jupyter notebooks' you can intersperse your Python code with block of text and you can write in LaTeX so produce equation etc. in the code!

12.8.2 Word

Okay let's talk about Microsoft Word. It is really very good at producing simple quick documents. It is a steaming pile of shite when trying to get it to produce nice complex documents - you'll be putting in equations, tables, figures, references. It can be done, Prof Wadsworth in Physics is a bit a guru. I on the other hand can't even get it to have a consistent fucking font size. I get angry just thinking about it.

Up to 2018/2019 we did have Word templates to use to write reports. But Word has updated and my files now produce a steaming pile of shite when viewed and printed.

The main issue is Word is, or at least pretends to be, a WYSIWYG - What You See Is What You Get. This a very hard to do nicely as Word is always second guessing you and in fact has lots of relatively hidden rules and regulations. Hence figures will move, or text change font seemingly at random just because you've added a word, or even worse tried a cut 'n' paste. Use Word if you wish, just as long as your final pdf file looks exactly like my template.

Section 13

Guide to: experimental statistics and uncertainties

Science is about making measurements, and nearly as important as your measurement is how much you believe your measurement. Any measurement 'result' is a combination of a value and its uncertainty.

For example, in 2018 there are two competing groups of thought on the exact value of the rate of expansion of the Universe, the Hubble constant. One side measures a high value, and the other measures a low value. They measured it using completely independent experiments. So what? They disagree beyond their uncertainties! So, either:

- one or both of the measurements are wrong,
- one or both of the uncertainties are wrong,
- or they are both right in their own ways, and it's our present understanding of physics that is wrong.

This last outcome is by far the most exciting, but seeing as we don't know the 'real' value of the Hubble constant, it is up to painstaking experiment (and a bit of theory) to really show that we are confident in our results, before we can declare some new physics.

This is how science advances, by showing the present physics is wrong, or at least incomplete. This is hard. But this is essentially the main job of all the lecturers in the Department. So you had better be sure of your measurements and their uncertainties before you announce that the current physics is false.

Here we have slightly less lofty goals. We aim to teach you how to work out how much you should trust your experimental results.

13.1 The two main types of uncertainty: random and systematic

There are two main types of uncertainty, random and systematic. Fig. 13.1 shows how systematic and random uncertainties affect a result's accuracy and precision in different ways.

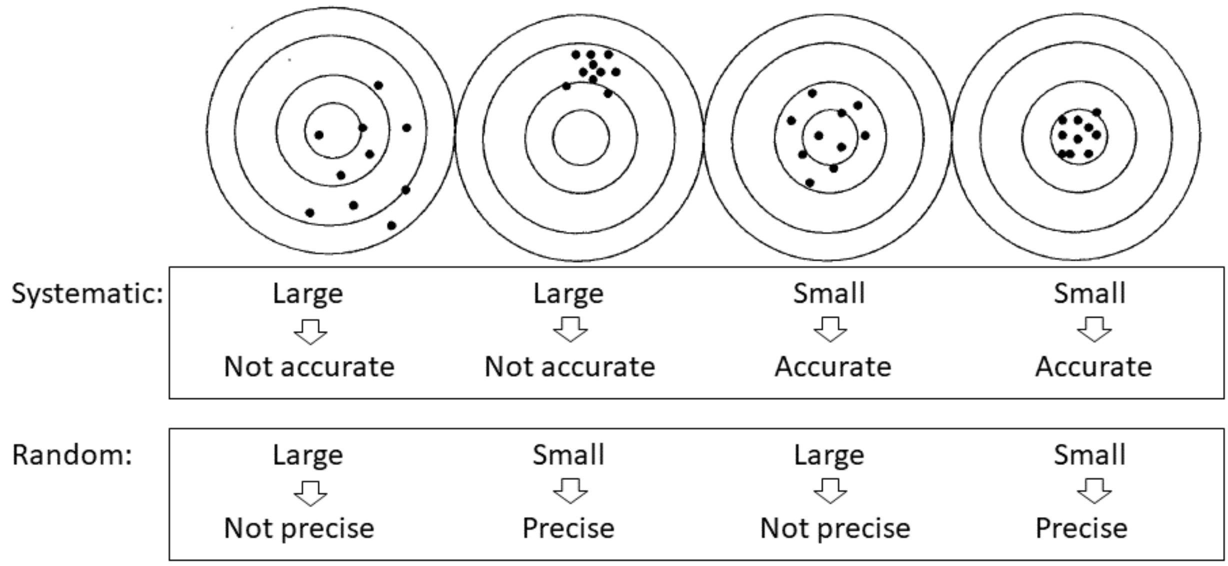

Figure 13.1: The effect of systematic and random uncertainties on the precision and accurancy of measurements. Assume the 'true' value lies at the centre of the bull's eye target. Adapted from ref [7].

13.1.1 Human blunders

A final source of error, called a blunder, is an outright mistake. A person may record a wrong value, misread a scale, forget a digit when reading a scale or recording a measurement, or make a similar blunder. These blunders should stick out like sore thumbs if we make multiple measurements or if one person checks the work of another. Blunders should not be included in the analysis of data.

Extract from ref [8].

But you have to be sure that an odd result really is a blunder and not just some new unexpected physics. So if a result is odd, repeat, repeat and do a lot of thinking and checking before you can, with scientific justification, remove it from your analysis and report.

13.1.2 Example experiment

You wish to find the diameter a cylinder. You use a special type of measuring device called Vernier callipers to measure the diameter and length of the cylinder.

If your measurement is precise enough then every time you measure the diameter at a particular position you may get a slightly different result. It could be that the force that holds the callipers is slightly different each time, or the callipers are not square onto the cylinder, or you grip the cylinder with different part of the calliper jaw, or a myriad of other possibilities. These experimental limitations will lead to **random** uncertainties in the measured value.

To 'zero' the callipers you shut the jaws and make a recording from the scale. It could be that the calliper jaws are not smooth or parallel, so this 'zero' is where two particular locations on

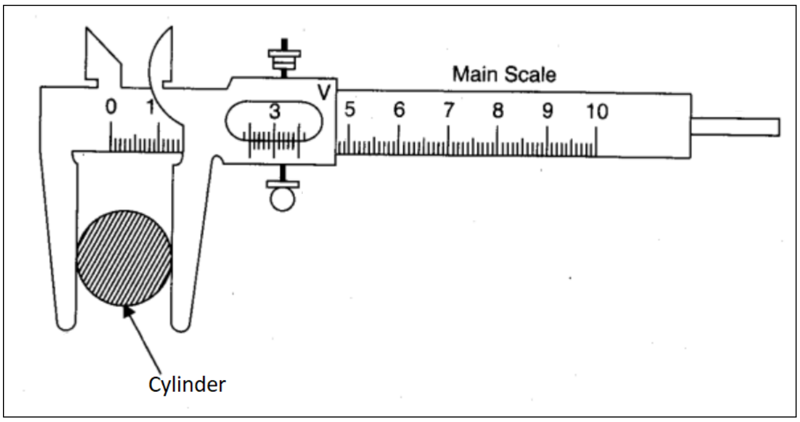

Figure 13.2: Diagram of Vernier callipers measuring the diameter of cylinder (end on view). See section 14 on page 93 for how to read a Vernier scale. Image reproduced from ref [9].

the jaws touch. But when measuring the cylinder, the cylinder touches different locations. Hence any measurement will have a built in shift, or **systematic** uncertainty.

13.1.3 Random uncertainty

- **Random:** The fact that one gets different results each time an experiment is repeated.
- **Precision:** A measurement is **precise** if these random uncertainties are small enough that you measure nearly the same result in repeat experiments.
- Random uncertainties could arise from, for example, fluctuation in the temperature of the laboratory, or cosmic rays, or shot-noise, or some other physical process that you have not captured in the analysis of your experiment. Very often the true source is unknowable and uncontrollable.
- **Mitigation:** Taking many readings will identify the best value to take for the representative average measurement.
- The quoted result of an experiment must include an estimate of the random uncertainty (more later).
- The random uncertainty is often just referred to as the statistical uncertainty.

13.1.4 Systematic uncertainty

- **Systematic:** A shift in the absolute measured value, compared to the true value.
- **Accuracy:** A measurement is considered **accurate** if it produces only a small shift from the true value.
- Related to the measuring device/apparatus/procedure itself.
- Measurements with systematic shift will **not** lie around the true value.

- Systematic uncertainties will **not** average out over many readings. The random uncertainties will average out but your mean value will not converge on the true value because of the overall systematic shift.
- **Mitigation:** To reduce systematic uncertainties, we calibrate measuring instruments so that they agree with a standard reference. Many instruments come with calibration certificates from the manufacturers. We can also regularly test this calibration by measuring known test standards.
- **Mitigation**: Another type of systematic uncertainty comes from using an inappropriate instrument. A micrometer would for example always measure the largest diameter between its jaws. If there are small bumps or depressions on the surface measured, the average of a large number of measurements will not give the true average diameter but a larger quantity. Thus, we must consider if an instrument can correctly measure the value we wish to evaluate.

13.1.5 Health warnings

- Simple repetition of the measurements will neither reveal nor reduce a systematic uncertainty. For this reason, systematic uncertainties are potentially more dangerous than random uncertainties.
- If large random uncertainties are present in an experiment, they will manifest themselves in a large value of the final estimated uncertainty. See section 13.2.5.

There is no general rule for finding and eliminating systematic uncertainties. It is a matter of thinking about the particular method of doing an experiment and drawing on past experience. One of the aims of the laboratory work is to train you to be on the lookout for any systematic uncertainties and to demonstrate ways of eliminating them. For particularly important and difficult experiments, such as the most accurate determinations of time and distance, or the search for the Higgs boson, different teams working independently and using different methods will, all being well, have different systematic uncertainties which will then allow an estimation of the presence or absence of systematic uncertainties.

13.1.6 When an uncertainty is (incorrectly) called an error

In this booklet I have been careful to use the term ‘uncertainty’ to describe the trust you have in a measured value. This is to focus your mind that that uncertainty is inherent to your experiment and procedure. However, a lot of people incorrectly call the **same** things ‘errors’. (In my mind an error is a blunder - see section 13.1.1 on page 72.) So if you read books or on the internet, you will find much information about ‘error analysis’. For your first encounter with uncertainties it is best to stick with ‘uncertainty’ as to call them ‘errors’ sounds like you made a blunder, that is **not** what we are analysing here. Hence the use of ‘uncertainty’ throughout.

But annoyingly, to depict a value and its uncertainty on a graph you plot the data point and its ‘error bar’. Figure 13.3 shows a typical example of a nice graphical representation of 50 data points and their associated uncertainty. These graphical depictions of the uncertainty are called error bars both in Python (the program you’ll use to plot graphs) and Excel (can plot graphs but not as easy) so there is no way to call them ‘uncertainty bars’ here. It’s arbitrary I know but that’s just the way it is.

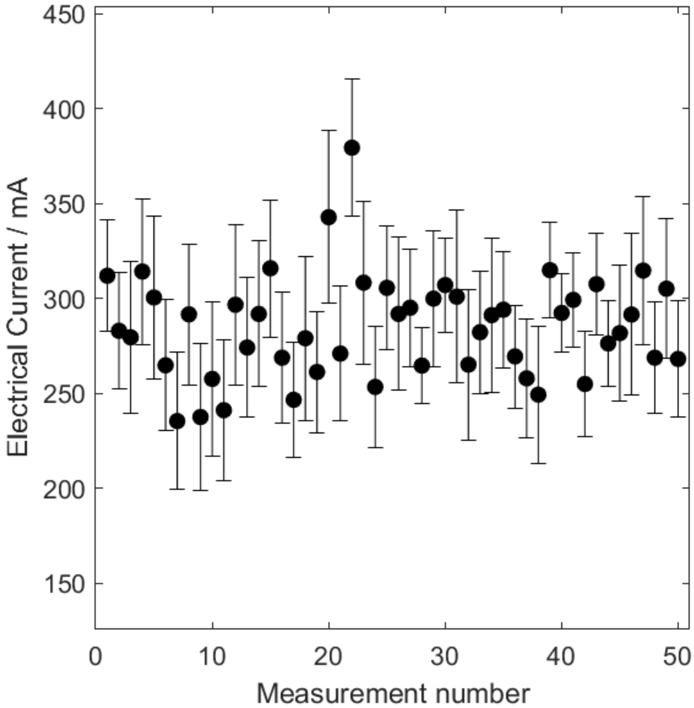

Figure 13.3: An example graph depicting individual data points and their individual uncertainties. Each data point has its standard deviation depicted by the 'error bar' range. In this example the mean value of the current was (285.1 ± 3.9) mA with that uncertainty the standard error on the mean of the 50 measurements.

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13.2 Mathematical approach to uncertainty analysis

We must remember that as we are doing an experiment, the 'true value' is not something which we know, and is usually something which it is impossible to know. All we can do is make more and better measurements. In the statistical analysis that follows we need to imagine that there is a 'true value' but you will see that at the end you can derive the precision of a measurement from your measured results themselves.

13.2.1 Ideal theoretical case: probability distributions

Suppose that we were able to repeat a measurement of a quantity x a very large number of times N. We call this hypothetical collection of measurements a **probability distribution** $p(x)$, see Fig. 13.4. The mean value of the distribution $\langle x \rangle$ (the angle brackets indicate to take the mean value of x) gives the best estimate of the true value X of the quantity being measured which, for a near infinite set of individual measurements (representing the 'ideal' case) is,

$$\langle x \rangle = \frac{x_1 + x_2 + x_3 + \ldots + x_N}{N}. \tag{13.1}$$

Assuming that there is no systematic uncertainty, for a very large number of measurements

$$\langle x \rangle \approx X. \tag{13.2}$$

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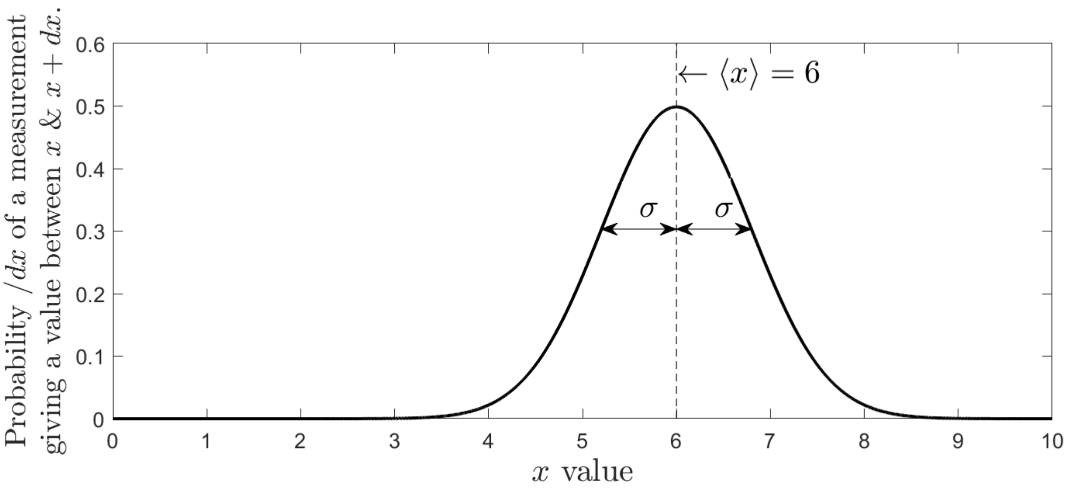

Figure 13.4: The shape of a 'Normal' distribution, i.e., one that has only random uncertainties, here with standard deviation σ around a mean value, here $\langle x \rangle = 6$.

The width of the distribution (loosely defined for the moment) gives the value of the random uncertainty. The uncertainty e_i is how far from the true value the i^{th} measurement was, and is given by

$$e_i = x_i - X. \tag{13.3}$$

If there is no systematic uncertainty then $\langle e \rangle = 0$ since the same number are bigger than X than smaller than X. Therefore $\langle e \rangle$ does not give any information about the width of the distribution.

For you, the most important average is the root-mean-square value of e, denoted by σ. This can be calculated from the probability distribution $p(x)$, the function present in figure. 13.4, by,

$$\sigma = \sqrt{\int (x - \langle x \rangle)^2 \, p(x) \; dx} \tag{13.4}$$

where the integral runs over all possible values of x and we can write in a similar way,

$$\langle x \rangle = \int x \; p(x) \; dx. \tag{13.5}$$

Sigma, σ, is known as the **standard deviation**.

13.2.2 What does the standard deviation mean?

The standard deviation σ tells us about the spread of the values in the distribution. We can express this more quantitatively by asking: what fraction of the measurements lie within a certain range centred on the true value X? The values in Table 13.1 are worth remembering - strictly, they apply when the data follow a Normal (or Gaussian) probability distribution but they are good enough for almost all experimental applications.

If you measure a current, say, 20 times and get a mean of 8.0 A and a standard deviation $\sigma = 0.1$ A, then for one measurement there is a 67 % chance that it will lie between 7.9 and 8.1 A.

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Range	Approximate % chance of a measurement lying **inside** of the range	Or **outside** of the range
$X \pm \sigma$	67	33
$X \pm 2\sigma$	95	5
$X \pm 3\sigma$	99.75	0.25
$X \pm 4\sigma$	$\approx$ 100	0.00625

Table 13.1: Standard deviations and what they mean

- σ: Strict definition: Only two thirds of the measurements will lie within the mean and one standard deviation of the mean, $\langle x\rangle - \sigma$ to $\langle x\rangle + \sigma$.
- σ: Slightly incorrect definition: Any new point taken has a $\approx \frac{2}{3}$ chance of falling within the range $\langle x\rangle - \sigma$ to $\langle x\rangle + \sigma$. (Note, once you have that new point you must recalculate σ.)
- σ: Tells us something inherent about our individual measurements. Make it small by having a better experiment.
- σ: Does not change when you perform more experiments: σ is inherent to your experimental apparatus.
- Note: If you increase the number of measurements you will end up with a more precise mean and the uncertainty associated with that mean will get smaller with more measurements - see section 13.2.5.

In essence, this analysis assume you have made a near infinite number of measurement in order to construct a probability distribution as in Fig. 13.4. You will mostly have a set of data less than that. How then to determine σ?

13.2.3 A real life set of measurements: what you'll do

The maths above assumes you know X and σ for your experiment, in advance! But when doing an experiment you do not know X or σ (this is the point of science). Moreover, usually the number of readings you take is not very large, say five or ten, which is somewhat less than the infinity assumed in Fig. 13.4. Therefore the discussion above needs modification to reflect your actual experimental work.

The basic idea is that your set of n measurements is to be regarded as a random sample taken from the possible distribution of measurements. If you want more details and background on uncertainty analysis, see for example ref [3].

Suppose we measure the same quantity n times and obtain the values x_1, x_2,... x_n. If there is no systematic uncertainty in the measurements then the best estimate for X is the sample mean

$$\langle x\rangle = \frac{1}{n}(x_1 + x_2 + \ldots x_n). \tag{13.6}$$

Now we now need to obtain an estimate for σ based on that same set of n measurements.

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13.2.4 Usual mathematical method for estimation of σ

Most scientific calculators have a statistical function (which does the maths outlined below) which will provide a value for σ if you type in values of the individual measurements. It is important to remember that if the sample is small (say ten measurements or fewer) then, however it is produced, your estimate of σ will not be very good simply because it is based on insufficient data. Hence a quick estimate of σ is just as valid as a painstaking calculation, and whatever method you use it gives an **estimate** of the uncertainty, which means that it is only worth **at most two** significant figures.

The residual of a reading, say the i^{th}, shows how far from the mean is it, is defined by

$$d_i = x_i - \langle x \rangle. \tag{13.7}$$

Unlike the 'true' uncertainty e_i, which is unknown because the 'true' value X is unknown, the residual d_i is a known quantity. There are many ways to link the measured d_i values to σ, you are encouraged to delve a little deeper into this in your own time. But for the purposes of this guide it is sufficient to know how to compute an estimate of σ from your readings.

$$\sigma \approx \frac{1}{\sqrt{n-1}}\sqrt{(d_1^2 + d_2^2 + \ldots d_n^2)}. \tag{13.8}$$

The $\approx$ sign indicates that equation (13.8) provides only a good estimate for the value of σ rather than a definition.

Advice: If you only have one data point, $n = 1$, then the uncertainty this way is undefined, and you may want to propagate your instrumentation uncertainty, see section 13.6. Or for one set of experimental parameters, measure your values a few times to allow a calculation of σ, then use that value for all other readings taken with the same procedure and apparatus, but different experimental parameters. This therefore assumes that the underlying probability distribution is the same for all sets of experimental parameters, but it often is the best you can do given time constrains.

13.2.5 The standard error of the mean: the most important uncertainty number

The standard deviation σ is related to how good any **one** measurement is. It will not change if more measurements are taken (except for fluctuations when the sample number n is very small). However, the accuracy of the mean, $\langle x \rangle$, as a representation of the true value, X, gets better with more measurement. So we need an uncertainty associated with the mean value that **does** take into account the number n of experiments. We call this new term the **standard error of the mean** s_{mean}. It is calculated simply by

- $s_{\text{mean}} = \frac{\sigma}{\sqrt{n}}$.
- s_{mean}: standard error of the mean: Uncertainty associated with the mean of a set of measurements.
- s_{mean}: The true value has a $\approx \frac{2}{3}$ chance of falling within the range $\langle x \rangle - s_{\text{mean}}$ to $\langle x \rangle + s_{\text{mean}}$.

- s_{mean}: Tells us something inherent about our whole set of measurements.
- Make s_{mean} smaller by having a better experiment to reduce σ.
- Make s_{mean} smaller by taking more measurements to increase n. But note, doubling the number of experiments only reduces s_{mean} by a factor $\sqrt{2}$. So it takes longer and longer to get a better and better s_{mean}. Law of diminishing returns - nature is elusive.

Most experimentalists try to reduce the inherent uncertainty σ first (more later) before just applying brute force to increase n as much as they can before running out of time or money.

In many of your experiments in physics you will be looking for a particular value which will be the mean of several repeat experiments. The most important thing is usually how well you know the mean, s_{mean}. There is, however, always a potential for confusion in writing and reading reports as to which measure of uncertainty has been reported. It is helpful to state in your text whether you are quoting the standard deviation or the standard error of the mean of the measurements. If you also state n then your readers can convert from one to the other if they wish.

- When quoting your s_{mean} values, please do so to at most 2 significant figures.

13.3 What if the individual measurements have different uncertainties?

The analysis just presented assumes each data point, e.g., x_1 has the same uncertainty associated with it as all the others. What if each one has its own individual uncertainty and they are a bit different? Then we make use of a weighted mean. Say there is a set of n results of a quantity x with a different uncertainty σ for each measurement: $x_1 \pm \sigma_1, x_2 \pm \sigma_2, \ldots, x_n \pm \sigma_n$. Then we can define the weight of each data point w_i as

$$w_i = \frac{1}{\sigma_i^2}. \tag{13.9}$$

The smaller the uncertainty σ the more precise you know the data point and more weight it has in the statistical analysis. The weighted mean is given by,

$$x_{\mathrm{best}} = \frac{\sum\limits_{i=1}^{i=n} w_i x_i}{\sum\limits_{i=1}^{i=n} w_i} \tag{13.10}$$

and the standard error on the weighted-mean itself is

$$s_{\mathrm{best}} = \frac{1}{\sqrt{\sum\limits_{i=1}^{i=n} w_i}} \tag{13.11}$$

So you can then present your values as $x_{\mathrm{best}} \pm s_{\mathrm{best}}$.

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13.4 Data that looks bad

If the difference between two measurement, say x_i and x_j, is much greater than both the uncertainties σ_i and σ_j then those two measurements are **inconsistent**. This applies for both data that has the same uncertainties and for those that have different uncertainties for each data point. For a set of results, one result may be inconsistent with the rest. That result can then be examined for a possible systematic error, or algebraic error, or writing down error. Then you may work out why it's so odd and fix it - see blunders in section 13.1.1 on page 72. However, if there is no justifiable reason for excluding it you must include it in your analysis.

It's not up to you to second guess nature - what do you know past your own guesses and biases what's really going on? how are you going to discover unexpected phenomenon if you casually disregard things that don't agree with your assumptions?

Having said that, you could, for example, run an analysis both with and without the errant point and then make a comment on this in your discussion. Perhaps in your graphs you can give the point a different marker to highlight it is there, but perhaps not included in your straight-line fit.

13.5 Presenting your results: value and uncertainty

The significant figures in a number are the meaningful digits that indicate its precision. Never quote a result to more figures than you can justify in terms of the uncertainty of your measurements. See section 12.4 for details.

13.6 Propagating an uncertainty

What if you only have one measurement so can't calculate σ from your results? Or if your values for σ and s_{mean} look odd? Well, then you can compute what σ may be, based on your understanding of your experimental apparatus. For example, if a volt meter is accurate to 1 V, how would that uncertainty effect the final result of, say, using that voltage to work out a resistance? What you have to do is propagate the uncertainty through the mathematical relationship that links your measured value with the final outcome.

Uncertainty propagation also allows the wary experimentalist to identify the major sources of uncertainty in their experiments. Does it matter how accurately you measure the voltage, if the uncertainty on the current is large?

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13.6.1 One variable and one uncertainty

Very often your measured quantity, say $\langle x \rangle \pm \Delta x$ is not the final outcome of the experiment. Remember that the angled brackets $\langle x \rangle$ indicate the mean measured value of x. So your value of $\langle x \rangle$ has to be manipulated by some equation, say $f(x)$, to produce a new result y. Thus

$$y = f(x). \tag{13.12}$$

How does a small change in x, say Δx, at the point $x = \langle x \rangle$ affect y? Any function $f(x)$ can be expanded about a point, here the point of interest is $x = \langle x \rangle$, using the Taylor Expansion

$$f(\langle x \rangle + \Delta x) = f(\langle x \rangle) + \left.\frac{\mathrm{d}y}{\mathrm{d}x}\right|_{\langle x \rangle} \times \Delta x + \frac{1}{2}\left.\frac{\mathrm{d}^2 x}{\mathrm{d}y^2}\right|_{\langle x \rangle} \times (\Delta x)^2 + \ldots \tag{13.13}$$

$$\tag{13.14}$$

What is this? For the expression

$$\left.\frac{\mathrm{d}y}{\mathrm{d}x}\right|_{\langle x \rangle}, \tag{13.15}$$

first take the function $y = f(x)$ and differentiate it as normal with respect to x. Then calculate the value of that differential, which is just a gradient, at the position we're interested in $\langle x \rangle$. Now we make the **assumption** that Δx is small and so terms with $(\Delta x)^2$ (small $\times$ small $=$ tiny) or higher can be ignored. Hence,

$$\Delta y = f(\langle x \rangle + \Delta x) - f(\langle x \rangle) \tag{13.16}$$

$$\approx f(\langle x \rangle) + \left.\frac{\mathrm{d}y}{\mathrm{d}x}\right|_{\langle x \rangle} \times \Delta x - f(\langle x \rangle) \tag{13.17}$$

$$\Delta y \approx \left.\frac{\mathrm{d}y}{\mathrm{d}x}\right|_{\langle x \rangle} \times \Delta x \tag{13.18}$$

This is just the slope of $f(x)$ evaluated at the position $\langle x \rangle$ times the 'step length' Δx. Some maths examples,

$$y = ax + c \qquad \Rightarrow \qquad \Delta y = a\Delta x. \tag{13.19}$$

Here it would be wise to try to minimise the value of a, and it makes no difference what the value of $\langle x \rangle$ is. Next,

$$y = \frac{a}{x} \qquad \Rightarrow \qquad \Delta y = -\frac{a}{\langle x \rangle^2}\Delta x. \tag{13.20}$$

Here a large value of $\langle x \rangle$ would be called for to minimise Δy and the minus sign can be ignored. Next,

$$y = a\sin(bx) \qquad \Rightarrow \qquad \Delta y = ab\cos(b\langle x \rangle)\Delta x. \tag{13.21}$$

Here remember to use **radians**. A small a and b would be wise, or take data at a value of $\langle x \rangle$ whereby $\cos(b\langle x \rangle) = 0$ or close to it (see next section). Next let's try a natural logarithm,

$$y = \log_e\left(\frac{x}{x_0}\right) \qquad \Rightarrow \qquad \Delta y = \frac{1}{\langle x \rangle}\Delta x. \tag{13.22}$$

For a base 10 logarithm,

$$y = \log_{10}\left(\frac{x}{x_0}\right) \qquad \Rightarrow \qquad \Delta y = \frac{1}{\langle x \rangle \log_e(10)}\Delta x. \tag{13.23}$$

For an exponential function

$$y = ae^{bx} \qquad \Rightarrow \qquad \Delta y = abe^{bx}\Delta x. \tag{13.24}$$

And finally for a power of 10,

$$y = a10^{bx} \qquad \Rightarrow \qquad \Delta y = ab\log_e(10)10^{bx}\Delta x. \tag{13.25}$$

Sometimes you can do these things, sometime these constant values are fixed by nature or your experimental apparatus.

13.6.2 Straight line fit equivalence

This Taylor expansion analysis is the equivalent of fitting a straight line to $f(x)$ at your value of $\langle x\rangle$ and then mapping how your $\langle x\rangle$ and Δx values translate to y and Δy values. Figure 13.5 shows a simple sinusoidal wave with two possible $\langle x\rangle$ values but with the same Δx value. The upper graph maps to a much larger value of Δy than the lower graph example. This is just a graphical representation of the mathematics in section 13.6.1 above.

13.6.3 Combining more than one variable and uncertainty

What if multiple different measurements are involved in getting to a final result? Say you need a voltage, a temperature and a height. You may know how these things combine to give you, say, the speed of light. But how do you propagate the individual uncertainties of the voltage etc. to give you an uncertainty of the speed?

The general approach is Pythagoras in many dimensions, which is just adding the squares of individual uncertainties. Let's have a function z of several experimental measurements x and y

$$z = f(x, y) \tag{13.26}$$

then for $\langle x\rangle$ and its associated Δx and $\langle y\rangle$ and its associated Δy

$$\Delta z = \sqrt{\left(\left.\frac{\partial z}{\partial x}\right|_{\langle x\rangle} \times \Delta x\right)^2 + \left(\left.\frac{\partial z}{\partial y}\right|_{\langle y\rangle} \times \Delta y\right)^2} \tag{13.27}$$

What is

$$\left.\frac{\partial z}{\partial x}\right|_{\langle x\rangle}? \tag{13.28}$$

First take the function $z = f(x, y)$ and differentiate it with respect to x treating y as a **constant**. To show this we use 'curly' ∂ instead of a straight d. This is known as partial differentiation. Then we calculate the value of the gradient at the position we're interested in $\langle x\rangle$. Essentially this is the same as the single variable case above, except we have to bear in mind that we're keeping the other variable constant. Then we do the same again but differentiate with respect to y keeping x constant. For example

$$z = x + y \quad \Rightarrow \quad \Delta z = \sqrt{(\Delta x)^2 + (\Delta y)^2} \tag{13.29}$$

$$z = x \times y \quad \Rightarrow \quad \Delta z = \sqrt{(\langle y\rangle \Delta x)^2 + (\langle x\rangle \Delta y)^2} \tag{13.30}$$

$$z = \frac{x}{y} \quad \Rightarrow \quad \Delta z = \sqrt{\left(\frac{1}{\langle y\rangle}\Delta x\right)^2 + \left(\frac{\langle x\rangle}{\langle y\rangle^2}\Delta y\right)^2} \tag{13.31}$$

13.7 General rules for uncertainty analysis

- Concentrate on identifying and reducing the dominant uncertainties. The largest uncertainties will dominate the final uncertainty. During an experiment, identify where the largest uncertainty comes from and try to minimise it. Make sure you identify it in your lab book and report. You can use uncertainty propagation to guide you.

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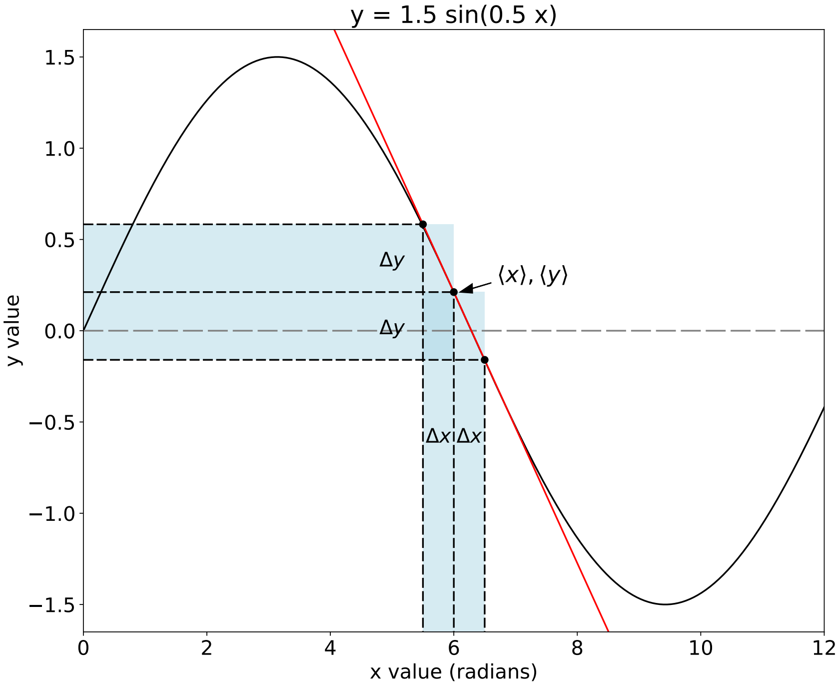
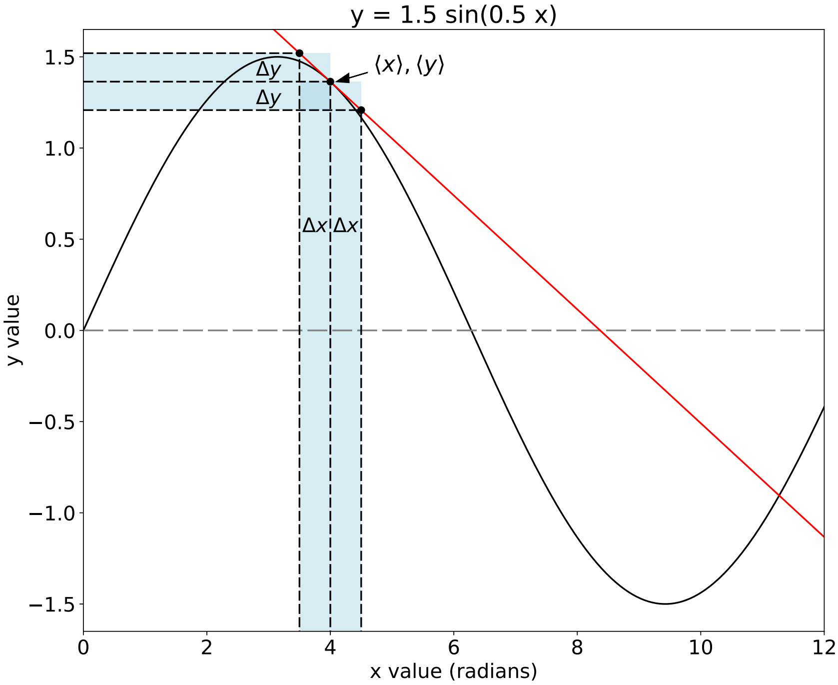


(a) Δx produces a bigger uncertainty in y.



(b) Δx produces a smaller uncertainty in y

Figure 13.5: Examples of mapping an uncertainty in x through to an uncertainty in y.

- Take care when differences and powers are involved, as small differences can result in large uncertainties overall.
- Do not worry about uncertainties on the uncertainties. Remember the discussion of significant figures; only quote any uncertainty to 2 significant figures.

13.8 Uncertainty estimates from equipment

In order to understand and propagate the uncertainty on your final result, you will need to know the uncertainty on each individual measurement that you have made. Think carefully about this, the answer is rarely that the uncertainty is 'half the smallest division on the instrument'. Ideally you would make several repeats of each individual measurement and then work out the uncertainty as the standard deviation of that data.

You may not have to repeat all of your data points. There is often good reason to think that the uncertainty on each point will be similar (they are all measured on the same instrument) and so you only need to check one data point. For example, at a particular voltage, measure the current many times to get a standard deviation of the current reading. Then you may be able to use that uncertainty on all subsequent measures of the current for any set voltage as you'd be using the same experimental apparatus and procedures, but do check how it propagates. Therefore for the point you measured many time you can report its s_{mean} while for the others you'd have to use σ, as they only have one measurement point. So then a weighted fitting would be in order to reflect your greater knowledge of that one particular data point.

Since the uncertainty is to at most 2 significant figures, you also may be able to make a good guess of the uncertainty. For example you may be looking at a voltage reading and it is fluctuating over time. By watching it you will be able to guess the mid-point and the amount of fluctuation. When writing any data value in your log book, always include the associated uncertainty, and the reasons you believe that is the uncertainty.

13.8.1 Stats or propagation?

If you have a large enough sample set n of x values, then you can calculate a set of the actual thing you're after, y. From that you can directly use the statistical maths to determine σ and s_{mean} for y without all the bother of uncertainty propagation from x. However, while the measurements of x should naturally capture all the variation on your measurement, it is often interesting to take all the possible uncertainties you can think of and propagate them through to the final answer y and see if the two match. If not, why not? Perhaps there is some extra source of uncertainty? or you're underestimating an uncertainty, or overestimating?

To repeat (as it's important), the propagated uncertainty should **match** the uncertainty derived from many measurements. If they are inconsistent then it may be some other source of uncertainty has gone unnoticed, or that your physical model is missing something. But it can give you another clue as to how your preconceptions match (or don't match) with the reality of your measurement of nature.

An advanced comment Moreover, analysing your experiment in this way you can determine if your experiment will be able to measure to the precision you require. You can then even estimate how many experimental measurements n you'd need to take to get s_{mean} to an acceptable level.

You may find you just don't have the time! So back to redesigning your experiment to get σ lower. Welcome to the world of experimental physics. If you get to PhD level you will begin to worry about these things.

13.9 Uncertainty estimates on and from graphs

13.9.1 What to plot: part I

Measurements are usually made by varying one quantity x, the independent variable, and measuring another y, the dependent variable. For each value of x you will have some set of measurements, perhaps very many, perhaps one. If you measured many times you'll have an associated s_{mean} value, otherwise, for the others you'd have to use σ as they only have one measurement point.

The reason for measuring a range of values is usually so you can demonstrate some physics connection or mathematical relationship between the independent and dependent variables.

Whenever possible choose a form of these quantities so that you can plot a straight line: $y = a + bx$. For this booklet we're going to use this algebraic form of a line, rather than the traditional $y = mx + c$ as I get confused with mass m and the speed of light c.

13.9.2 What to plot: part II

Sometimes you will have a mathematical dependence between the independent and dependent variable which is non-linear. But you still want to fit the data. The easiest option is to rearrange the equation into a linear form. Say you have controlled the velocity v of a particle with unknown mass m and measured its kinetic energy E. You want to find the mass m. Well,

$$E = \frac{1}{2}mv^2 \tag{13.32}$$

which is not linear in v. Therefore, you could plot your independent parameter (the one you set) as v^2 (not just v) on the x-axis and the dependent (measured) quantity on the y-axis. A straight line fit will have a slope of $\frac{1}{2}m$, hence you can determine the mass and the uncertainty on the mass using all your data points AND show that the relationship $E = \frac{1}{2}mv^2$ works (or perhaps doesn't work).

Health warning You must get all your units, e.g., $\mathrm{m\,s^2}$, $\mathrm{km\,s^2}$, $\mathrm{mm\,fs^2}$ etc. correct. Get your data and uncertainties into nice manageable units with nice SI Prefixes (see section 12.4.2 on page 66) but then remember them when working out the gradient etc. Quite easy to do but just keep an eye on it as it is also very easy to make simple algebraic blunders.

13.9.3 What not to do

Do not rearrange to get,

$$\frac{2E}{v^2} = m \tag{13.33}$$

than calculate m for each of your v and E measurements and then take a mean of all the resulting m's. Doing that will not demonstrate that $E = \frac{1}{2}mv^2$ was the right connection between E and v in the first place. Remember you must 'show and tell'! If you just show m then you'd miss out a critically important point, that you have shown that $E = \frac{1}{2}mv^2$ does in fact describe your system. As a good scientist, only once you shown an equation really fits your results well, can you begin to extract numbers from it.

Moreover, say there was a systematic uncertainty in the measurement of E, say E_{Offset}, then we could write $E_{\text{measured}} = E_{\text{true}} + E_{\text{Offset}}$ hence

$$E_{\text{measured}} = E_{\text{true}} + E_{\text{Offset}} \tag{13.34}$$

$$E_{\text{measured}} = \frac{1}{2}mv^2 + E_{\text{Offset}} \tag{13.35}$$

A straight line fit would reveal the correct linear dependence with a slope of $\frac{1}{2}m$ and an unphysical intercept that was due to the systematic uncertainty. If you simply rearranged you'd get,

$$\frac{2E_{\text{measured}}}{v^2} \neq m. \tag{13.36}$$

Instead the underlying dependency would give

$$\frac{2E_{\text{measured}}}{v^2} = m + \frac{2E_{\text{Offset}}}{v^2} \tag{13.37}$$

which is no good at all, and worse, you wouldn't even know that E_{Offset} was there at all.

13.9.4 What to plot: part III: making use of lovely logs

Nature often connects independent and dependent variables by power laws, in the example above it was $E = \frac{1}{2}mv^2$, or for example, the rate of a reaction R can be dependent on the electrical current I in the form $R = b \times I^a$. If you control I and measure R how do you get at the power a? First it is obvious this is not linear in a. How can we show from our data that $E = \frac{1}{2}mv^2$ fits? or extract the exponent a? $\log$s, and lots of $\log$s.

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13.9.4.1 log: natural e or base 10?

Although you can use any base to take a logarithm, the two most common bases are the natural base e and the base 10. Usually the natural logarithm is written as $\ln$ but it can also be written as $\log_e$. The base 10 logarithm is sometimes just written as $\log$, here we will explicitly write $\log_{10}$. Moreover, if you do happen to use log-paper to plot a graph that is inherently base 10. So to ensure consistency here all the logarithms are given as base 10 - although it does make the maths a bit messy. You can ponder what difference a different base may make.

13.9.4.2 Taking a log

Careful now, the mathematical operator $\log$ (any base) only works on positive **numbers**. So let's say you have a set of kinetic energy measurements with the smallest value of 1.2 J. So divide each measurement by 1 J. Let's give the value 1 J the symbol E_0 (table 13.2 gives a few more examples). So we have

Table 13.2: Examples of divisors for generating nice log-able values.

minimum energy value E	E_0	E/E_0
1.2 J	1.0 J	1.2
0.24 J	0.1 J	2.4
17 kJ	10 kJ	1.7
-89 nJ	-10 nJ	8.9
-53 MJ	-10 MJ	5.4

$$E = \frac{1}{2}mv^2 \tag{13.38}$$
$$\frac{E}{E_0} = \frac{1}{2}\frac{m}{E_0}v^2 \tag{13.39}$$

take $\log$s of both sides.

$$\log_{10}\left(\frac{E}{E_0}\right) = \log_{10}\left(\frac{1}{2}\frac{m}{E_0}v^2\right) \tag{13.40}$$

This is nice as now the left-hand-side term starts at near 0 and goes positive. If we'd chosen 1000 J then it would return a negative number and be nasty to plot. What about the right-hand-side? Say the minimum speed was 8.9 ms^{-1} then we say that a new constant $v_0 = 1$ ms^{-1}. And by the noting the relationship

$$E_0 = \frac{1}{2}m_0 v_0^2 \tag{13.41}$$
$$\therefore m_0 = \frac{2E_0}{v_0^2} \tag{13.42}$$

you can work out m_0. So,

$$\log_{10}\left(\frac{E}{E_0}\right) = \log_{10}\left(\frac{m}{m_0}\left[\frac{v}{v_0}\right]^2\right) \tag{13.43}$$

so each part of the right-hand-side is dimensionless and we can now separate to get

$$\log_{10}\left(\frac{E}{E_0}\right) = \log_{10}\left(\frac{m}{m_0}\right) + \log_{10}\left(\left[\frac{v}{v_0}\right]^2\right) \tag{13.44}$$
$$\underbrace{\log_{10}\left(\frac{E}{E_0}\right)}_{y} = \underbrace{\log_{10}\left(\frac{m}{m_0}\right)}_{a} + \underbrace{2}_{b}\underbrace{\log_{10}\left(\frac{v}{v_0}\right)}_{x} \tag{13.45}$$
$$\tag{13.46}$$

So for all your experimental pairs of E and v use your nice values for E_0 and v_0 to compute $y = \log_{10}(E/E_0)$ and $x = \log_{10}(v/v_0)$. Then plot them as 'y' and 'x' respectively on normal graph paper and fit a straight line to them to give you the exponent for your data (here it should be nearly 2) and its uncertainty! The intercept will give you the $\log_{10}(m/m_0)$ term. Work out what m_0 is from your chosen E_0 and v_0 values and so you'll also get, here, the mass and its uncertainty.

Now given we're taking $\log_{10}$ you need to be careful to propagate your uncertainties on E and v through to the plotted x and y values. Using the procedure of section 13.6.1 on page 80 we get,

$$\Delta y = \frac{1}{E\log_e(10)}\Delta E \tag{13.47}$$

$$\Delta x = \frac{1}{v\log_e(10)}\Delta v \tag{13.48}$$

which means that even if all the E measurement have the same uncertinty ΔE, each value of y will have a different Δy. Fitting a straight line, $y = a + bx$, will then give you b (the power law exponent) and its uncertainty Δb. The intercept a gives you

$$a = \log_{10}\left(\frac{m}{m_0}\right) \tag{13.49}$$

$$\therefore m = m_0 10^a \tag{13.50}$$

following the procedure in section 13.6.1 for propagating uncertainties

$$\Delta m = m_0 a \log_e(10)10^a\Delta a \tag{13.51}$$

Hence you will have shown that

$$E = (m \pm \Delta m)v^{b\pm\Delta b} \tag{13.52}$$

And you can then check whether the mass and exponent fits within its uncertainty with the model. That is much better than just fitting a quadratic.

13.9.4.3 log-paper graph

A graph on log-paper changes space to reflect the $\log_{10}$ operator, but since you never actually perform a $\log_{10}$ operation you don't need all the work above to get your data into dimensionless form. So just plot the values of E and v on log graphing paper and that paper will transform your power law into a straight line. From that you can see if it really is a straight line, in which case you have a power law. This is a nice quick way to check your measurements as they come in by hand-drawing such a graph. However, for a full analysis it's just more difficult to extract the exponent etc. from such a log-paper graph.

13.9.5 Plots and error bars

Figure 13.6 shows a plot where every data point has a vertical line through it with end caps. This is the 'error bar' of the data point. It is just the graphical representation of the uncertainty of the data point. In this case each point has a different uncertainty associated with it, hence the spread in the heights of the error bars. The error in the distance measurement is too small to plot and has been omitted.

In the example of section 13.9.2 above you would end up plotting v^2 and not just v. You would, naturally, have an uncertainty associated with each value of v, and then you'd have to propagate to work out the uncertainty for v^2. Lets say $y = v^2$ then $\Delta y = 2v\Delta v$.

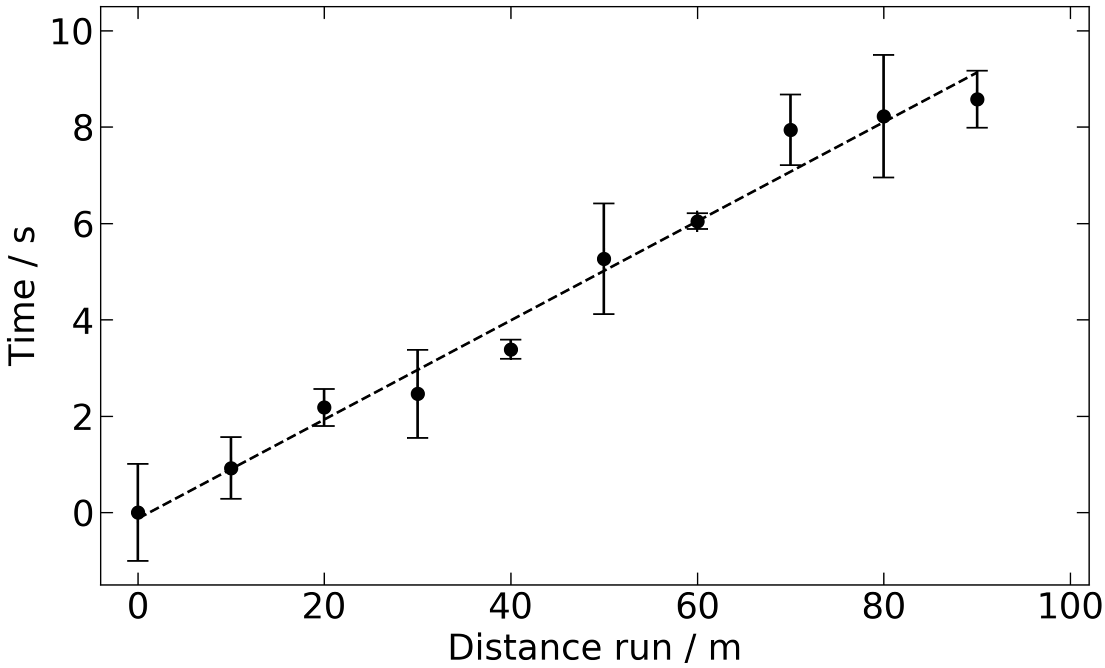


Figure 13.6: An example of a plot with error bars. Taken from the Python example on moodle.

13.9.6 What you expect to see

In practice, the points cannot lie exactly on a straight line. If you have random uncertainties following a normal distribution then only 67 % of your data points should fall within their uncertainty on the line. In other words, as long as you have say more than about 5 data points plotted with their associated error bars, then the spread of the data points about an ideal straight line should be about the same as the size of your error bars. If you have less then 5 data points and associated uncertainties then the spread of the data points will not fully capture the uncertainty of the overall experiment.

13.9.7 What to get from the plot

Once plotted you need to determine the 'line of best fit'. That will give you a numerical number for the slope, an uncertainty on that slope, the intercept and an uncertainty on that intercept. There is a proper statistical method known as the 'method of least-squares' for determining the best straight line and the uncertainty in its slope and intercept.

13.9.8 Straight line fits: paper and ruler

A good estimate can also be made directly from a graph by eye using a transparent ruler. While this is not as accurate as the method of least squares, it gives you a better feeling of what is happening. The method is called the **parallelogram of uncertainty**. To construct the parallelogram of uncertainty (Figure 13.7.):

- Plot a graph of your data, with error bars, and plot by eye a line of best fit.

- Next consider the graph carefully,
- If the number of data points > 5 do **data** method
- if the number of data points $=< 5$ do **data and error bar** method.

13.9.9 Data method

- Draw two lines *parallel* to your line of best fit, these lines should enclose approximately 68% of data points.
- Now draw two vertical lines, one touching your first and one touching last data points. You have constructed a parallelogram.
- Next draw on lines between the opposite corners of your parallelogram. Find the gradient of these two lines to find your maximum (b_{max}) and minimum gradient (b_{min}).

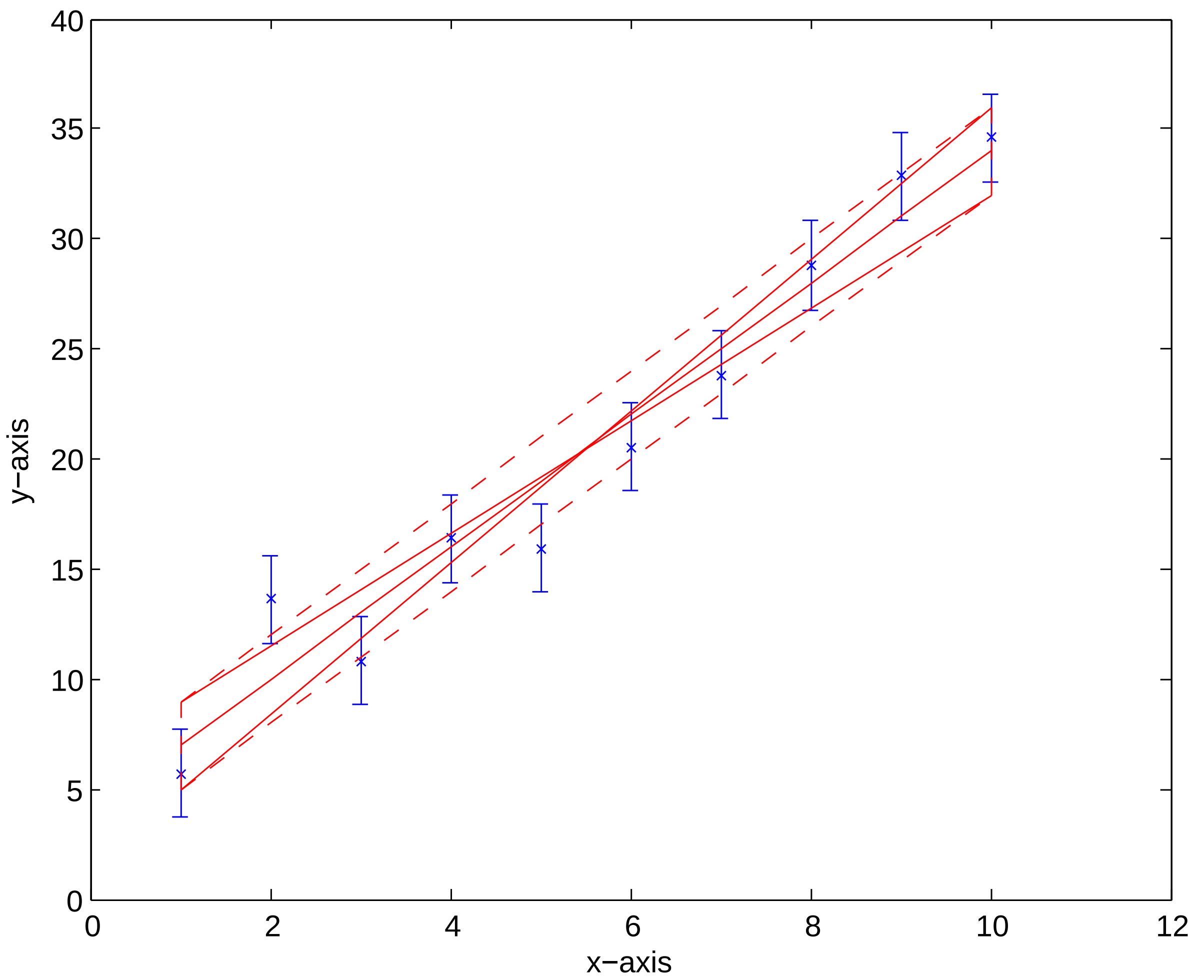


Figure 13.7: Construction of an uncertainty parallelogram, including the maximum and minimum gradients.

- The standard error on the gradient (S) can be found as

$$S = \frac{b_{\text{max}} - b_{\text{min}}}{2\sqrt{N-2}} \tag{13.53}$$

13.9.10 Data and error bar method

- Draw two lines *parallel* to your line of best fit, these lines should enclose approximately 68% of data points **including their error bars**.
- Now draw two vertical lines, one touching your first and one touching last data points. You have constructed a parallelogram.
- Next draw on lines between the opposite corners of your parallelogram. Find the gradient of these two lines to find your maximum (b_{max}) and minimum gradient (b_{min}).
- The standard error on the gradient (S) can be found as

$$S = \frac{b_{\text{max}} - b_{\text{min}}}{2\sqrt{N}} \tag{13.54}$$

Whatever method you use for calculating the best straight line, you should always plot the points on a graph and draw the calculated straight line to see if it looks to be a reasonable fit. In estimating the uncertainty in a gradient or intercept, remember the convention that the standard error is quoted: thus, there is a 1 in 3 chance that the correct value is outside the range $b \pm S$. The advantage of estimates using graphs compared to a point measurement is that all the data is used and systematic uncertainties can often be minimised or at least spotted.

13.10 Statistical analysis using computers: Python and Excel

To understand your results you'll need to know how confident you are in your measured or derived output - we'll use statistics for that. Both on a set of results measuring the same thing multiple times, and for when there is a linear dependence between to parts of your experiment, so controllably change one 'x' and measure the response of the other 'y', then fit a straight line.

There are many more exciting and subtle ways of doing all this, here we just want to introduce you to the key statistical methods we normally use and how to do them in practice. See the guide to statistic in section 13 on page 71 for all you need to know.

In semester 1 year 1 we'll run a few Tuesday afternoon session to show the maths of the stats and how to use the computer programming language Python to get a computer to do all the calculations for you. Python is freely available for you all to download and use on any computer. All the University computers have access to Python. It is a widely used language and will, I hope, be useful outside this experimental physics course. However, we're only just going to introduce Python enough so you can do the statistical analysis we wish, it'll be up to you to play about (and google) if you wish to know more and do more. There are a variety of examples on moodle for all the analysis you need, just download and fiddle about.

The ubiquitous spreadsheet program Microsoft Excel can do some statistical analysis, but generally badly and in a non-transparent way. It can however, be useful for capturing data by directly typing into an Excel spreadsheet. But then I use Python to read that data directly from the Excel file and do the actual statistical analysis and graph plotting. Horses for courses.

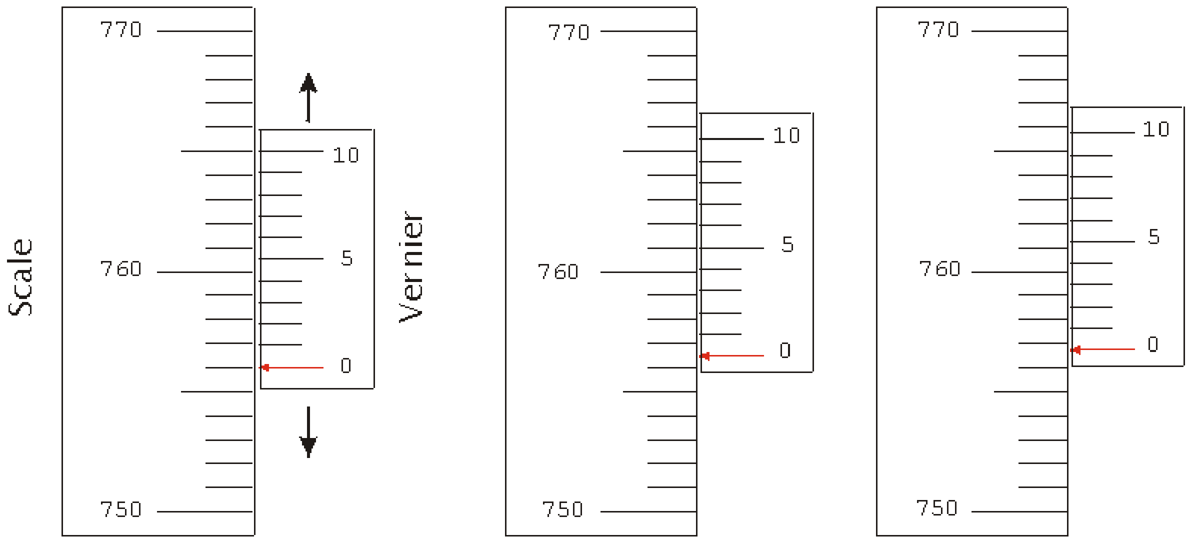
13.10.1 Straight line fits: Python

See templates on moodle. The template will gently introduce the Python programming language, including how to import and input data, manipulate it, plot graphs and fit straight lines. Just amend it or use it for inspiration for your own fitting.

- There is an example for fitting a straight line to data.
- There is an example for fitting a straight line to data with weightings given by the uncertainty of each data point.

Section 14

Guide to: Vernier scales



(a) Vernier 1 (b) Vernier 2 (c) Vernier 3

Figure 14.1: How to read a vernier scale

A Vernier allows a precise reading of some value. In the figure Vernier 1, the Vernier moves up and down to measure a position on the scale. This could be part of a barometer reading atmospheric pressure. The ‘pointer’ is the line on the Vernier labelled ‘0’. Thus the measured position is almost exactly 756 in whatever units the scale is calibrated in.

If you look closely you will see that the distance between the divisions on the Vernier are not the same as the divisions on the scale. The 0 line on the Vernier lines up at 756 on the scale, but the 10 line on the Vernier lines up at 765 on the scale. Thus the distance between the divisions on the Vernier are 90% of the distance between the divisions on the scale.

If we do another reading with the Vernier at a different position, the pointer, the line marked 0, may not line up exactly with one of the lines on the scale. In Vernier 2, the ‘pointer’ lines up at approximately 756.5 on the scale. If you look you will see that only one line on the Vernier lines up exactly with one of the lines on the scale, the 5 line. This means that our first guess was correct: the reading is 756.5.

In vernier 3 the Vernier is at yet another position. The pointer points to a value that is obviously greater than 756.5 and also less than 757.0. Looking for divisions on the Vernier that

Guide: Vernier scales

match a division on the scale, the 7 line matches fairly closely. So the reading is about 756.7. In fact, the 7 line on the Vernier appears to be a little bit above the corresponding line on the scale. The 8 line on the Vernier is clearly somewhat below the corresponding line of the scale. So, with sharp eyes, one might report this reading as 756.73 ± 0.02. This 'reading uncertainty' of ± 0.02 is probably the correct uncertainty to specify for all measurements done with this particular Vernier apparatus.

Section 15

Acknowledgements

This guide to labs has evolved organically from an original undergraduate lab-manual. It has been mostly re-written and updated by Dr Peter Sloan and with much input from Dr Paul Snow, Dr Julian Stirling, Dr Victoria Scowcroft, and insightful comments from Prof Philip Salmon, Dr Gary Mathlin, Prof William Wadsworth, Dr Zoe Bushell, Dr Jenny Williams, Isabel Wells and Prof Tim Birks. Any errors or inaccuracies should be reported to Dr Sloan.

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