THE UNIVERSITY OF SYDNEY

SCHOOL OF PHYSICS
Semester 2, 2017

EXPERIMENTAL PHYSICS

PHYS 1902
PHYSICS 1 (ADVANCED)

LABORATORY MANUAL

Name	:
Team	:

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INTRODUCTION TO THE PHYSICS LABORATORY

1 General Information

1.1 Reasons for experimental work

Physics is a science which tries to explain how and why things happen in the world around us. It is the most fundamental of the sciences; it deals with matter and energy and their interactions, at scales ranging from subatomic particles to the most distant galaxies. Like all sciences, physics is based on experiment. Anyone may propose a theory about what will happen in some situation, but the vital test is whether experiment shows that it really does happen.

Starting from an observation or a series of observations, perhaps of some aspect of the natural world that had not been studied before, we try to determine a set of rules describing what is happening; these are often called empirical laws. The next step is to relate these rules to other branches of physics to develop a theory. The theory is then used to predict what would happen in some particular circumstances and these are set up and the predictions, sometimes referred to as hypotheses, tested in an experiment. Sometimes two or more theories might be proposed, in which case experiments are used to decide which of the theories provides a better explanation. The rules and theories are then modified, taking into account the results of these observations. A new set of experiments are proposed and so on. As a result, scientific knowledge is extended into new areas. The foundation of all theories is experiment and/or observation.

1.2 Specific Objectives of the First Year Physics Experimental Course

Testing of theories is not the only purpose of experimental physics, and indeed it will not appear as the main focus of your experimental physics work. After finishing this course you should have met the following objectives:

- Gain experience in using equipment, including measuring instruments

- Learn how to conduct an experiment which tests a hypothesis or measures the value of a physical quantity.

- **Investigate for yourself** (this is crucial!) how certain systems behave **rather than have a lecturer or textbook tell you.**

- Learn to record, analyse and graph your experimental results, make sensible estimates of their uncertainties, and derive a meaningful conclusion from them.

- Gain experience in written and oral communication of experimental procedures and findings.

- Work effectively in a team whose members may not be of your choosing.

1.3 Overview of the Experimental Physics Course

1.3.1 Lab Experiments and Exercises

The first part of the experimental work for PHYS 1902 consists of five practical sessions in which you will cover several aspects of electrical circuits. ***Your experience with electrical circuits is deliberately concentrated in practical exercises in the lab, rather than a more theoretical presentation in lectures.***

You will be doing these lab exercises at the same time as the Electricity and Magnetism lectures, but it is likely that you will encounter topics not yet covered in lectures.

Therefore it is ESSENTIAL that you read the relevant sections of this Lab Manual and your textbook BEFORE each laboratory session

The notes in this manual will cover sufficient theory to enable you to understand and interpret the experiments, but your textbook will give you more background. If you come across something you don't understand, ask your tutor!

Don't forget that we have ***duty tutors*** *for you to get with any aspect of first year physics (laboratories, lectures or workshops). For details see your Unit of Study Outline.* ***Their purpose is to help you*** *with anything you don't understand. Please make use of them!*

We want you to understand how the circuits work. This could be achieved at home by reading the textbook, but it is best done in the lab. The main point of doing these experiments in the lab is that we also want you to learn how to connect circuits, how to measure voltages and currents in a circuit, and how to interpret the results. We want you to gain experience in connecting simple circuits, and to gain confidence that they behave as you would expect. Almost all experiments in physics, and in most other sciences, involve connecting circuits or electrical instruments of some sort.

1.3.2 Mid-Semester exam

After the last circuits session there will be a mid-semester exam conducted in the lab. The exam includes questions about circuits as well as questions about your lecture course content. See your Unit of Study Outline for more details and the lab timetable at the back cover of this manual for the date on which this test will be held.

1.3.3 Projects

In parallel with this work, **you will be preparing for projects in the second half of the semester.** In the first Lab session we will form you into project groups of six students (usually by joining two lab teams together). Each project group will need to decide on a research topic and submit a project proposal outlining what you will do and what equipment you will need. In the second half of the semester you will have three weeks to carry out the experimental work for your project. You will give an oral presentation on your project in the fourth project week and write a report about the project to be submitted online through your eLearning account.

1.4 Organisation

1.4.1 Attendance

The experimental work for PHYS 1902 consists of five practical sessions and four project sessions, which are designed to allow you to achieve the objectives stated above, in addition to reinforcing some of the material in the lectures. The timetable for the laboratory course can be found on the back cover of this manual.

- The laboratory sessions start at 10:00 am and 2:00 pm each day. Please be punctual. If you arrive late, you could disrupt work already in progress and may also miss important announcements.
- Most lab sessions require pre-work (worth one checkpoint, a quarter of the total laboratory session mark) to be done on eLearning/Blackboard.
- The laboratory sessions end at 12:50 pm and 4:50 pm each day.

You have been scheduled into one, three-hour practical session per week. Within your session you are grouped into teams of three (or sometimes two). You must stay with the team to which you have been assigned unless you have permission from your Lab supervisor or from the Lab Director, Joe Khachan (Physics, Rm 219B, joe.khachan@sydney.edu.au).

1.4.2 Missed classes

If the cause is **an illness or some other serious event,** such as an accident, you should notify the **Faculty of SCIENCE Student Information Office** (level 2 of the Carslaw building) within 7 days after the period for which consideration is sought, by completing an ***Application for Special Consideration*** with accompanying documentation. This is especially important if you miss an examination.

If you have another reason for the Science Faculty to take account of your circumstances such as religious commitments, legal commitments (e.g. Jury duty), elite sporting or cultural commitments (representing the University, state or country), or Australian Defence Force commitments (e.g. Army Reserve) - you should notify the **Faculty of SCIENCE Student Information Office** (level 2 of the Carslaw building) at least 7 days BEFORE the period for which consideration is sought, by completing an ***Application for Special Arrangements*** with accompanying documentation.

These two forms of Consideration should cover most allowable circumstances. However, if you have another reason for requiring the School of Physics to take account of your circumstances, you should notify the School of Physics Student Office (Physics Room 210, 9351 3037, physics.studentservices@sydney.edu.au) or the First Year Lab coordinator Joe Khachan (9351 2713, joe.khachan@sydney.edu.au) immediately.

Longer term health or emotional issues are better dealt with via the University's Disabilities Services unit rather than through the Special Consideration process.

See your unit outline for more information.

1.4.3 Supervisors and tutors

Each laboratory class has a supervisor who usually is an academic staff member or an experienced graduate student. A typical class will also have two or three laboratory tutors who may be graduate or undergraduate students. Find out the names of your tutors and the class supervisor. They should introduce themselves and be wearing name tags.

Tutors are there to assist you with your experimental work and will provide you with formal and informal assessments of your work so that you will know how well you are progressing. Please ask a tutor for feedback when you need it. Don't be backward in coming forward!

1.4.4 Working in teams

In the laboratories you work in teams of three. Each member of the team is expected to contribute to all the aspects of experimental work, including preparation, setting up equipment, making measurements, keeping records, discussing and analysing results and writing summaries and reports. Marks may be reduced for those who do not 'pull their weight'.

Each team has a team logbook where you keep records of work done in the laboratory. We will supply each team with a logbook which remains in the laboratory. The details of how to keep these records are given later in the Notes on Experimental Methods. Each member should spend about an equal amount of time recording entries in the team's logbook.

Because the team logbook is shared by all the members of the team, **you are expected to keep personal notes as well**. These can consist of annotations in this Laboratory Manual or, if you prefer, in a personal notebook.

1.4.5 What personal equipment to bring

Bring a scientific calculator, ruler, pen and pencil to all laboratory classes. A copy of this Laboratory Manual will be available online (through eLearning), on the laboratory computers and a hard copy you can borrow within the lab class. However, you may find it more convenient to purchase the laboratory manual or print the section containing the experiment relevant for your lab class.

1.4.6 How to prepare for each session

Each session requires some preparation before you come to the laboratory. You should read the appropriate session notes sufficiently thoroughly so that you know what you will be doing and how to get started. Preparation also includes reading some relevant sections of your text book and doing some brief pre-work exercises.

Pre-work for each of the lab sessions is available on, and done on, your unit eLearning/Blackboard page. Your mark for the pre-work will also be available on elearning and not via LabRat.

You *must* complete this *pre-work* before beginning each laboratory session. For all lab sessions, you will be expected to do the pre-work on eLearning.

1.4.7 Use of laboratory equipment

- Return all equipment issued to you from the service counters promptly, and certainly before the end of the session. If you leave it on the bench and it goes missing you may have to replace it.

- Do not move apparatus from one work place to another without your tutor's or supervisor's approval.
- Do not misuse the equipment in the laboratories. We regard it as a serious offence to tamper with the operation of computers or any other equipment in the laboratory.
- Please keep your work place tidy.

1.4.8 Assessment and Marks

See your Unit of Study Outline for a detailed explanation of the assessment of all the components of your Unit of Study. However, note that **you must at least pass the lab component in order to be eligible for a pass in the whole unit of study, although the lab marks will not directly be included in your final grade**. The lab component has 24 marks allocated to it: 10 marks for circuits and 14 marks for projects.

In the laboratory, marks are gained from completion of stages of the experimental program for each session. These are usually indicated as check-points:

➢ C1

You must present your lab book to the tutor for initialling when your team has completed each check-point. If the quality of the record keeping and/or the experimental work is not up to the required standard you will be told what needs to be done before you present the book again.

Marks will be deducted if you do not contribute sufficiently to your team's efforts.

Before you leave at the end of the session make sure your last completed check-point has been signed off.

1.4.9 Laboratory Prize

The Smith Prize in Experimental Physics is awarded to the student (or students, if shared) of sufficient merit who best combines the characteristics of experimental skill, proficiency and exceptional motivation in Junior Experimental Physics. The award is based on experimental and project work in the laboratory or work in the Talented Student Program. Tutors and supervisors assess student skills, understanding and motivation during discussions about experiments and projects.

1.4.10 Health and Safety Requirements

It is your responsibility to work safely in the laboratory. Any accident (no matter how apparently trivial) ***must be reported to your laboratory supervisor immediately.***

- **Shoes MUST be worn.** Bare feet, thongs, sandals or any other type of footware where your toes are exposed are not suitable. You will be asked to leave the laboratory if you do not have suitable shoes
- **Food and Drink: You may NOT eat, drink or smoke in the laboratory.**

- **Safe handling practices** must be observed with all laboratory apparatus and furniture - e.g. no kicking, throwing or playing with steel, rubber or synthetic balls; no standing or climbing onto chairs or stools.
- **Unauthorised repair** or adjustment of laboratory apparatus, printers or computer systems is not permitted. Faulty equipment must be reported to Teaching or Laboratory staff immediately.
- **Liquid spills** must be reported to laboratory staff immediately.
- **Laboratory Glassware** is fragile and dangerous if broken. Report all breakages to the laboratory supervisor immediately.
- **Mercury** is contained in some equipment e.g. some thermometers, pressure gauges etc. Immediately report all breakages involving mercury spillage since mercury vapour is harmful.
- **Lasers:** Do not look directly into a laser beam or point lasers at other people.
- **Radioactive sources:** Do not use unprotected hands. Handle radioactive sources using the tongs, beakers and containers provided. Store radioactive sources in the lead storage container provided.
- **Projectile launchers** must be used with care. Projectiles should not be launched a distance of more than 3 m horizontally and 1 m vertically (above laboratory bench height). Before launching projectiles, ensure that the area and direction in which the projectile will travel are clear.

1.4.11 Restrictions on the Use of 1st Year Student Computers and Printers

Unauthorized tampering with computer hardware or software is not permitted. Do not download or execute (double click) *.exe files. USB ports are reserved for networking and data acquisition purposes. Do not use USB ports for charging mobile phones, flash drives (memory sticks), or any other USB device not authorized for experimental and laboratory use. Student printer usage is restricted to print jobs relating to 1st Year Experimental Physics and Projects only. To avoid excessive toner usage print Excel graphs on a white background, not shaded or dark backgrounds. Please be environmentally conscious and keep print wastage to a minimum.

1.4.12 FIRE SAFETY

If there is a fire in the Carslaw building a warning will sound ordering evacuation of the building. In that case you should follow the Exit signs out of the lab and down the central stairwell (do not use the lifts), or the Fire Escape between Labs 401 and 402. You should then go to the open area in front of the new Law School along Eastern Avenue from the Carslaw building.

1.4.13 Enquiries

Routine enquiries about the course can usually be handled by your laboratory supervisor during class times. At other times you can ask for help at the Physics Student Office, room 210 in the Physics Building.

2 Notes on Experimental Methods

2.1 What are experimental methods?

The procedures and skills may be divided into five groups:

- Planning the experiment and choosing the equipment
- Setting up the apparatus.
- Performing the experiment and recording the data.
- Analysing the data and interpreting the results.
- Presenting a description of the work and the conclusions reached.

2.2 Individual records and team logbooks

Keeping good and accurate records of the progress of an investigation is an extremely important part of experimental work. Those records are used for subsequent analysis and later reference. It is essential to be able to find from your records what you did, and what you were trying to find out. If things went wrong, your records will help you track down the problem. Such records can also be legal documents showing that experiments were done ethically and honestly.

In this course each team of three students will keep an official laboratory logbook which we call a team logbook. ***The team logbook records the work performed by and for the team as a whole. The results are shared by the team.*** You should also keep your own personal records - these can be as annotations in your personal copy of this Laboratory Manual or in a notebook which you provide yourself.

2.3 What to record in your team logbook

- **All logbook entries should be made in ink or ballpoint pen.** Do not use pencil. (From a strictly legal view, logbooks are legal documents. In many organizations, the scientist has to sign the bottom of each page of her/his logbook, and have the signature witnessed and dated, just like an affidavit or contract).
- Whenever you start a new session make a note of the **name of the experiment, the date and list the names and SIDs of the team members present. This is the critical record if there is any dispute over the marks you have been given.** Note the name of the person doing the writing of the log. It is a good idea to also record where you are working and what equipment you are using.
- Your logbook has to be comprehensive and legible. It doesn't have to be pretty, but it DOES have to be easy for others to read and understand.
- If it feels like you are writing too much and putting in far too much detail, then you are probably getting it about right. As H.G. Nelson (the greatest scientist never to win a Nobel prize) should have said "Too much detail is never enough! "
- NEVER, NEVER, NEVER rely on your memory or scraps of paper. **Write it directly into your logbook!**
- If you make a mistake, neatly cross out the mistake and rewrite it. Don't get too enthusiastic with your crossing out, your first entry may be useful at a later stage. Make sure that you can still read it. Never use liquid paper to correct "errors".

- Your logbook should provide a record of what you did and why you did it. So as well as tabulations and graphs of your data, there should be concise explanations of what you are trying to find out, and what you actually did. Make as much use as you can of labelled diagrams - they take a few minutes to produce, but can show many aspects of an experimental setup much more clearly than a description in words. Use headings to clearly separate the various sections. If you have any difficulties with an experiment or otherwise depart from the standard procedure, it is especially important to record this in the logbook. Do not tear out pages if some work has to be repeated; instead, draw a line through the incorrect material, and write a brief annotation explaining what is wrong.

- The original records of data must appear in the team logbook. If the original records are printed out by a computer, stick the sheet in the team logbook.

- Analysis and interpretation of your results, as suggested by the module notes.

- The conclusions reached during team discussion.

- For most experiments your team will be expected to write a concluding summary on the experiment. Such a summary would be prepared by the team from notes you and your colleagues made during the experiment.

- Present the team logbook to the tutor for initialling as soon as your team has completed a task specified in the experiment notes, e.g. completion of the experiment up to one of the marked check points. If the quality of the record keeping and/or the experimental work is not up to the required standard you will be told what needs to be done before you present the book again.

An example of an experimental record in a logbook follows, to show the sort of information we would like to see in your team logbook.

2.4 What to record in your personal notebook or as annotations in this Laboratory Manual

- Preparatory work at home: e.g. notes from reading text, solutions to problems.

- In some sessions you will be given an individual assessment task which you have to do by yourself. The records for such a task would be kept in your notebook or in the spaces provided in the session notes. Sometimes the successful completion of the task would be recorded in the team logbook.

- Personal records will not be marked except where specific, individual, tasks are required to be done there. Such tasks might include preparatory work before you come to the laboratory or individual assessment tasks. You may, however, ask tutors to comment on your personal or team records at any time.

Oops! No names of group members

Start each experiment on a new page with title, date and names

Sample Logbook

The following is a sample of a good (but not perfect!) logbook record of an experiment. It is *not* just a few tables of numbers and a graph. It also features written notes to record exactly what was done and why and discusses the results.

Oops! No sketch of apparatus. Also needs a few words on what is being attempted – an "Aim"

LIQUID FLOW EXPERIMENT

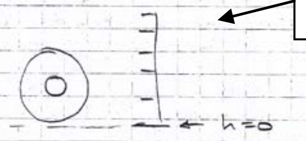
5/7/95.

Capillary selected: bore = 2.2 mm
length = 40 cm. (No 30 cm avail).

Note manometer reads 1.9 cm with inlet valve close and no flow. Is clearly above the capillary level. Presumably surface tension holding it?
Yes – Jim McC

Note also zero of h scale is not on centre line of capillary bore. Rather, it ~ at lower outside of tube:

Diagram to help explain the notes



Ran water through to stabilise temperature –
Air temp 18.0 C
Water temp 18.1 C .... probably = tank temp, and will take a long time to stabilise, ∵ tank capacity / slow mixing.

So will record water temp for each meas.

Set h = 18.8 cm; fluctuates significantly – several mm. – Problems w/ valve?

Using apparatus set nearest window.

Detailed observations during the experiment; decisions on procedures to use in taking data; notes on what was actually done

NOTES

Stopwatch – to time the collection intervals.

How to level the tube? (Apart from resting it on fixed support)

Hold finger over end to start / end collection? No, probably better to insert / remove collector.

Allow time for h to stabilise after changing inlet valve

h dropped a lot during first run. Tank is full to overflow point.
Possibly due to a bubble in the feed line? Can see ∃ a bubble ... quite large, must affect flow.
Cleared this bubble by removing capillary entirely (on other apparatus of ~~the~~ pair) and using max. flow rate

Retest stability at h = 20.3 cm. Still drops – eg to 20.1, 20.0. Probably usable.

Inlet valve has hysteresis?

For larger flows, convenient to run for time to get ~200 ml, ∵ have 250 ml meas cyl.

Stopwatch retriggers & so doesn't stop .. if press harder / longer ... for 'definite' stop!
Many readings had to be repeated ∵ of this.

NB Poss errors in converting min:sec → sec;
misreading meas cyl (div's 2 ml)
Not using bottom of meniscus

Exactly where is ~~the~~ position at which ~~the~~ manometer's pressure reading applies?
Ans – any place at h = 0 level on scale as used.

Notes on each measurement

Table of Data

h /cm	V /ml	t /sec	Water temp /°C	Notes
[17.6]		119.6	17.9	Down to 17.3, 17.2, 17.0, 16.0! 15.5
20.1–19.8				Flow osc ~ 2 s⁻¹

h /cm start	end	mean	V /ml	t /sec	water temp /°C	
20.1	19.8		154	75.6	17.0	Flow osc at ~2s
8.1	7.9		73.5	92	17.0	Runs back, not steady all the time.
29.6	29.6		230	81.4	16.5	Manometer fluctn. (slow)
41.9	41.9		253	~~69~~	~~16.4~~	h up to 42.5.
51.2	51.3		191	47.7	16.2	
56.5	56.4		212	48	16.1	Jerky flow stream
68.1			216	44.6	16.1	Jerky flow, man'r fluctns.
91.0			208	38.3	16.1	Inlet max open
4.4	4.3		45	120.9	16.4	man'r steady

Cross out bad data – but leave it legible (in case it was right after all)

Explanation of graph

Data plotted using Excel.
Fit line by eye, not computer, so can omit discrepant point(s), and fit separately to laminar and turbulent regions.

Needed another point (or more) at high end, ~ 6000 Pa.

* what units to use? SI? But Q ~~then~~ v. small...

Calculation of the relevant slopes – show details of the calculation for later checking

From plot, slope of Q vs P' in laminar region is

$$\frac{\Delta Q}{\Delta P'} = 72.2\text{ mm} \times \frac{6\text{ ml/s}}{115\text{ mm}} \Big/ 87\text{ mm} \times \frac{3000\text{ Pa}}{90.3\text{ mm}}$$

$$= 1.30 \times 10^{-3}\ \text{ml s}^{-1}\ \text{Pa}^{-1}$$ 'best fit' (solid line)

And ~~upper limit (dotted line) has~~ slope

$$\frac{\Delta Q}{\Delta P'} = 74.7 \times \frac{6}{115} \Big/ 85.7 \times \frac{3000}{90.3}$$

$$= \underline{1.37 \times 10^{-3}\ \text{ml s}^{-1}\ \text{Pa}^{-1}}$$

~~i.e. uncertainty in slope~~ ~ 5%.

Significant results should be underlined to stand out – include units

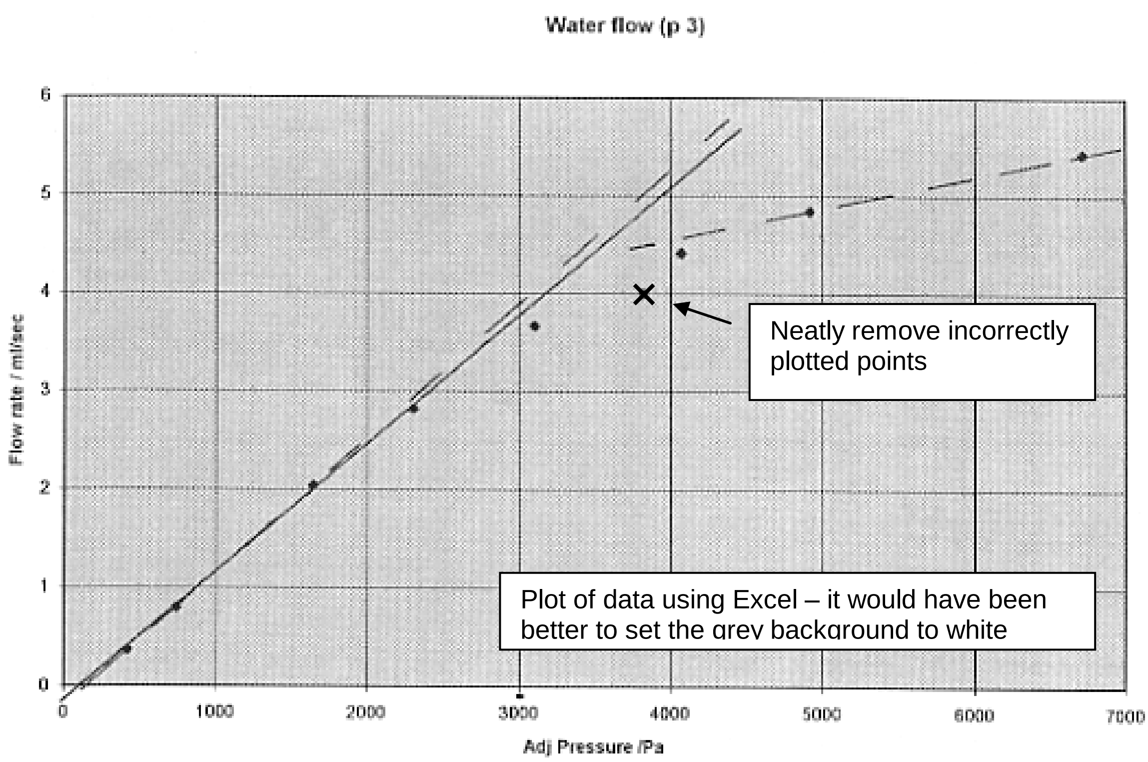


Table of data in Excel – with explanatory notes

6/7/95.
Data p 3

Sheet1

A	B	C	D	E	F	G	H	I
Capillary diam d =		2.2	mm					
h /cm	V /ml	t /sec	Water temp /C	Q ml/sec	P /Pa	Delta P /Pa	P' /Pa	Q ml/sec
4.35	45	120.9	16.4	0.372208	426.3	10.35442	415.9456	0.372208
8	73.5	92	17	0.798913	784	47.70373	736.2963	0.798913
19.95	154	75.6	17	2.037037	1955.1	310.1352	1644.965	2.037037
29.6	230	81.4	16.5	2.825553	2900.8	596.7056	2304.094	2.825553
41.9	253	69	16.4	3.666667	4106.2	1004.838	3101.362	3.666667
51.25	191	47.7	16.2	4.004193	5022.5	1198.349	3824.151	4.004193
56.45	212	48	16.1	4.416667	5532.1	1457.95	4074.15	4.416667
68.1	216	44.6	16.1	4.843049	6673.8	1753.037	4920.763	4.843049
91	208	38.3	16.1	5.430809	8918	2204.359	6713.641	5.430809

↑ $B7/$C7

↑ (A7/100)*9.8*1000

↑ 8*2.16*1000*(E7/10^6)^2/((PI()^2)*POWER((C$2/1000),4))

↑ F7-G7

↑ $B7/$C7

Calculation of an important final result – showing details for later checking

Calculation of η:

See notes p 6:

$$\eta = \frac{\pi d^4}{128\,L}\left(\frac{10^6}{\text{slope } \frac{\Delta Q}{\Delta P'} \text{ in ml s}^{-1}\text{ Pa}^{-1}}\right) \quad \text{in SI ie Pa.s.}$$

$$= \frac{\pi\,(2.2/1000)^4}{128 \times 40 \times 10^{-2}} \times \frac{10^6}{1.30 \times 10^{-3}}$$

$$= 1.11 \times 10^{-3} \text{ Pa.s}$$

Estimate uncertainty

Don't know uncertainty in d (but could be serious, ∵ raised to 4th power). Using 5% uncert from slope,

$\eta = (1.11 \pm 0.06) \times 10^{-3}$ Pa.S at T ~ 16.5 °C. is my result.

Quote final result – with uncertainty and units

Comparison of η with accepted value

Enter Table C2.1 data for viscosity of water vs temp into another sheet of excel.
(Temp in first column, ~~then~~ η, so plot on correct axes)

What can we do about fitting a smooth curve to this ...? ∃ Trendlines ~~and~~ in 'Insert'.. but is not available on my plot – why not?
Have to select the data ... still n/w.
Yes, click on data points (one will do) in the graph.
This highlights ~~the~~ points – then trendline avail.

An intelligent discussion (or "Conclusion") is the most important (but most difficult) part of the logbook write up

Not very good results with polynomial order 2 or 3 but degree 4 looks quite good, although clearly not perfect.
Would be better to have $\Sigma \frac{1}{T^n}$ type of series.

From the polynomial fit I get $\eta = 1.091$ m.Pa.s at temp = 16.5.
ie experimental value was 2% high, and well within error bound!

Learning goals

The circuits section of the laboratory course is intended to complement the lectures in the Electricity and Magnetism module of this unit by offering practical experience of electrical circuits and extra theory specifically related to electrical circuits.

The following list collects together the Learning Goals from each of the five circuits experiments. Some are in italics to indicate that they are primarily related to practical laboratory skills. The remainder are more related to concepts of circuit theory. Both may be assessed in the online Skills Test. In addition, one question in the end of semester examination will be devoted to circuit theory.

Week 1:

- *be able to construct a simple circuit and measure values of current and voltage using a digital multimeter,*
- be familiar with the concept of resistance,
- understand the operation of resistors in series and parallel,
- understand the operation and applications of a voltage divider,
- *be able to measure the resistance of a circuit component.*

Week 2:

- understand the concept of time-varying voltages and currents,
- *have a basic ability to control the display and triggering of a waveform on a digital oscilloscope,*
- *be able to identify and measure on an oscilloscope waveform characteristics such as amplitude, peak-to-peak voltage, frequency and period,*
- *be able to use the signal generator,*
- *be able to construct a simple circuit and measure voltage and current values using an oscilloscope,*
- understand the use of complex notation to describe alternating currents and voltages,

Week 3:

- understand the concept of an inductor and a capacitor,
- understand the concept of reactance of non-resistive devices,
- understand the concept of impedance and Ohm's law for simple AC circuits,
- *be able to measure phase differences on an oscilloscope,*
- be able to use complex notation to perform calculations of amplitude and phase with time-varying voltages and currents.

Week 4:

- *be able to construct a simple RC circuit and measure voltages at various points in the circuit using an oscilloscope,*
- *be able to measure the frequency response of the circuit using an oscilloscope,*
- understand the concept of impedance in simple circuits.
- understand the concept and use of high- and low-pass filters.

Week 5:

- understand the concept of resonance as it occurs in simple RLC circuits,
- *be able to measure the frequency response of a resonant circuit using an oscilloscope,*
- understand concepts related to resonance such as bandwidth and Q-factor.

Assumed knowledge - review of complex numbers

In MATH1001/MATH1901, you were introduced to the concept of complex numbers. In this course, you will use complex numbers as a convenient mathematical tool to represent the response of circuits to applied voltages that vary with time. In case you have forgotten complex numbers shortly after the end of semester examination or have not done MATH1001/MATH1901, the following contains a brief introduction to complex numbers as needed for this course and some sample questions to test your understanding. If you have difficulty with the sample questions, please consult a duty tutor or one of your lab tutors.

Complex numbers were introduced in order to allow solutions to equations that have no real solution. For example, the equation

$$z^2 + 1 = 0 \tag{1}$$

has no real solution. To solve this equation, we define an imaginary number $j = \sqrt{-1}$. The solutions to the equation are then $z = j$ and $z = -j$ (**Note: in mathematics, you used $i = \sqrt{-1}$. However, in circuits i is reserved for the instantaneous current, so we use j instead**).

A complex number is a number of the form

$$z = x + jy\,, \tag{2}$$

where x and y are real numbers that are referred to as the *real* and *imaginary* parts of z respectively. By introducing complex numbers, every polynomial equation has a solution.

We can use the real and imaginary parts of a complex number to plot a complex number as a vector in a cartesian plane, which is referred to as an Argand diagram. To do this, we plot the real component on the x (horizontal) axis and the imaginary component on the y (vertical) axis, as shown in Fig. 1.

To add complex numbers together, we simply add the real and imaginary components separately. That is, for two complex numbers $z = x + jy$ and $c = a + jb$, we have

$$z + c = (x + a) + j(y + b)\,. \tag{3}$$

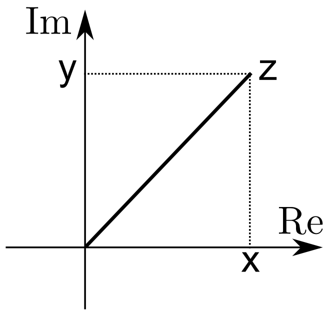


Figure 1: Argand diagram representation of a complex number $z = x + jy$.

On an Argand diagram, this corresponds to the 'tip-to-tail' rule for vector addition. To add two vectors c and z 'tip-to-tail', you draw the two vectors on a cartesian plane such that the tip of vector c touches the tail of vector z as in Fig. 2 (a). Then draw a vector from the tail of vector c to the tip of vector z as in Fig. 2 (b). This vector is $c + z$.

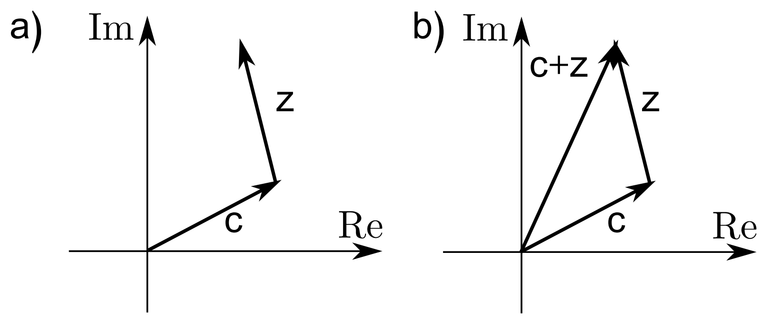


Figure 2: Argand diagram representation of the 'tip-to-tail' method of adding two complex numbers, c and z.

To multiply two complex numbers, $z = x + jy$ and $c = a + jb$, we multiply them as normal and make use of the fact that $j^2 = -1$. That is,

$$
\begin{aligned}
z * c = (x + jy) * (a + jb) &= x * a + x * jb + jy * a + jy * jb \\
&= xa + j^2 * yb + j(xb + ya) \\
&= xa - yb + j(xb + ya)\,.
\end{aligned}
\tag{4}
$$

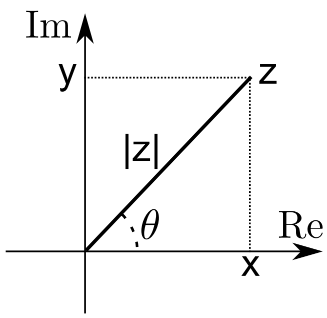


Figure 3: Polar form of a complex number $z = x + jy = |z| \exp^{j\theta}$.

By considering the Argand diagram in Fig. 3, a complex number can be viewed as the hypotenuse of a right-angled triangle, where the lengths of the other sides are given by the real and imaginary parts. Therefore for a complex number $z = x + jy$, the length of z, denoted $|z|$, is given by Pythagoras' theorem, i.e.,

$$|z| = \sqrt{x^2 + y^2}\,. \tag{5}$$

$|z|$ is also called the modulus of z and is always a real number with $|z| \geq 0$. If we are given $|z|$ and the angle θ that z makes with the positive real axis as in Fig. 3, then we can work out the real and imaginary parts of z using standard trigonometric relations, as

$$\begin{aligned} x &= |z|\cos\theta \\ y &= |z|\sin\theta\,. \end{aligned} \tag{6}$$

Conversely, if we are given the real and imaginary parts, we can work out $|z|$ and θ by using the definition of $|z|$ and noting that

$$\tan\theta = \frac{y}{x}\,. \tag{7}$$

If we define a complex exponential,

$$e^{j\theta} = \cos\theta + j\sin\theta\,, \tag{8}$$

then from Eq. (6), we have

$$z = x + jy = |z|(\cos\theta + j\sin\theta) = |z|e^{j\theta}\,. \tag{9}$$

Putting complex numbers into this form (called polar form) allows us to easily multiply and divide complex numbers by using simple properties of the exponential function. Recall that

$$\begin{aligned} e^x * e^y &= e^{x+y} \\ \frac{1}{e^x} &= e^{-x}\,. \end{aligned} \tag{10}$$

So if we have two complex numbers, $z = |z|e^{j\theta}$ and $c = |c|e^{j\phi}$, then

$$\begin{aligned} z * c &= |z|e^{j\theta} * |c|e^{j\phi} = |z| * |c|e^{j(\phi+\theta)} \\ \frac{z}{c} &= \frac{|z|e^{j\theta}}{|a|e^{j\phi}} = \frac{|z|}{|c|}e^{j\theta}e^{-j\phi} = \frac{|z|}{|c|}e^{j(\theta-\phi)}\,. \end{aligned} \tag{11}$$

Sample questions

For the following questions, let $c = 1 + j$ and $z = 1 + j\sqrt{3}$.

1. Draw Argand diagrams for c and z.
2. Find $c + z$.
3. Express c and z in polar form.
4. Find $c * z$ and $\frac{c}{z}$.
5. Calculate $\frac{1}{c} + \frac{1}{z}$.

ADV 1: DC Circuits and Resistors

1 Introduction

The objective of this experiment is to study circuits with combinations of resistors. In doing this experiment you will learn how to use digital multimeters to measure resistance values and *direct current* (DC) values of current and voltage in a simple circuit.

1.1 Learning goals

On the completion of this session you should:

- be able to construct a simple DC circuit and measure values of current and voltage using a digital multimeter,
- be familiar with the concept of resistance,
- understand the operation of resistors in series and parallel,
- understand the operation and applications of a voltage divider,
- be able to measure the resistance of a circuit component.

Since this topic may be new to you it is ESSENTIAL that you read these notes before this laboratory session. It is also STRONGLY RECOMMENDED that you read the relevant sections of Young and Freedman, *especially:*

- *25.3 Resistance,*
- *26.1 Resistors in Series and Parallel, 26.2 Kirchhoff's Rules and 26.3 Electrical Measuring Instruments.*

Have you done your pre-work?

For each week of the Circuits component of the lab course you **must** complete pre-work **before** coming to the lab.

The pre-work is available and is done on the eLearning/Blackboard page for this unit. Your mark is also available via eLearning.

If you have questions about the pre-work, ask your lab tutors or the Duty Tutors.

2 Measurement of Resistance

(about 1 hr)

The objective of the first practical exercise is to measure the DC current I_0 through a resistor as a function of the voltage V_0 across the resistor, and hence obtain a value of the resistance using Ohm's Law,

$$R = \frac{V_0}{I_0}. \tag{1}$$

Resistance is measured in ohms (Ω) with 1 ohm = (1 volt)/(1 amp). In principle any resistor R could be used, but we'll pick one — the 4.7 kΩ resistor. It is marked by yellow, violet and red coloured bands (as described in the resistor colour code on page S.3).

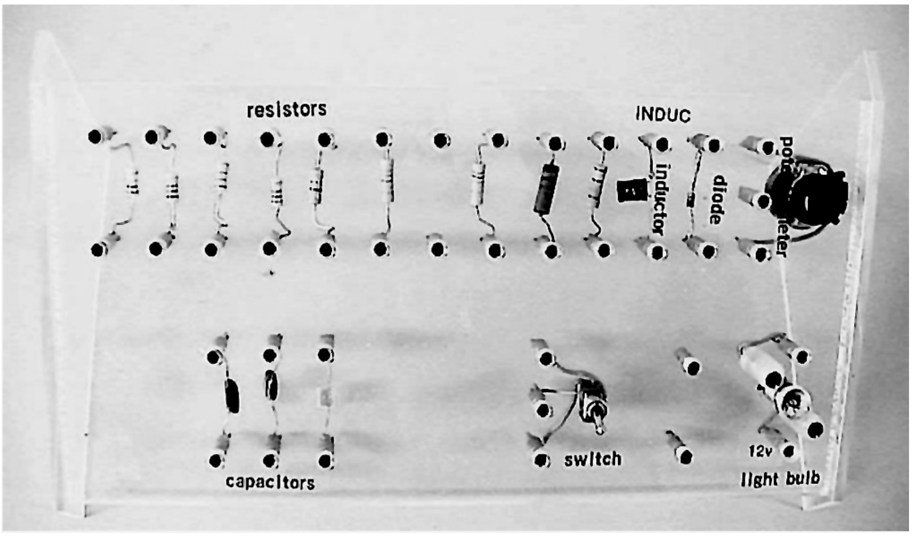


Figure 1: Component board used for the circuits experiments.

- Measure and record the resistance of the 4.7 kΩ resistor using the Resistance (Ω) setting of the Digital Multimeter (see Figure 2). Measurement of resistance using multimeters is described in *Using the Multimeter* (pages M.1-6).

The voltage source could be a battery, but it is not possible to vary the voltage of a battery. Instead, you should use the power supply available on the bench. It has a knob that you can use to vary the voltage continuously from 0 to 10 V and a selection of different, fixed voltages from 0 to 10 V in 2 V steps.

Two meters are available on your bench to measure V_0 and I_0 in the circuit. Both are digital multimeters with a switch to let you measure V_0, I_0 or R. There is a Common (**COM**) terminal for one connection to the meter (negative for DC measurements, ground for AC), and the other terminal (positive for DC) is the one labelled **VΩmA** or similar. The third terminal, labelled **10ADC**, is only for high current measurements and is not used in these experiments.

The digital multimeters have a rotary switch that you can use to select an appropriate range for the quantity that you will measure. For example, if you are measuring a current, set the switch to the least sensitive (200 mA) scale and then adjust the switch down through progressively more sensitive scales (20 mA, 2 mA, 200 μA) provided the measurement remains below the scale

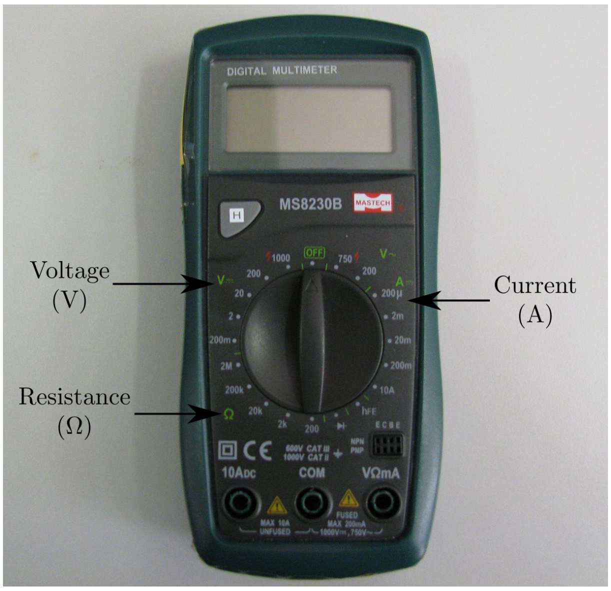


Figure 2: An example of a Digital Multimeter.

maximum. The measured current is the value on the display in the units of the current setting, i.e., if the setting is 200 μA, then the units are μA, otherwise the units are mA.

- Connect the circuit shown in Figure 3 after first checking you have the correct resistor. *Hint*: It is always easier to connect the main circuit consisting of the voltage source, ammeter and resistor first. The ammeter (if used) is an essential part of this circuit as, without the ammeter, there is no closed path for current to flow through. The voltmeter is just a supplementary measuring instrument, which should be connected last.

Logbook 1.1 Choose the *fixed* 10 V voltage source and measure the current I_0 (in mA), and voltage V_0 (in V). Make sure you use the voltmeter to make an accurate reading of voltage produced by the voltage source. Repeat with the different fixed voltage sources: 0, 2, 4, 6 and 8 V. Measure the voltages and currents accurately and make a table of your readings in your team logbook.

Completely disconnect the resistor from the circuit and re-measure its resistance directly with the digital meter, switched to the appropriate range. The digital meter is correct to within 2% or the round-off error, whichever is the greater. Make a note of your reading and its uncertainty.

Logbook 1.2 Use Excel to plot a graph for your logbook of I_0 (vertical axis) vs V_0 (horizontal axis) and add a line of best fit (a trendline) *that passes through the origin.* The results should ideally lie on a straight line of slope I_0/V_0. (If they don't, then one or both of the meters may be slightly in error. Meters are NEVER perfectly accurate, but the digital meters in the lab should be correct to about 2%.

Use LINEST (see page A.24) to estimate the slope s of your graph and its uncertainty Δs. The value of resistance R is given by $R = 1/s$ and the uncertainty in the resistance ΔR is given by $\Delta R/R = \Delta s/s$ (can you explain why from the table on page A.10?).

Compare the value of the resistance obtained from the graphical method with that found using the digital meter. Do your two values of R agree, i.e., are they the same to within the experimental uncertainty? If not, discuss with your tutor and comment.

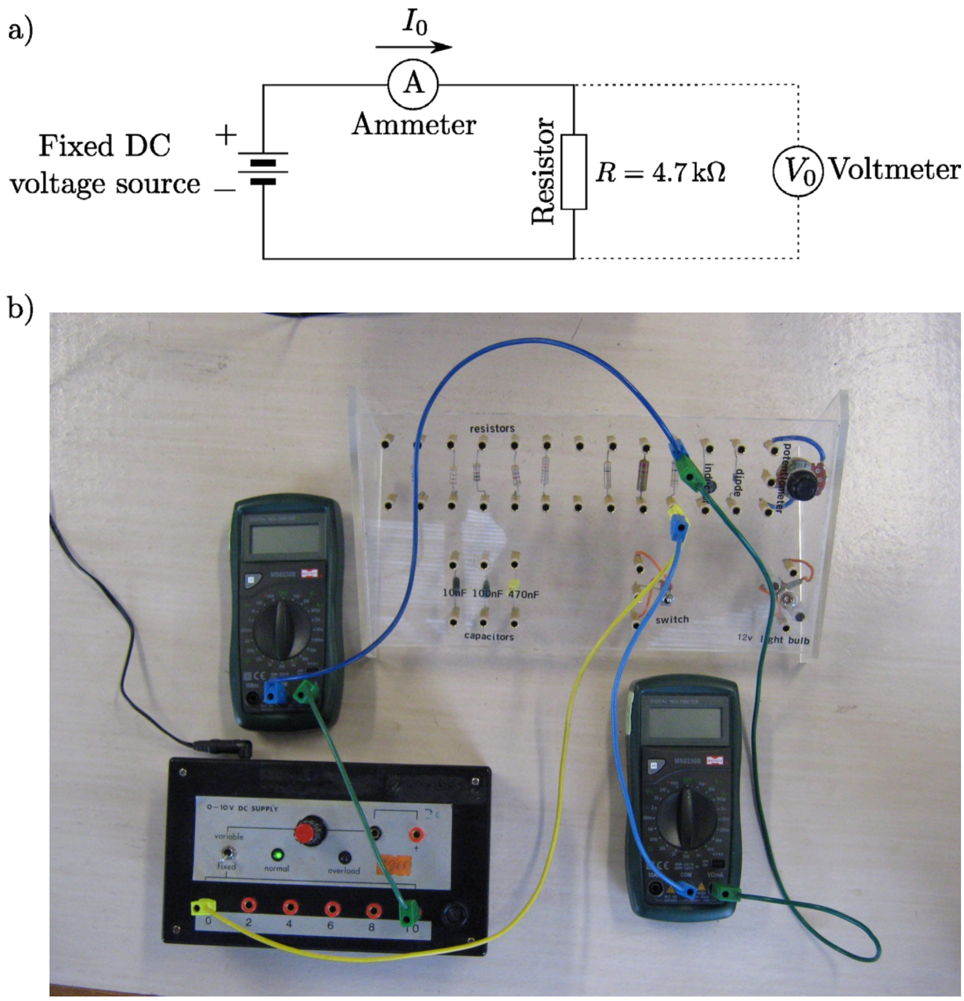


Figure 3: a) Circuit diagram for the first experiment. b) Photo of the corresponding circuit with $V_0 \approx 10\,\mathrm{V}$.

When measuring the resistance of a resistor, you should have found that the two values of R agreed to within the experimental uncertainty. That is, you should have found that the resistance, R, was approximately independent of the applied voltage. This is a special property of resistors that allows them to be used in the design of circuits. Other devices, such as incandescent light bulbs or light-emitting diodes (LEDs), exhibit a more complicated dependence on the applied voltage. For example, when a light bulb is cold, the resistance of the filament is low, but when a large current flows in the filament, the filament gets hot and its resistance increases.

➤ C1

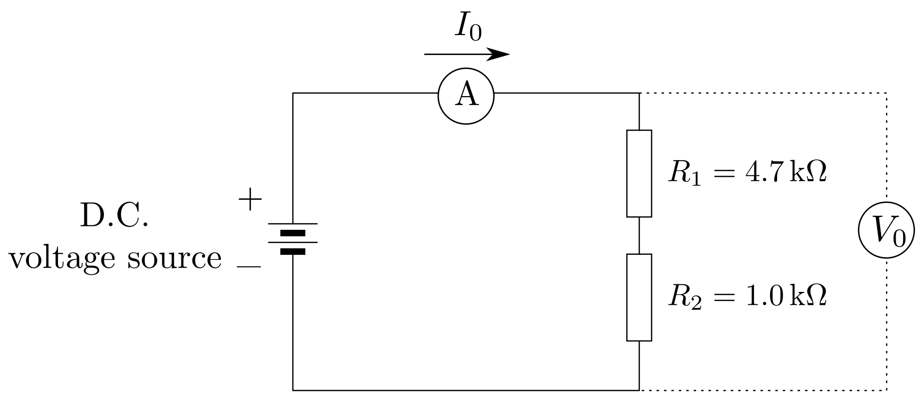


Figure 4: Resistors in series.

3 Resistors in Series

(About 10 min.)

- Connect the circuit shown in Figure 4 with two resistors in series.
- Choose the 10 V voltage source and measure I_0 and V_0. Calculate the total resistance, $R = V_0/I_0$, of the two resistors in series and estimate the uncertainty in your result.
- Disconnect the circuit and measure the total resistance of R_1 and R_2 in series, and then one at a time, with the digital meter.

Logbook 2.1 Record your results and check that they show that $R = R_1 + R_2$. If not, discuss with your tutor.

4 Voltage Divider

(About 20 min.)

- Reconnect the circuit shown in Figure 4, but now measure the voltage V_2 across the $1.0\,\mathrm{k\Omega}$ resistor instead of across the two resistors in series.

You should discover that the voltage across the $1.0\,\mathrm{k\Omega}$ resistor is LESS than 10 V, since only part of the 10 V across the two resistors appears across the $1.0\,\mathrm{k\Omega}$ resistor, and the remaining part appears across the $4.7\,\mathrm{k\Omega}$ resistor. This arrangement is known as a voltage divider ("divide" means "share in a fixed ratio" in this context). Voltage dividers are widely used in circuits to reduce a fixed voltage to another, smaller, value.

Logbook 2.2 Check that the voltage V_2 across the resistor R_2 is as expected, i.e., $V_2 = R_2 I_0$. I_0, set by the total resistance, is given by $I_0 = V_0/(R_1 + R_2)$. Thus

$$\frac{V_2}{V_0} = \frac{R_2}{R_1 + R_2}. \tag{2}$$

Voltage dividers are used to produce an output voltage V_2 across a resistor R_2 that is a specific fraction of an input voltage V_0, i.e., to *attenuate* the input voltage. By choosing the ratio of two resistors, R_1 and R_2, we can choose the ratio V_2/V_0. This can be used to protect a sensitive electronic component by lowering the voltage that is applied to it. Other applications include the volume control on a radio or audio amplifier, which use a continuously variable resistor.

Logbook 2.3 Copy Figure 4 into your logbook, leaving out the voltmeter and ammeter. Indicate on this diagram the two points at which you would connect a component that requires a voltage of:

a) $\frac{10}{5.7}$ V,
b) $\frac{47}{5.7}$ V,

assuming the fixed D.C. voltage source delivers 10.0 V. Use Kirchoff's loop law (which states that the algebraic sum of the voltages around any closed loop is zero) to justify your answers.

- Reconnect the circuit shown in Figure 4 with the fixed 10 V voltage source, but now measure the voltage V_A *across the ammeter*. Set the ammeter to the 20 mA range.

Logbook 2.4 Why do we measure a voltage across the ammeter?

Using Ohm's law (Eq. (1)) and your values of V_A and I_0, calculate the resistance of the ammeter.

For what values of R (the total resistance in the circuit) will the ammeter resistance be significant?

Why do ammeters generally have small resistances?

➢ C2

5 Resistors in Parallel

(About 20 min.)

When two resistors R_1 and R_2 are connected in parallel, the combined resistance, R, is less than either of the separate resistors, where

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2} \tag{3}$$

or

$$R = \frac{R_1 R_2}{R_1 + R_2} \tag{4}$$

Logbook 3.1 Using Eq. (3) or Eq. (4), show that $R < R_1$ *and* $R < R_2$, i.e., the combined resistance is always less than either of the separate resistances. (*Hint*: resistances are always positive)

- Connect the circuit shown in Figure 5, where resistors R_1 and R_2 are connected in parallel. Use the variable DC voltage source.

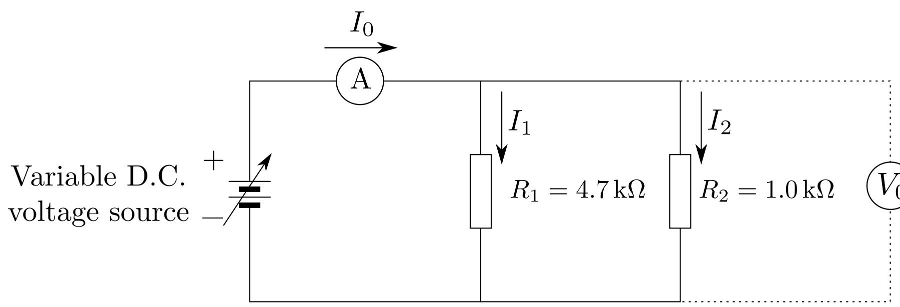


Figure 5: Resistors in parallel.

Logbook 3.2 Measure I_0 with V_0, the voltage across the resistors, set to 9.0 V. Calculate the resistance, $R = V_0/I_0$, of the two resistors in parallel.

Measure I_1 and I_2 with $V_0 = 9.0$ V. This is done most easily by disconnecting each resistance one at a time. The ammeter then measures the current through the other resistor alone. For each measurement, adjust V_0 to be 9.0 V. Note that two resistors in parallel act like two water pipes in parallel — the two resistors together carry more current than just one, like two water pipes together will carry more water than just one.

Disconnect the circuit and measure the resistance of the two resistors in parallel, and then one at a time, with the digital meter. Check that your results confirm that when two resistors are connected in parallel, the resistance, R, is less than either of the separate resistors, and that the parallel combination has resistance given by Eq. (4).

If not, discuss with your tutor.

Logbook 3.3 In Figure 5, $I_0 = I_1 + I_2$. Since part of the total current I_0 flows through R_1 and the rest flows through R_2, which resistor carries the larger current? Use your measurements of I_0, I_1 and I_2 to check that they are related as expected.

We will now use the principles of series and parallel resistances to illustrate the importance of a voltmeter.

- Connect the circuit shown in Figure 6 with $V_0 \approx 10$ V. Note that a voltmeter is not normally connected in series with a resistor as it is here, but our aim is to determine the resistance R_2 of the voltmeter.

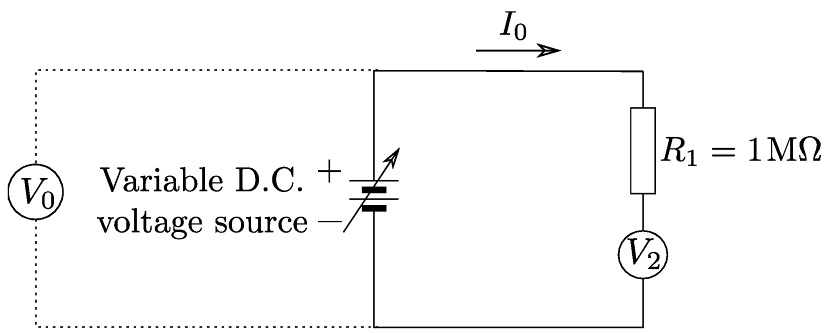


Figure 6: Circuit to determine the resistance of a voltmeter using the concept of a voltage divider.

Logbook 3.4 Record the reading V_2 on the voltmeter in series with the $1\,\mathrm{M\Omega}$ resistor, and use a second voltmeter to measure the voltage V_0 across the D.C. power source.

Using Eq. (2), show that

$$R_2 = \frac{R_1}{(V_0/V_2) - 1},$$

and hence calculate the voltmeter resistance, R_2, and its uncertainty. Why is the fractional uncertainty in $(V_0/V_2) - 1$ greater than the fractional uncertainty in (V_0/V_2)?

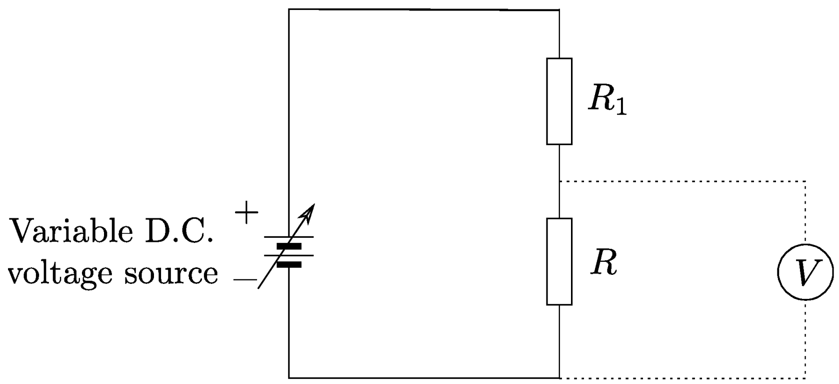


Figure 7: Voltage divider circuit with voltmeter V connected in parallel with a resistor R.

Logbook 3.5 We now look at the effect of the voltmeter's resistance on the voltage it is measuring. In the circuit of Figure 7, use your value for the resistance of the voltmeter from Logbook 3.4 to calculate the total resistance when the voltmeter is connected *in parallel* with resistor R, and R has a value of:

a) $1\,\mathrm{k\Omega}$, and
b) $1\,\mathrm{M\Omega}$.

How will the measured voltage across R in the circuit in Figure 7 be affected in each case?

Given that voltmeters are normally used in parallel with a component like a resistor, when does the resistance of the voltmeter affect the reading the most?

Why do voltmeters generally have a large resistance?

6 Conclusion

Logbook 3.6 List the main properties of DC circuits and multimeters that you have seen in this experiment (e.g. resistors are devices with constant resistance over a range of applied voltages).

➢ C3

When you've finished and your work has been marked by a tutor, please remember to turn off all equipment and dismantle your circuit.

ADV 2: Introducing AC Circuits

1 Introduction

The objective of this experiment on alternating current (AC) circuits is to learn how to use a signal generator, a frequency meter and an oscilloscope to measure the relations between alternating voltages and currents in simple circuits, such as those examined in the first experiment.

1.1 Learning goals

On the completion of this session you should:

- understand the concept of time-varying voltages and currents,
- be able to use the signal generator,
- have a basic ability to control the display and triggering of a waveform on a digital oscilloscope,
- be able to identify and measure on an oscilloscope waveform characteristics such as amplitude, peak-to-peak voltage, frequency and period,
- be able to construct a simple circuit and measure voltage and current values using an oscilloscope,
- understand the concept of internal resistance of a signal source
- understand the use of complex notation to describe alternating current and voltages,

Since this topic may be new to you it is ESSENTIAL that you read these notes before this laboratory session. It is also STRONGLY RECOMMENDED that you read the relevant sections of Young and Freedman, *especially:*

- *31.1 Phasors and Alternating Currents. Note that this is done without introducing complex numbers.*
- *the theory in section 4 of this experiment.*

Have you done your pre-work?

For each week of the Circuits component of the lab course you **must** complete pre-work **before** coming to the lab.

The pre-work is available and is done on the eLearning/Blackboard page for this unit. Your mark for the pre-work is also available via eLearning.

If you have questions about the pre-work, ask your lab tutors or the Duty Tutors.

2 Using a Signal Generator and Digital Oscilloscope

(45 min)

The Signal Generator

The signal generator can deliver a sine or square wave signal with an amplitude up to about 10 V and a frequency between 10 Hz and 1 MHz. Several types may be available, but the main features of a typical generator are illustrated in Figure 1.

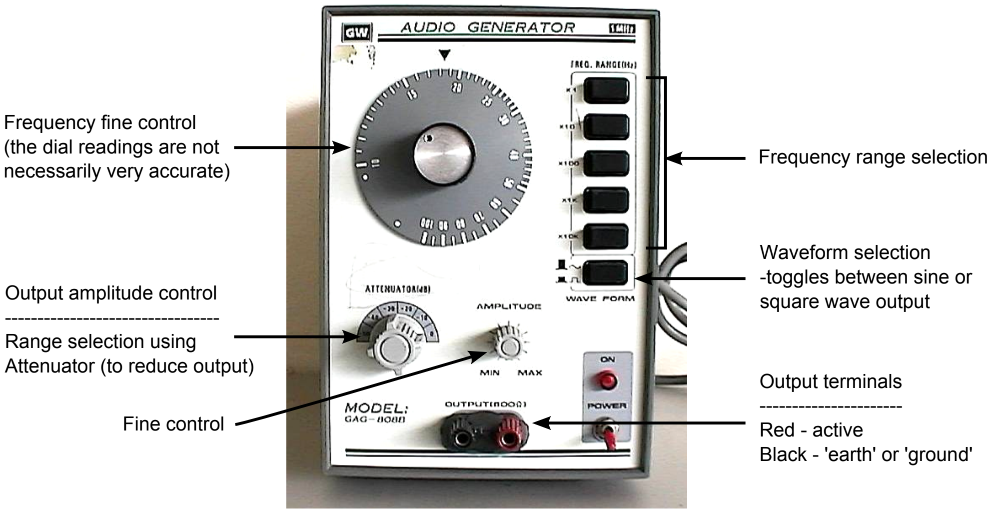


Figure 1: Front panel of a signal generator.

To set a particular frequency you need to use both the fine frequency setting on the dial and the coarse range setting using the buttons on the right. For example, to set a frequency of 2 kHz you would set 20 on the dial and $\times 100$ with the frequency range button. The dial settings are not accurate, so you should use the inbuilt frequency counter in the digital oscilloscope to measure frequency accurately.

All instruments in this lab (and most other labs in the world) that are connected to a power point are connected to the 'earth' (also called 'ground') through the power point and the power cable. The metal frame of all such instruments is thereby connected to the earth. If one of the input or output terminals on these instruments are connected to the metal frame, then these terminals are also earthed, and are said to be at zero (or earth) potential. The earth terminal is usually labelled with a small downward-pointing arrow or 3 horizontal lines, as shown below.

Symbol	Name	Meaning
	Earth ground	Used for zero potential reference and electrical shock protection
	Chassis ground	Connected to the chassis of the circuit
	Signal or Common ground	Low voltage return in equipment or signal interconnection between equipment

When one instrument is connected to another, you need to be careful ***not*** *to connect the output signal of one instrument to the earth terminal of the other instrument.* **If you do, the output signal is short-circuited to earth**. Ask your tutor to explain if you are not sure about this.

The Oscilloscope

The Digital Storage Oscilloscope (DSO or oscilloscope) is an instrument that measures voltage as a function of time. It is an AC voltmeter. It displays this information in the form of a voltage-time graph drawn by a bright spot moving across the screen. The operation of the DSO is described in *Using the Digital Storage Oscilloscope* (pages O.1–16).

- Work through section 2 of *Using the Digital Storage Oscilloscope*, trying all the controls.
- Connect the signal generator to channel 1 of the oscilloscope using a suitable coaxial cable. Note that the ‘BNC’ connector used on the signal input to the oscilloscope has the signal on the centre hole (or the pin of the matching connector on the coaxial cable). The outer ring of the connector is connected to earth and thereby ‘earths’ the sheath of the coaxial cable, helping to shield the signal from interference. Make sure you connect the black connector to the ground (black terminal) of the signal generator, otherwise the oscilloscope will not be able to display the signal.
- To start with, always check the probe value for each channel, by pressing the channel number and selecting “probe” with the softkeys. The probe value **must** be $\times 1$.
  We suggest the following settings:
  - **signal generator:** sine wave, maximum output voltage, frequency 10 kHz.
  - **oscilloscope:** select channel 1, adjust **Vertical scale** and **Horizontal scale** or use **Auto-Scale**
- Select the inbuilt frequency counter using the **Measure** button, then scroll down the menu to the **Counter** button to toggle the counter on. The frequency display will then appear at the top right of the screen.

The display should now look like Figure 2. The horizontal scale (near the top left corner) probably says 50.00 μs/. The vertical scale (in the bottom left corner) probably says 5.00 V/ or 2.00 V/, depending on your signal generator. These are, respectively, the time and voltage per division, where each division refers to the main 1 cm grid on the screen.

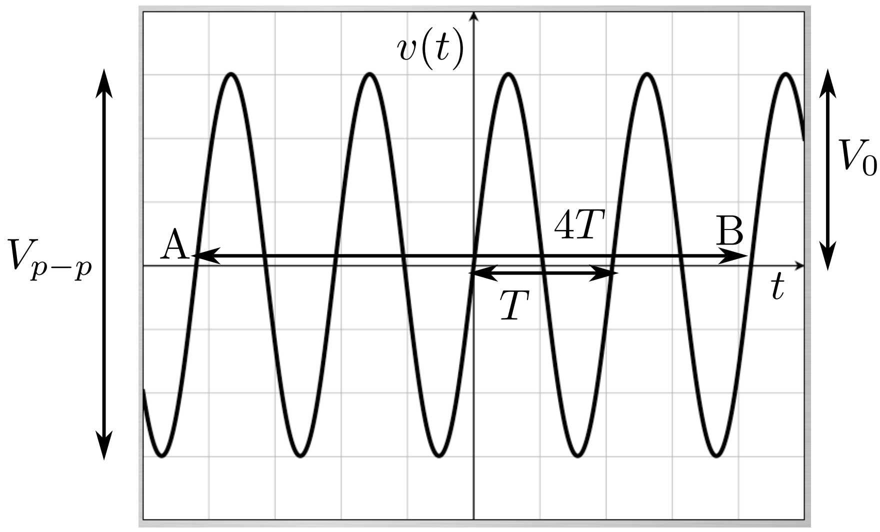


Figure 2: Oscilloscope display.

- Now examine the effect of changing the various settings one at a time.
  On the signal generator, change:
  - sine to square output
  - output voltage using the amplitude or attenuator controls
  - frequency

  On the oscilloscope, change:
  - **vertical scale** and **vertical position**
  - **horizontal scale** and **horizontal position**
- Return to the original settings (10 kHz, maximum output voltage), either by adjusting the vertical and time scales, or using the **Auto-Scale** button. Note that the menu can always be removed from the screen by pressing the **Menu on/off** button.

- Go to section 3.4 of *Using the Digital Storage Oscilloscope* to see how to use the cursors. The cursors can measure either voltage or time intervals. Cursor positions are moved by selecting each one in turn using the soft keys and then rotating the **Entry** knob (between the [**Softkeys**] and the **Horizontal Scale** knob) to adjust their positions.
- Select **Voltage** and place **Cur A** along the crests of the waveform and **Cur B** along the troughs. For the most accurate measurement the vertical scale should be adjusted so that the signal is as large as possible on the screen (see Figure 2).

  Logbook 1.1 Record your value of the peak-to-peak voltage ($\equiv |\Delta Y|$) and make an estimate of its uncertainty.

  In the cursor menu, now select **Time** and estimate the period T of the signal by centring the voltage waveform on the horizontal centre line of the screen (press the **vertical position** knob) and positioning the cursors to measure the time interval $|\Delta X|$ between crossings of this 'zero' centre line 4 periods apart (e.g., as in the interval between points A and B in Figure 2).
  Why do we measure time intervals between zero crossings rather than between peaks or troughs?

  Calculate the frequency using $f = 1/T$. Does this frequency agree (to within about 2%) with the reading on the inbuilt frequency counter.

- Select **Cursors** again to turn the cursor display off.
- Go to section 3.2 of *Using the Digital Storage Oscilloscope* and read section *2. Measurements* to see how to use the **Measure** button. Select **Voltage** and rotate the **Entry** knob to V_{pp} and then press the knob to select this choice. The value of V_{pp} should appear at the bottom of the screen.

  Logbook 1.2 Compare your estimate of peak-to-peak voltage obtained via the cursors with the direct measurement using the **Measure** facility, taking uncertainty into account.
  In future all of your DSO measurements in these experiments will take advantage of the tools within the DSO's **Measure** facility.

Triggering the Oscilloscope

If you are displaying a periodic signal on an oscilloscope you will want to have the plot of voltage against time start at the same place in the cycle every time. In this way the display looks constant, rather than starting at random points in the period and being different for every sweep of the spot across the screen. This is achieved by starting the display at the same *phase* of the periodic signal on each sweep across the screen. The oscilloscope has a means of doing this called the *trigger control*. When the sweep reaches the right end of the display, the spot is turned off and goes back to the left, but does not start again until the trigger sets it off.

The source for the trigger can be *internal*, meaning that it uses the signal from one of the two input channels (CH 1 or CH 2) to decide when to start. The source can also be *external*, meaning that it uses a signal from a special **Ext Trig** input; or it may be from the *AC Line*, meaning that it is synchronised with the 50 Hz frequency of the mains power. The channel used for triggering is set by the Source item in the Trigger **Menu** — the button near the right hand edge of the oscilloscope front panel.

The trigger starts the sweep when the input potential difference (voltage) of the trigger signal goes above a certain level set by the **Trigger Level** knob. You will normally use the automatic setting (usually labelled AUTO and automatically chosen when you choose **Auto-Scale**) that either triggers when there is sufficient voltage to cause a significant vertical deflection of the spot on the screen, or just sweeps continuously (free running) if there is not. Finally, the trigger slope item in the **Trigger Menu** sets whether the trigger operates when the voltage is increasing (+) or decreasing (−).

- Return the oscilloscope to its original settings using **Auto-Scale** or, preferably, using the manual controls.
- Adjust the **Trigger Level** control and watch what happens to the display. Make sure you move the trigger level above and below the maximum and minimum levels of the waveform.

Logbook 1.3 Write down your observations, explaining in your own words how the display changes as you adjust the trigger level.

$\boxed{\blacktriangleright\ \textbf{C1}}$

3 Internal Resistance of a Signal Generator

(About 20 min.)

Set the **vertical scale** to 1 V/div and adjust the signal generator output to produce a 6 V peak-to-peak sinewave at 1 kHz. A direct measurement of V_{pp} can be obtained if you press the **Measure** button, then use the softkeys to select source as 'CH 1' and voltage as 'V_{pp}'.

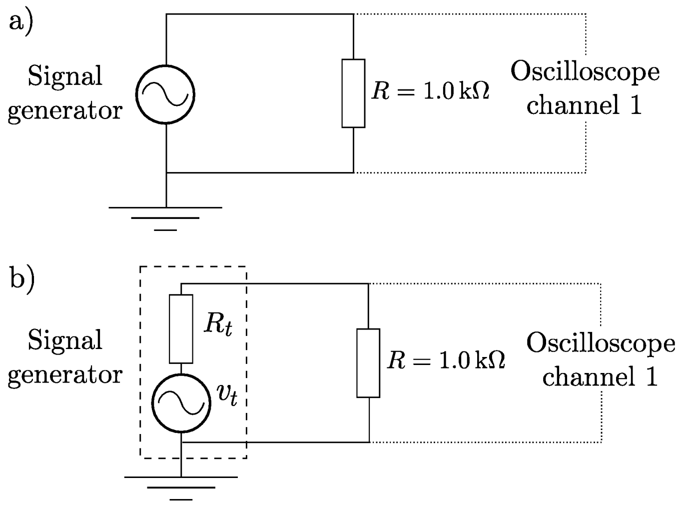


Figure 3: a) Circuit for Logbook 2.1. b) Showing the equivalent circuit of the signal generator.

> **Logbook 2.1** Leaving the oscilloscope connected to the signal generator, now connect a 1 kΩ resistor, R, across the output of the signal generator, creating the circuit in Figure 3(a). Use the multimeter to ensure you have the correct resistor. Record the peak-to-peak voltage. How does this value compare with the 6 V peak-to-peak that you set?

The circuit you have created can be re-drawn as seen in Figure 3(b), where R_t is the internal resistance of the signal generator. This is the effective resistance inside the signal generator seen by any current produced by the generator. All real signal sources will have some internal resistance. The simple circuit inside the dashed line in Figure 3(b) is called the 'Thévenin equivalent' circuit, which behaves in *exactly* the same way as the more complex circuit actually inside the signal generator.

Thévenin's theorem is one of the most useful circuit theorems you will meet in this course. It states that "Any linear network of resistors and signal sources (DC or AC) can be represented by a single voltage source v_t in series with a resistor R_t". In this particular situation, connection of a known resistor across a two-terminal network, i.e., the signal generator, creates a voltage divider and allows you to determine the internal (or Thévenin equivalent) resistance R_t.

The voltage divider in Figure 3(b) consists of R_t and R, with an input voltage v_t (or open-circuit voltage) of 6 V peak-to-peak and an output voltage v_R. With resistance R connected across the output of the signal generator, the voltage divider equation tells us that

$$\frac{v_R}{v_t} = \frac{R}{R + R_t}, \tag{1}$$

or, by rearranging the equation,

$$\frac{v_t}{v_R} = \frac{R_t}{R} + 1, \quad \text{and hence} \quad R_t = R\,(\frac{v_t}{v_R} - 1)\ . \tag{2}$$

Logbook 2.2 Use Eq. (2) to determine R_t and its uncertainty. How does your value compare with the nominal R_t value written on the front of the signal generator? You can assume that the DSO voltage measurements have an uncertainty of 2%.

➢ C2

4 AC Circuits with Resistance

(About 30 min.)

Theory: AC, complex numbers and phasor diagrams

An AC (alternating current) source supplies a sinusoidally varying voltage (potential difference) $v(t)$. A sinusoidally varying voltage might be represented by a function such as

$$v(t) = V_0 \cos \omega t\ . \tag{3}$$

In this representation, we follow the convention that lower case letters indicate instantaneous values and upper case letters with a subscript 0 indicate peak values, i.e., the amplitude of the oscillation.

The current induced by this potential difference can be represented in the same way as

$$i(t) = I_0 \cos \omega t\ . \tag{4}$$

In these expressions, $\omega = 2\pi f$ is the angular frequency of the oscillating voltage, measured in radians/second. In Australia, AC power is distributed to your house with a frequency $f = 50$ Hz, i.e., $\omega \approx 314$ rad.s^{-1}. In the US and some other countries, $f = 60$ Hz.

Recall from MATH1001/1901 (also see the background material in the Learning Goals section of this Manual) that

$$e^{\pm j\theta} = \cos\theta \pm j \sin\theta\ , \tag{5}$$

where $j = \sqrt{-1}$. ***Note: in mathematics, you used*** $i = \sqrt{-1}$***. However, since*** i ***is reserved for the instantaneous current, we use*** j ***instead when dealing with circuits.*** So if we define a *complex voltage,* $\boldsymbol{v}$

$$\boldsymbol{v} = V_0 e^{j\omega t}\ , \tag{6}$$

then the instantaneous voltage is simply the real component of the complex voltage, i.e.,

$$v(t) = \mathrm{Re}[\boldsymbol{v}] = V_0 \cos \omega t\ . \tag{7}$$

Similarly, we can define a *complex current,* $\boldsymbol{i}$

$$\boldsymbol{i} = I_0 e^{j\omega t}\ , \tag{8}$$

then the instantaneous current is simply the real component of the complex current, i.e.,

$$i(t) = \mathrm{Re}[\boldsymbol{i}] = I_0 \cos \omega t \ . \tag{9}$$

Note that the complex voltages (and other complex quantities that you will meet in this lab course) are not real physical quantities! They are mathematical constructs designed to help us describe and analyse physical quantities that vary sinusoidally with time. Complex quantities enable us to combine sinusoidal quantities with phase differences by simple combination of complex numbers.

We can represent complex quantities, such as complex voltages, using an Argand diagram, such as the one shown in Figure 4. In an Argand diagram, the real component is plotted on the x (horizontal) axis and the imaginary component is plotted on the y (vertical) axis. From Figure 4, you can see that the instantaneous voltage v is the horizontal (i.e., real) component of the complex voltage $\boldsymbol{v}$. Argand diagrams of complex quantities associated with electrical components are also known as *phasor diagrams*.

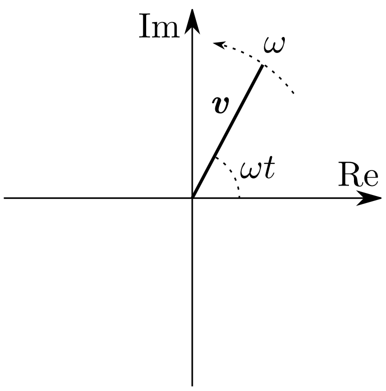


Figure 4: Argand diagram representation of a complex voltage $\boldsymbol{v}$.

At a time t, the complex voltage in Figure 4 is at an angle ωt to the positive real axis. It rotates counter-clockwise with angular speed ω. Note that as the complex voltage $\boldsymbol{v}$ rotates, its modulus $|\boldsymbol{v}|$ (i.e., length) remains constant and is always equal to the amplitude of the oscillating *instantaneous* voltage.

Two quantities (e.g., voltage and current) whose associated complex quantites (e.g., complex voltage and complex current) always have a constant angle ϕ between them are said to have a *phase difference of* ϕ. If $\phi = 0$ (i.e., at any instant, the two complex quantities make the same angle with the positive real axis) then the two quantities are said to be *in phase.*

Experiment

In the following experiments we are going to use an instrument designed *in-house* to measure alternating (AC) current, a type of current probe.

- Connect the circuit in Figure 6 after first checking the resistor value with the multimeter. Connect the signal generator and the resistor first, using the special lead running through the current probe box.

  Then connect the oscilloscope lead to measure the voltage across the resistor. Check the polarity of the connections.

- Set the signal generator to a frequency of 10 kHz and maximum output voltage. Select **Auto-Scale** on the oscilloscope. It should display sinusoidal waveforms on CH 1 (voltage) and CH 2 (current).

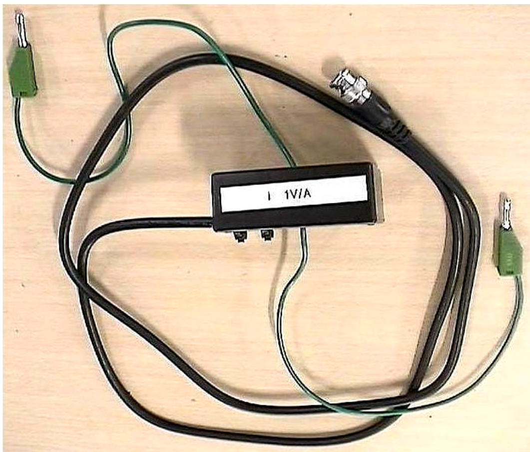


Figure 5: Current probe.

The current probe consists of a transformer in the black plastic box plus a coaxial lead to Channel 2 of the oscilloscope. The calibration factor is 1 V/A, meaning that 1.0 A in the lead passing through the black box generates a voltage of 1.0 V at the oscilloscope, or 2 mA will generate a voltage of 2 mV, etc. ***Be sure to connect the current probe with the correct polarity — the arrow should face away from the active (red) terminal of the signal generator.*** If it is wrong, the waveform on the oscilloscope will be inverted.

- If the signal on CH 2 (current) is noisy you can improve the signal-to-noise by turning on bandwidth limiting (see Section 3.3.2 on page O.10 in this Manual). If the signal is still too noisy for a reliable measurement, please consult a tutor.
- Adjust the signal generator output voltage to 12 V peak-to-peak.

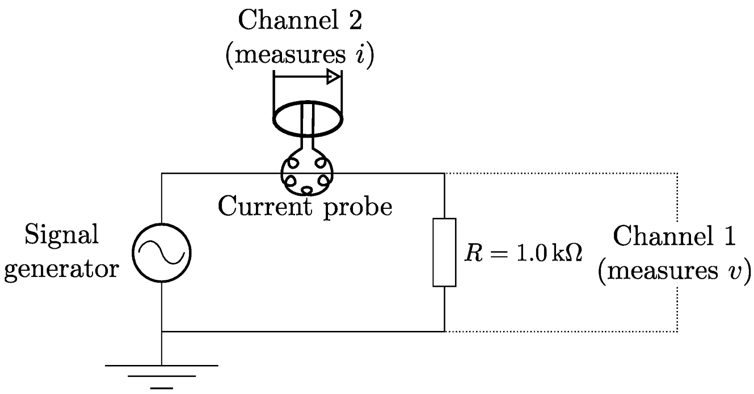


Figure 6: Measuring resistance in an AC circuit.

In this circuit, the instantaneous voltage across the resistor is related to the instantaneous current in the circuit by $v(t) = Ri(t)$, so, using the expression $i(t) = I_0 \cos(\omega t)$ introduced earlier, we have

$$v(t) = i(t)R = I_0 R \cos \omega t \ . \tag{10}$$

The complex current and voltage are also related by Ohm's law, so the complex voltage is

$$\boldsymbol{v} = R\boldsymbol{i} = I_0 R e^{j\omega t} = V_0 e^{j\omega t} \ . \tag{11}$$

These equations tell us three things:

1. The amplitude of the voltage across the resistor is related to the amplitude of the current in the circuit by Ohm's law ($V_0 = I_0 R$).
2. The voltage waveform v and current waveform i are *in phase*, i.e., they are both proportional to $\cos \omega t$. The two functions pass through zero at the same time, reach their maximum values at the same time and reach their minimum values at the same time.

3. The complex voltage $\boldsymbol{v}$ and complex current $\boldsymbol{i}$ are also in phase because they are both proportional to $e^{j\omega t}$.

Logbook 3.1. Measure and record the peak-to-peak voltages on CH 1 and CH 2. Calculate R from $V_{\text{pp}}/I_{\text{pp}}$ and compare it with the value of R you obtained from the multimeter.

Sketch the CH 1 and CH 2 traces on a voltage vs time graph (as on the oscilloscope screen). Does this illustrate the expected phase relationship between them?

In your logbook write a brief summary of the above results and comment on any discrepancies that may have occurred.

5 Conclusion

Logbook 3.2. List the main properties of signal generators and oscilloscopes as illustrated in this experiment.

➢ C3

When you've finished and your work has been marked by a tutor, please remember to turn off all equipment and dismantle your circuit.

ADV 3: Introducing Capacitors and Inductors

1 Introduction

The objective of this experiment is to introduce the concepts of *capacitance* and *inductance* and the related concepts of *reactance* and *impedance* in AC circuits. You will also use an oscilloscope to measure phase differences.

1.1 Learning goals

On the completion of this session you should:

- understand the concept of a capacitor and an inductor,
- understand the concept of reactance for capacitors and inductors,
- understand the concept of impedance and Ohm's law for simple AC circuits,
- be able to measure phase differences on an oscilloscope,
- be able to use complex notation to perform calculations of amplitude and phase with time-varying voltages and currents.

Since this topic may be new to you it is ESSENTIAL that you read these notes before this laboratory session. It is also STRONGLY RECOMMENDED that you read the relevant sections of Young and Freedman, *especially:*

- *31.2 Resistance and Reactance. Note that this is done without introducing complex numbers.*
- *The theory in sections 2 and 3 of this experiment - using complex numbers.*

Have you done your pre-work?

For each week of the Circuits component of the lab course you **must** complete pre-work **before** coming to the lab.

The pre-work is available and is done on the eLearning page for this unit. Your mark for the pre-work is also available via eLearning.

If you have questions about the pre-work, ask your lab tutors or the Duty Tutors.

2 AC Circuits with Capacitance

(About 1 hr)

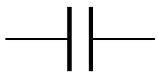


Figure 1: Circuit symbol for a capacitor.

Theory

A capacitor consists of any two conductors separated by an insulator. Capacitors are often constructed from two sheets of aluminium foil separated by a thin sheet of plastic insulation, and rolled up in a small package with two wire leads, one lead connected to each foil. The two sheets of foil are sometimes called plates, since old-fashioned capacitors were made from two parallel metal plates separated by air. Capacitors are widely used in all sorts of electrical circuits.

When a capacitor is connected to a battery, an electric charge $+q$ appears on one plate and $-q$ on the other. The charge q is proportional to the voltage, v, across the capacitor, and is given by

$$q = Cv\,, \tag{1}$$

where C is known as the capacitance and is measured in farads (F). Here you will use a $10\,\mathrm{nF}$ (10 nanofarad or $10^{-8}\,\mathrm{F}$) capacitor.

Current is the rate of flow of charge, so the current in a circuit is given by differentiating the charge with respect to time

$$i = \frac{dq}{dt} = C\frac{d\boldsymbol{v}}{dt}\,. \tag{2}$$

[You may wonder how a current can flow 'through' a capacitor if there is an insulating gap between the plates of the capacitor. Remember that the current is alternating, i.e., changing direction periodically. Thus at each instant a charge flows onto one plate and off the other, and then reverses a short time later.]

Just as with currents and voltages, we can define a *complex charge*, $\boldsymbol{q}$, with

$$\boldsymbol{q} = C\boldsymbol{v}\,, \tag{3}$$

and

$$\boldsymbol{i} = \frac{d\boldsymbol{q}}{dt}\,. \tag{4}$$

If $\boldsymbol{i} = I_0 e^{j\omega t}$, then integration gives

$$\boldsymbol{q} = \frac{I_0}{j\omega}e^{j\omega t}\,. \tag{5}$$

Then, since $\boldsymbol{q} = C\boldsymbol{v}$,

$$\boldsymbol{v} = \frac{I_0}{j\omega C}e^{j\omega t}\,. \tag{6}$$

This can be re-written as

$$\boldsymbol{v} = \frac{1}{j\omega C}\boldsymbol{i} \quad \text{or} \quad \boldsymbol{v} = \frac{-j}{\omega C}\boldsymbol{i} \quad \text{or} \quad \boldsymbol{v} = \frac{1}{\omega C}\boldsymbol{i}e^{-j\frac{\pi}{2}}\,. \tag{7}$$

> **Logbook 1.1** Show how the three results in Eq. (7) are mathematically equivalent to Eq. (6).

There are two important results in these equations:

i) *Amplitude*: the amplitude of the voltage is given by

$$V_0 = |\boldsymbol{v}| = \frac{I_0}{\omega C}\,. \tag{8}$$

ii) *Phase*: the current and voltage waveforms of a capacitor are $\frac{\pi}{2}$ (90°) out of phase, unlike a resistor where current and voltage are in phase. This results from the $e^{-j\frac{\pi}{2}}$ term in Eq. (7) and can be illustrated using the phasor representation on the Argand diagram in Figure 2.

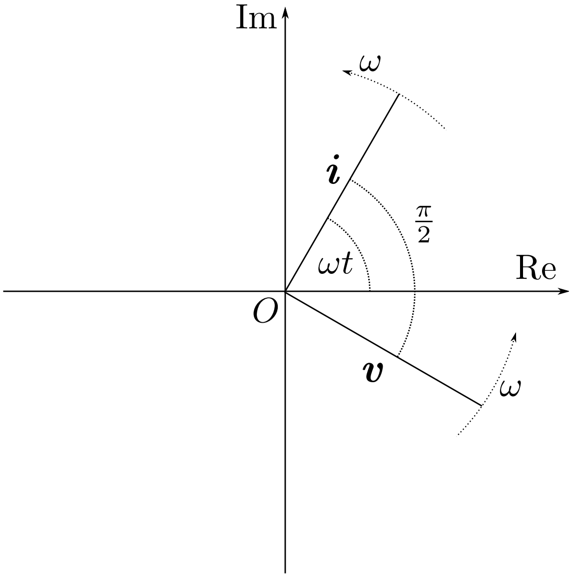


Figure 2: Voltage and current phasors for the capacitor in the circuit in Figure 3.

The diagram shows the complex current $\boldsymbol{i}$ and voltage $\boldsymbol{v}$ at time t with the current phasor at angle ωt to the horizontal axis. *The voltage phasor for a capacitor 'lags' $\frac{\pi}{2}$ behind the current phasor* as both rotate counterclockwise with time.

Remember — the instantaneous values of current and voltage are the real parts of the corresponding complex quantity, i.e., the projection onto the real (horizontal) axis.

Logbook 1.2 Given that i =Re[$\boldsymbol{i}$], show that the current i through a capacitor and the voltage v across a capacitor can be written as

$$i = I_0 \cos \omega t\,, \tag{9}$$

$$v = V_0 \sin \omega t = \frac{I_0}{\omega C} \sin \omega t\,. \tag{10}$$

Explain how this shows a $\frac{\pi}{2}$ (90°) phase difference between i and v.

Impedance and Reactance

The ratio of *real* (measurable) voltage and current, v/i, varies with time. However, the ratio of *complex* voltage and current, $\boldsymbol{v}/\boldsymbol{i}$, does not. For any component in an AC circuit, the ratio $Z = \boldsymbol{v}/\boldsymbol{i}$ is called the **impedance** of the component.

Ohm's law for AC circuits is then

$$\boldsymbol{v} = Z\boldsymbol{i}\,, \tag{11}$$

or, in terms of the real voltage,

$$v = Re[Z\boldsymbol{i}]\,. \tag{12}$$

If the impedance is *real*, then it acts just like resistance in a DC circuit. However, if the impedance is complex, e.g.,

$$Z = Z_0 e^{j\theta}\,, \tag{13}$$

then a phase shift of θ is introduced between the voltage and the current. This distinction between the behaviour of the real and imaginary components of Z leads us to define the real part of Z as the **resistance**, R and the imaginary part of Z as the **reactance**, X, i.e.,

$$Z = R + jX\,, \tag{14}$$

where R and X are both real. Since R, X and Z are all obtained by dividing a voltage by a current, they are measured in ohms.

From Eq. (7), the **impedance of a capacitor** is

$$Z = \frac{\boldsymbol{v}}{\boldsymbol{i}} = \frac{1}{j\omega C} = \frac{-j}{\omega C} = \frac{1}{\omega C} e^{-j\frac{\pi}{2}}\,. \tag{15}$$

Z is purely imaginary, so from Eq. (14), th resistance of an *ideal* capacitor is $R_C = 0$ and the reactance is $X_C = -1/\omega C$. From Eq. (8), the reactance can also be written as $X_C = -V_0/I_0$, the ratio of the amplitudes V_0 and I_0, which is easier to determine experimentally.

Note that **the reactance of a capacitor depends on the frequency** ω.

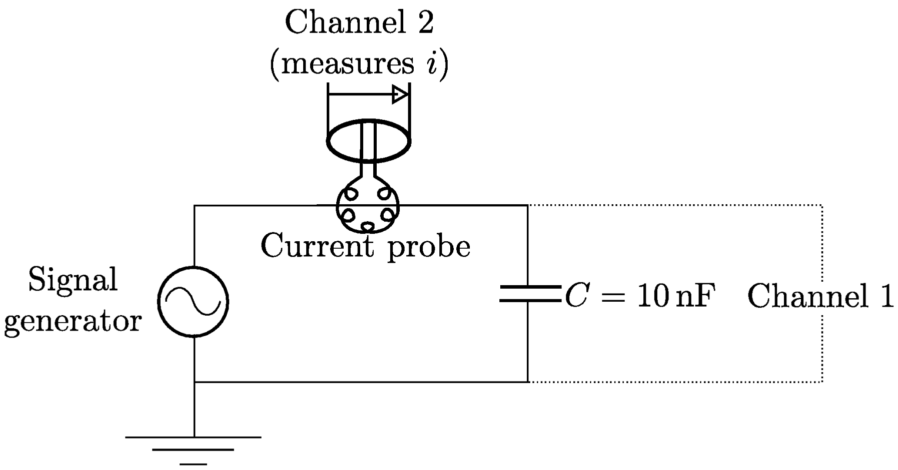


Figure 3: Determining the reactance of a capacitor.

Experiment

- Measure the value of the 10 nF capacitor on the component board with a digital LCR meter (located on a side bench in the lab). These meters allow you to measure directly the values of capacitors, inductors and resistors.
- Set up the circuit shown in Figure 3. Set the signal generator to a frequency of 15 kHz, with the voltage set to maximum. Check that the probe on each channel is set to $\times 1$.
- If the signal on CH 2 (current) is noisy you can improve signal-to-noise by turning on bandwidth limiting (see Section 3.3.2 on page O.10 in this Manual).

Logbook 1.3 Measure and record the peak-to-peak voltages of CH 1 (voltage across the capacitor) and CH 2 (current through the capacitor). The most convenient way is to press the **Measure** button, then use the 'softkeys' to select 'source' as 'CH 1' and 'voltage' as 'V_{pp}'. Repeat this setup for CH 2.

Logbook 1.4 Sketch the two traces in a way that clearly shows the phase relationship between them. Is this what you expect?

Measure and record the magnitude and sense of the phase difference between the two signals. To do this, first push the **vertical position** knobs on CH 1 and CH 2 (labelled 'Push to zero'). Then, using the cursors on the oscilloscope, measure the interval between the upward 'zero-crossings' of the two signals (x in Figure 4), and the interval between successive zero-crossings ($T/2$ or y in Figure4). Convert this to a phase angle using

$$\Delta\phi = \frac{x}{y} \cdot \pi \,\text{radians} = \frac{x}{y} \cdot 180^\circ \,. \tag{16}$$

Why is this better than measuring the time difference between the peaks of the signals?

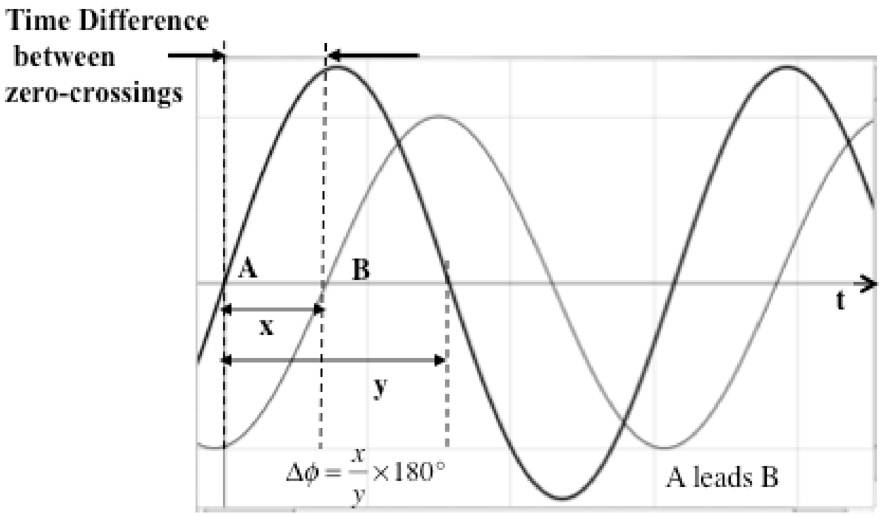


Figure 4: Measuring phase difference using 'zero crossings'.

Logbook 1.5 Repeat your measurement of the phase difference using the softkey functions. To do this, press **Measure** then select 'time', scroll down to the bottom and select 'Phas A→ B ⨍'. You may then need to turn the menu off to see the value.

Record this value. How does it compare with your previous measurement?

Logbook 1.6 Calculate the reactance $X_C = V_0/I_0 = V_{\text{pp}}/I_{\text{pp}}$ at this frequency and use this to estimate the capacitance C, noting that angular frequency and your measured frequency are related by $\omega = 2\pi f$.

Does this agree with your measured value of C? Comment.

How would your results differ if you had used a frequency of 1.5 kHz?

$\boxed{\text{➢ C1}}$

3 AC Circuits with Inductance

(About 45 min.)

Figure 5: Circuit symbol for an inductor.

Theory

An inductor consists of a coil of wire, usually with many turns, sometimes wound on an iron or ferrite core. A current through the inductor generates a magnetic field. If the current changes with time, the magnetic field also changes with time and induces an emf in each turn proportional to the rate of change of the magnetic field. The voltage across the inductor is given by

$$v = L\frac{di}{dt}\,, \tag{17}$$

which also implies that

$$\boldsymbol{v} = L\frac{d\boldsymbol{i}}{dt}\,. \tag{18}$$

The constant of proportionality L is known as the inductance and is measured in henries (H). [The symbol L comes from Heinrich Lenz, of Lenz's Law fame. Why is his name appropriate to describe an inductor?] The equation implies that voltage across an inductor is proportional to the rate of change of the current.

If $\boldsymbol{i} = I_0 e^{j\omega t}$, then differentiating gives

$$\boldsymbol{v} = j\omega L I_0 e^{j\omega t} = j\omega L\boldsymbol{i} = \omega L\boldsymbol{i}e^{j\frac{\pi}{2}}\,. \tag{19}$$

As for the capacitor, there are two important results in these equations:

i) *Amplitude*: the amplitude of the voltage is given by

$$V_0 = \omega L I_0\,. \tag{20}$$

ii) *Phase*: the current and voltage waveforms of an inductor are $\frac{\pi}{2}$ (90°) out of phase, but in the opposite sense to a capacitor. Here, the voltage '*leads*' the current by $\frac{\pi}{2}$. This results from the $e^{j\frac{\pi}{2}}$ term in Eq. (19) and can be illustrated using the phasor representation on the Argand diagram in Figure 6.

As for the capacitor, the ratio v/i varies with time but the impedance $Z = \boldsymbol{v}/\boldsymbol{i}$ does not. From Eq. (19), the **impedance of an inductor** is

$$Z = \frac{\boldsymbol{v}}{\boldsymbol{i}} = j\omega L = \omega L e^{j\frac{\pi}{2}}\,. \tag{21}$$

This is purely imaginary, so from Eq. (14), the resistance of an *ideal* inductor is $R_L = 0$ and the reactance is $X_L = \omega L$. From Eq. (20), the reactance can also be written as $X_L = V_0/I_0$, the ratio of the amplitudes V_0 and I_0, which is easier to determine experimentally.

Note that the sign of the reactance of an inductor is positive while the sign of the reactance of a capacitor was negative. This reflects the fact that in an inductor the voltage 'leads' the current, while in a capacitor the voltage 'lags' the current. The following mnemonic may help you remember these rules:

$\overline{\text{CIV}}$IL Capacitor (C) Current (I) leads Voltage (V)

CI$\overline{\text{VIL}}$ Voltage (V) leads Current (I) in an Inductor (L)

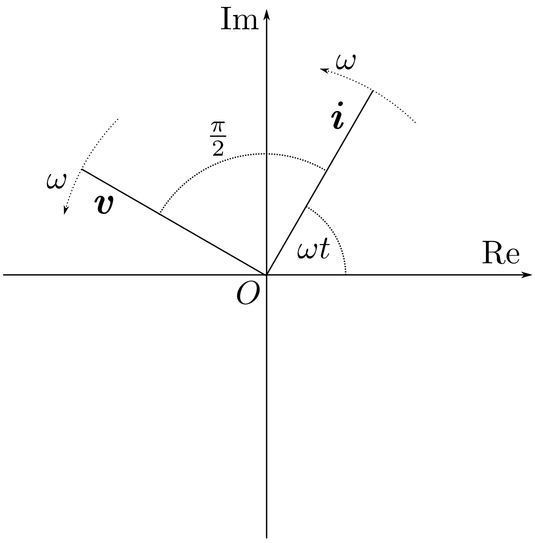


Figure 6: Voltage and current phasors for the **inductor** in the circuit in Figure 7.

The diagram shows the complex current $\boldsymbol{i}$ and voltage $\boldsymbol{v}$ at time t with the current phasor at angle ωt to the horizontal axis. *The voltage phasor 'leads' the current by* $\frac{\pi}{2}$ as both rotate counterclockwise with time.

Remember — the instantaneous values of current and voltage are the real parts of the corresponding complex quantity, i.e., the projection onto the real (horizontal) axis.

Experiment

- Measure the inductance of the inductor on the component board with the LCR meter.
- Set up the circuit shown in Figure 7. Set the signal generator to a frequency of 15 kHz and the output voltage to maximum.

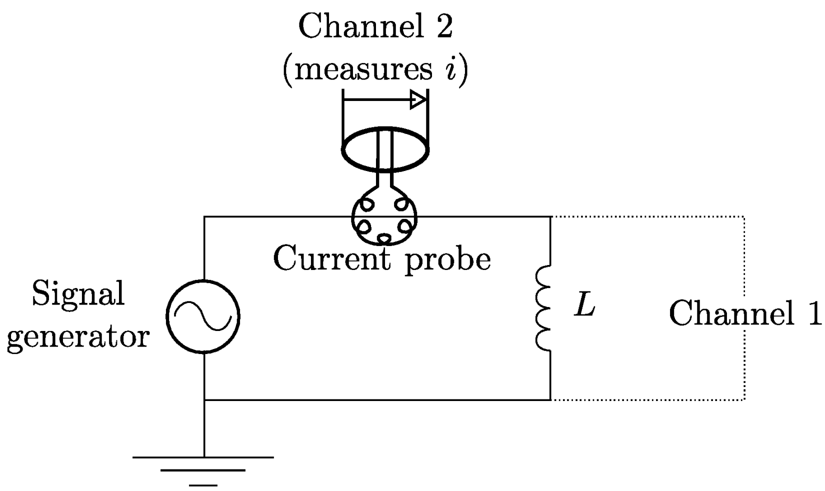


Figure 7: Determining the reactance of an inductor.

Logbook 2.1 Measure and record the peak-to-peak voltages of the two signals. As before, use the 'BW limit' function to reduce the noise on CH 2.

Sketch the two traces in a way that clearly shows the phase relationship between them and record the phase difference. Is this what you expect?

Calculate the reactance X_L at this frequency and use this to estimate the inductance L. Does this agree with your measured value of L? Comment.

How would your results differ if you had used a frequency of 1.5 kHz?

➢ C2

4 Non-ideal Inductors

(About 45 min.)

For ideal inductors, the impedance Z is purely imaginary. However, because a real inductor is essentially a coil of wire, it conducts a DC current with some non-zero resistance R_L. The total impedance of the inductor is therefore

$$Z = R_L + j\omega L\,. \tag{22}$$

The complex voltage for a non-ideal inductor is

$$\boldsymbol{v} = (R_L + j\omega L)\boldsymbol{i}\,, \tag{23}$$

and can be represented in terms of the *resistance* and *reactance* components as in Figure 8.

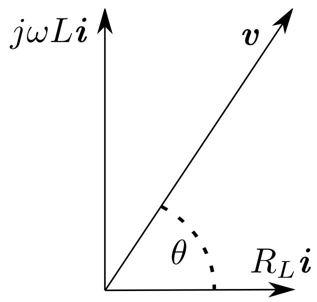


Figure 8: The voltage phasor for an inductor is the complex sum of the *resistance* and *reactance* components. The resistance component ($R_L\boldsymbol{i}$) is *in phase* with the current through the inductor, while the reactance component ($j\omega L\boldsymbol{i}$) is *out of phase* by $\frac{\pi}{2}$ with the current through the inductor. The modulus of the resistance component is *constant* but the modulus of the reactance component *increases with frequency* ω.

Logbook 3.1 What is the limiting phase difference (i.e., θ) between the voltage across an inductor and the current through an inductor when
(a) $\omega = 0$ and (b) $\omega \to \infty$?

- Measure and record the DC resistance, R_L, of the inductor with the digital LCR meter. Set up the circuit shown in Figure 7 again. Set the signal generator to a frequency of 15 kHz and a peak-to-peak voltage of 10 V.

Logbook 3.2 Measure the phase difference between v and i.

Change the frequency to 200 Hz and re-measure the phase difference between v and i.

Using $\tan\theta = \omega L/R_L$, calculate the expected phase differences from your measured values of L, R_L and ω and comment on how your measured phase differences compare with the calculated values.

5 Conclusion

Logbook 3.3 Summarise the properties of capacitors and inductors found in this experiment, differentiating clearly between their values of R, X and Z.

➢ C3

When you've finished and your work has been marked by a tutor, please remember to turn off all equipment and dismantle your circuit.

ADV 4: High and Low-Pass Filters

1 Introduction

The objective of this second AC circuits experiment is to study the response of more complex circuits involving resistors and capacitors. These have important practical applications as simple filters.

1.1 Learning goals

On the completion of this session you should:

- be able to construct a simple RC circuit and measure voltages at various points in the circuit using an oscilloscope,
- be able to measure the frequency response of the circuit using an oscilloscope,
- understand the concept of impedance in simple circuits,
- understand the concept of high- and low-pass filters as examples of AC voltage dividers,
- use high- and low-pass filters.

Since this topic may be new to you it is ESSENTIAL that you read these notes before this laboratory session. It is also STRONGLY RECOMMENDED that you read the relevant sections of Young and Freedman, *especially:*

- *Review 31.1 Phasors and Alternating Current, 31.2 Resistance and Reactance,*
- *Review the theory in sections 2 and 3 of the previous experiment,*
- *Review the section on the Decibel Scale in 16.3 Sound Intensity.*

Have you done your pre-work?

For each week of the Circuits component of the lab course you **must** complete pre-work **before** coming to the lab.

The pre-work is available and is done on the eLearning page for this unit. Your mark for the pre-work is available via eLearning.

If you have questions about the pre-work, ask your lab tutors or the Duty Tutors.

2 AC Voltage Dividers

Circuits such as the low-pass and high-pass filters in this experiment can be considered as simple voltage dividers. In Experiment 1, we looked at a voltage divider consisting of two resistors. For the circuits in this experiment the voltage divider consists of a capacitor and a resistor. While the analysis is the same as for the resistive voltage divider, we now have one component (the capacitor) with a complex impedance $Z_C = 1/j\omega C$. The other component, the resistor, has a real impedance $Z_R = R$. Figure 1 shows the general circuit of an AC Voltage Divider.

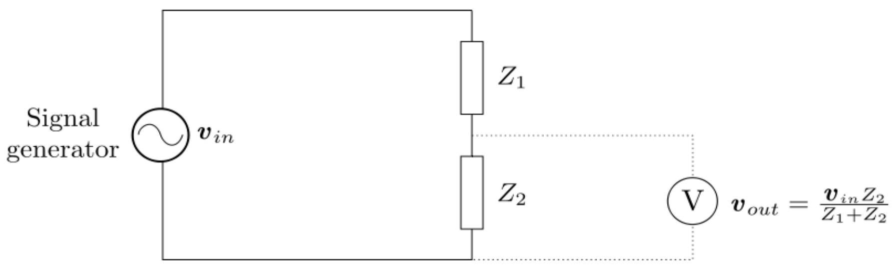


Figure 1: An AC Voltage Divider.

Case 1: Z_1 is a Capacitor and Z_2 is a Resistor

$$v_{out} = v_R = v_{in}\, Z_2/(Z_1 + Z_2) = v_{in}\, R/(R + 1/j\omega C)$$

$$|v_R/v_{in}| = \left| \frac{R}{R + 1/j\omega C} \right| = \frac{1}{\sqrt{1 + \frac{1}{\omega^2 R^2 C^2}}} \tag{1}$$

Case 2: Z_1 is a Resistor and Z_2 is a Capacitor

$$v_{out} = v_C = v_{in}\, Z_2/(Z_1 + Z_2) = v_{in}\, (1/j\omega C)/(R + 1/j\omega C)$$

$$|v_C/v_{in}| = \left| \frac{1/j\omega C}{R + 1/j\omega C} \right| = \frac{1}{\sqrt{1 + \omega^2 R^2 C^2}} \tag{2}$$

From Eq. (1) and (2) it is clear that the output depends on the value of ωRC, where $\omega = 2\pi f$. The frequency responses are shown schematically in Figures 2 and 3.

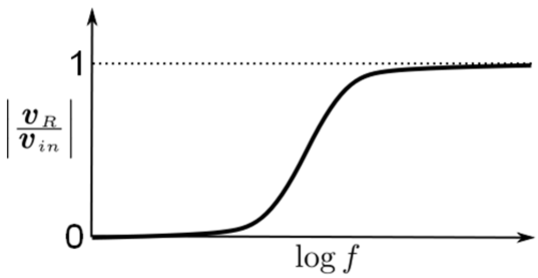


Figure 2: High-pass filter response. Output is close to the input voltage at high frequencies, but is attenuated at low frequencies.

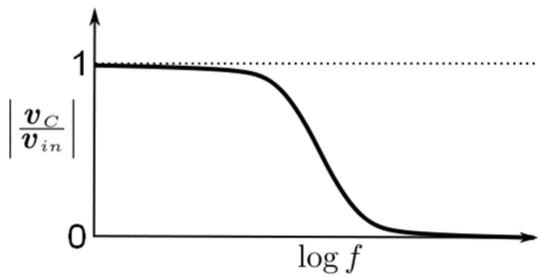


Figure 3: Low-pass filter response. Output is close to the input voltage at low frequencies, but is attenuated at high frequencies.

3 RC Low-pass Filter

(about 1 hr)

In this section we study a low-pass filter (Case 2 in the last section on AC Voltage Dividers).

> **Logbook 1.1** Before you construct the circuit, use the LCR meter on the side bench to measure an accurate value of R for the $10\,\mathrm{k\Omega}$ resistor and C for the $10\,\mathrm{nF}$ ($\equiv 0.01\,\mu\mathrm{F}$) capacitor on your component board. Record the values of R and C.

- Connect up the circuit in Figure 4. Check that both channels are set to $\times 1$, and set the signal generator to a peak-to-peak voltage of $\sim 10\,\mathrm{V}$.
- You will be measuring voltages v_1 and v_2 using CH 1 and CH 2 of the oscilloscope.
  - v_1 is the 'input' signal, the oscillating voltage supplied by the signal generator.
  - v_2 is the 'output' signal, the oscillating voltage across the **capacitor**.

As in previous experiments, the oscilloscope measures voltages with respect to the earth point at the oscilloscope. Therefore we cannot directly measure the voltage across the resistor, v_R, because to do so would require connecting the earth point to the resistor to act as a reference point, which would "short circuit" the rest of the circuit.

- For a range of frequencies, from $100\,\mathrm{Hz}$ to $50\,\mathrm{kHz}$, measure the voltages v_1 and v_2. Do not assume that v_1 will be constant.
- Press **Measure** then go to the bottom of the menu and set 'Counter' to 'ON' to also display the frequency.
- These measurements can be made very quickly by using the V_pp measurement function of the oscilloscope, as described in the last experiment. You will need to adjust the **vertical scale** for v_2 as you vary the frequency.
- Think carefully about how to space your measurements in frequency. Since you will eventually be plotting them on a log scale, you need to choose intervals that will be approximately equally-spaced in $\log f$, e.g., 100, 200, 500, 1000, 2000, ...

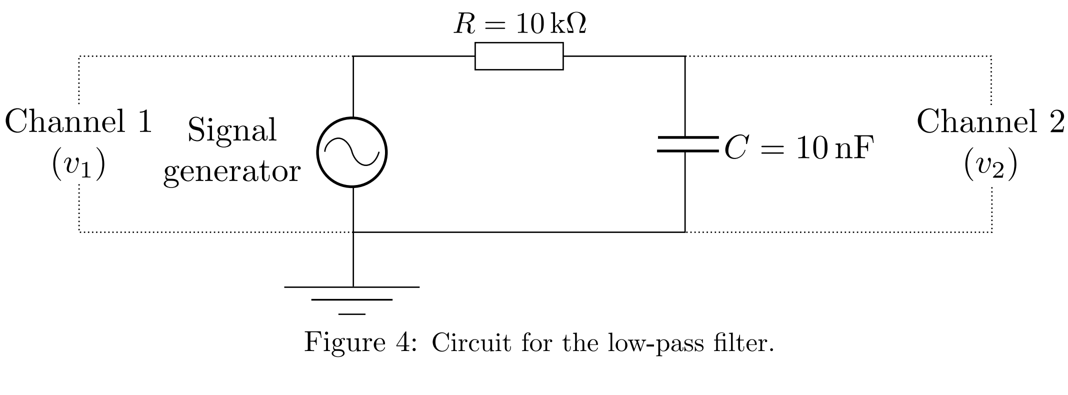


Figure 4: Circuit for the low-pass filter.

> **Logbook 1.2** Record the peak-to-peak voltages v_1 and v_2 at your chosen frequencies in an Excel table.

Since we will use the ratio of these voltages, this is equivalent to measuring amplitudes and forming the ratio V_2/V_1.

Plot V_2/V_1 versus f in Excel. Do this first on a linear scale and then use 'Format axis' to select 'Logarithmic axis' for frequency. Set a minimum value of 0.1 (kHz) on the frequency axis, and add minor gridlines and axis labels. Print the spreadsheet and plot for your logbook.

Consider what your graph should look like. First, note that the same current i flows through R and C. Second, at low frequencies, the reactance of the capacitor $X_C = \frac{1}{\omega C}$ is much greater than the resistance R of the resistor. This means that the amplitude of the voltage across the capacitor will be much greater than the amplitude of the voltage across the resistor (recall the concept of voltage dividers from page 1.5).
On the other hand, at high frequencies X_C is much less than R so the amplitude of the voltage across the capacitor will be much smaller.
Therefore, V_2 will be close to V_1 at low frequencies but V_2/V_1 will be $\ll 1$ at high frequencies. So if we regard v_1 as the input and v_2 as the output, we have a circuit that readily passes low frequencies but severely attenuates high frequencies. The circuit is known as a *low-pass filter*.

Logbook 1.3 Calculate X_C at 100 Hz and 50 kHz. Remember that angular frequency and your measured frequency are related by $\omega = 2\pi f$. Do your results show the behaviour you expected?

In your logbook write a brief summary, explaining what you understand by the term low-pass filter.

➤ C1

4 RC High-pass Filter

(about 30 min)

In this section we study a high-pass filter (Case 1 in the section on AC Voltage Dividers).

- Connect up the circuit in Figure 5 with the signal generator set to a peak-to-peak voltage of 10 V.
- Note that, compared with Figure 4, the resistor and the capacitor have changed positions relative to the signal generator and the 'common' earth point at the oscilloscope. This does not change the potential difference across the individual components but it now allows us to measure the voltage v_R versus frequency.
- So for these measurements:
  - v_1 is the 'input' signal, the oscillating voltage supplied by the signal generator,
  - v_2 is the 'output' signal, the oscillating voltage v_R across the *resistor*.
- Measure the voltages v_1 and v_2 over the same range of range of frequencies as in **Logbook 1.2**.

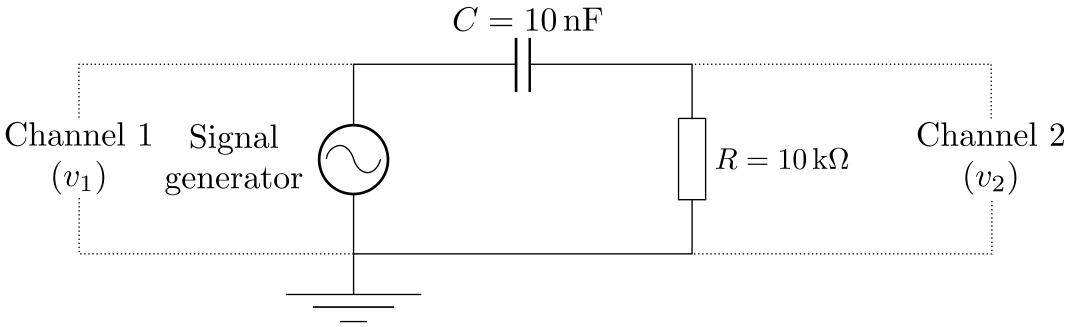


Figure 5: Circuit for the high-pass filter.

Logbook 2.1 Record the peak-to-peak voltages v_1 and v_2 at your chosen frequencies in the same Excel spreadsheet you used for the low-pass filter.

Plot v_C/v_1 and v_R/v_1 together versus f. As before, do this first on a linear scale and then use 'Format axis' to select 'Logarithmic axis' for frequency. Set a minimum value of 0.1 (kHz) on the frequency axis, and add minor gridlines and axis labels. Print the spreadsheet and plot for your logbook.

Logbook 2.2 Use an argument similar to the one used earlier to show that V_2 will be close to V_1 at high frequencies but will be very small at low frequencies. If we regard v_1 as the input and v_2 as the output, we now have a circuit that readily passes high frequencies but severely attenuates low frequencies, i.e., a *high-pass filter*. Do your results show this behaviour?

➢ C2

5 Corner frequency

(about 30 min)

Logbook 3.1 The aim is to determine as accurately as possible the frequency, f_0, where the two curves cross, i.e., the frequency where

$$(V_2/V_1 \text{ for the capacitor}) = (V_2/V_1 \text{ for the resistor})\,. \tag{3}$$

This is best done by returning the frequency axis to linear and restricting the frequency range to 1–2 kHz and the vertical scale to 0.5–0.9. The addition of finer grid steps will also help in estimating the coordinates (and uncertainties) for the crossover point. Record your crossover-point estimates for V_2/V_1 and f_0.

This crossing point occurs at the *corner frequency* or *-3 dB point* of the RC filters. Decibels, or dB, are units used to measure power or intensity ratios. The ratio of two voltage amplitudes, V_1 and V_2 in dB is given by

$$20\log_{10}\left|\frac{V_2}{V_1}\right|\,. \tag{4}$$

So if $V_2 = V_1/\sqrt{2}$, then the ratio in dB is $20\log_{10}(0.707) \approx -3\,\mathrm{dB}$.

[Note that when dB are used to measure *power* ratios, the formula becomes $10\log_{10}(P_1/P_2)$. The different formulae arise because $P \propto v^2$.]

We can work out the corner frequency using complex voltages *(which are vector quantities!)*. The current $\boldsymbol{i}$ through the capacitor and resistor are equal at any point in time, so, using equations from previous experiments, the complex voltage across the *resistor* is

$$\boldsymbol{v}_{\mathrm{R}} = I_0 R e^{j\omega t}\,, \tag{5}$$

and the complex voltage across the *capacitor* is

$$\boldsymbol{v}_{\mathrm{C}} = \frac{I_0}{\omega C} e^{j(\omega t - \frac{\pi}{2})}\,. \tag{6}$$

From Kirchhoff's loop theorem, the sum of voltage drops around a circuit is zero. In this case, this means that the voltage across the capacitor and resistor in series is related to the input voltage v_{in} by

$$\boldsymbol{v}_{\mathrm{in}} = \boldsymbol{v}_{\mathrm{R}} + \boldsymbol{v}_{\mathrm{C}}\,. \tag{7}$$

Remember that this is a vector equation. It can be represented as phasors as shown in Figure 6, where $\boldsymbol{v}_{\mathrm{R}} = R\boldsymbol{i}$ and $\boldsymbol{v}_{\mathrm{C}} = -j(\frac{1}{\omega C})\boldsymbol{i}$.

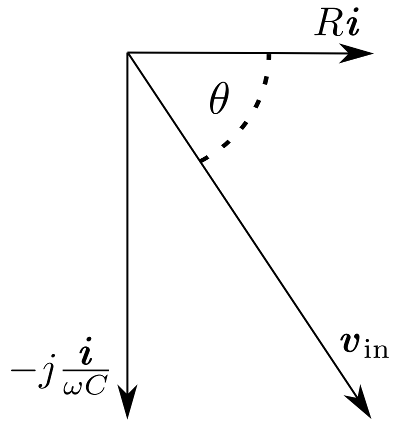


Figure 6: Phasor representation of the RC filter circuit at an arbitrary frequency.

> **Logbook 3.2** By referring to the phasor diagram of Figure 6, derive an expression for the frequency f_0 at which $|\boldsymbol{v}_{\mathrm{C}}| = |\boldsymbol{v}_{\mathrm{R}}|$.
>
> Explain why the phase difference between $\boldsymbol{v}_{\mathrm{R}}$ and $\boldsymbol{v}_{\mathrm{in}}$ at this frequency is 45°.
>
> What is the ratio of $V_{\mathrm{R}}/V_{\mathrm{in}}$ at this frequency?
>
> Comment on how well these calculated values of corner frequency and $V_{\mathrm{R}}/V_{\mathrm{in}}$ compare with the values estimated from your graph.

The oscilloscope provides an easy way to measure these values using the fact that the phase difference between $\boldsymbol{v}_{\mathrm{R}}$ and $\boldsymbol{v}_{\mathrm{in}}$ at the corner frequency is 45°.

- Connect up the circuit in Figure 5 again. Set the signal generator to a peak-to-peak voltage of 10 V.
- Use the **Vertical scale** controls to get suitably scaled displays of v_1 and v_2 on the oscilloscope screen.

- Press **Measure** then select 'time', scroll down to the bottom and select 'Phas A→ B ⨍' to display the phase difference between CH 1 and CH 2 (i.e., v_1 and v_2).
- Slowly adjust the frequency of the signal generator about your calculated f_0 until the phase difference is 45°. You should do this a few times to estimate the uncertainty in your measured value of f_0. The best accuracy is obtained by adjusting the **Vertical Scale** and **Vertical Position** controls for CH 1 and CH 2 to maximise the amplitude of both waveforms on the screen.

Logbook 3.3 When the phase difference is 45°, what is the ratio V_2/V_1 (i.e., $V_{\mathrm{R}}/V_{\mathrm{in}}$) determined from the individual values on the oscilloscope screen?

Comment on how well these measured values of corner frequency and $V_{\mathrm{R}}/V_{\mathrm{in}}$ compare with your calculated values.

6 Conclusion

Logbook 3.4 List the main properties of low-pass and high-pass RC filters that you have seen in this experiment.

➢ C3

When you've finished and your work has been marked by a tutor, please remember to turn off all equipment and dismantle your circuit.

We are all in the gutter, but some of us are looking at the stars. — Oscar Wilde

ADV 5: Resonance

1 Introduction

The objective of this final AC circuits experiment is to study the response of circuits involving resistors, capacitors and inductors. These have important practical applications as resonant circuits.

1.1 Learning goals

On the completion of this session you should:

- understand the concept of resonance as it occurs in simple LCR circuits,
- be able to measure the frequency response of a resonant circuit using an oscilloscope,
- understand concepts related to resonance such as bandwidth and Q-factor.

Since this topic may be new to you it is ESSENTIAL that you read these notes before this laboratory session. It is also STRONGLY RECOMMENDED that you read the relevant sections of Young and Freedman, *especially:*

- *31.5 Resonance in Alternating Current Circuits,*
- *31.3 The L-R-C Series Circuit - note that this is not the same as the parallel circuit used in this experiment.*

  and also resonance in other situations:

- *13.8 Forced Oscillations and Resonance,*
- *16.5 Resonance and Sound.*

Have you done your pre-work?

For each week of the Circuits component of the lab course you **must** complete pre-work **before** coming to the lab.

The pre-work is available and is done on the eLearning/Blackboard page for this unit. Your mark for the pre-work is also available on eLearning.

If you have questions about the pre-work, ask your lab tutors or the Duty Tutors.

2 Theory

Resonance is the tendency of a system to oscillate at maximum amplitude when excited at its natural frequency. ***Electrical resonance*** occurs when the impedance of part of the circuit reaches a maximum or minimum at a particular frequency. This is called the ***resonant frequency*** and its value depends on the circuit elements involved.

This experiment uses an inductor and a capacitor in parallel, connected in series with a resistor (see Figure 1). This is a slightly more complicated version of a **voltage divider** seen in the earlier experiments. In this situation, one of the components of the voltage divider is the parallel combination of a capacitor and inductor, with the combination having an impedance varying with frequency. With this arrangement some of the current i flows in the capacitor and some in the inductor. At low frequencies, the inductor carries most of the current because its impedance $Z_{\mathrm{L}} = j\omega L$ is low. At high frequencies, the capacitor carries most of the current because its impedance $Z_{\mathrm{C}} = 1/j\omega C$, is low.

At some point in between, when $|Z_{\mathrm{L}}| = |Z_{\mathrm{C}}|$, you might expect that the inductor and the capacitor would each carry half the current. However, this is not the case because we're now dealing with vector quantities. For this condition we in fact have resonance, as shown below.

The condition $|Z_{\mathrm{L}}| = |Z_{\mathrm{C}}|$ can be written

$$\omega L = \frac{1}{\omega C} \quad \text{or} \quad \omega_0 = \frac{1}{\sqrt{LC}} \quad \text{and} \quad f_0 = \frac{1}{2\pi\sqrt{LC}} \tag{1}$$

Assuming that the capacitor and inductor are both ideal, we can calculate the total impedance Z_{T} of the capacitor and inductor in **parallel** when $|Z_{\mathrm{L}}| = |Z_{\mathrm{C}}|$.

Impedances are combined just like resistances so we have:

$$\begin{aligned} 1/Z_T &= 1/Z_C + 1/Z_L \\ &= 1/(1/j\omega C) + 1/j\omega L \\ &= j\omega C + 1/j\omega L. \end{aligned}$$

For $|Z_{\mathrm{L}}| = |Z_{\mathrm{C}}|$ we have $\omega\, L = 1/\omega\, C$ and so

$$\begin{aligned} 1/Z_T &= j\omega C + (1/j)\omega C \\ &= j\omega C - j\omega C \\ &= 0. \end{aligned}$$

This means that Z_T is (theoretically) infinite.

> **Logbook 1.1** Using Ohm's law for AC circuits, what is the total current going through the capacitor and inductor when $|Z_{\mathrm{L}}| = |Z_{\mathrm{C}}|$?
>
> What is the magnitude of the current through the capacitor and inductor individually?
>
> How is the direction of the current through the inductor related to the direction of the current through the capacitor?

Resonance of a circuit involving capacitors and inductors occurs because, at certain times, the collapsing magnetic field of the inductor generates a voltage, $v = Ldi/dt$, that charges the capacitor. A little later, the discharging capacitor provides an electric current, $i = Cdv/dt$, that builds the magnetic field in the inductor. The process is repeated continually as the circuit oscillates. In effect there is (ideally) an AC current in the inductor-capacitor loop with no current required from the signal generator.

Real inductors have some resistance R_L (as discussed in section 4 of Experiment 3) so the combined reactance at resonance is large, but not infinite. In practice, at resonance a small current is required from the signal generator to maintain the current in the inductor-capacitor loop, otherwise it would die away as energy is dissipated in the inductor's resistance.

3 Experiment

Logbook 1.2 Choose the (nominal) 10 nF capacitor, the inductor (which has an inductance $\approx 10\,\text{mH}$), and the $10\,\text{k}\Omega$ resistor. Measure L, C, R and R_L using the LCR meter on the side bench and record these values in your logbook. (Note that these values are typically accurate to within 2%.)

Calculate the resonant frequency f_0 (not the angular frequency ω_0).

- Connect up the circuit in Figure 1. Set the signal generator (v_1) to $\sim$10 V peak-to-peak.
- Use the built-in counter in the oscilloscope to measure the frequency of the signal generator. To do this, press **Measure** and use the menu buttons to set 'Counter' to 'ON', then 'time' and 'Phas A→ B $\not f$' to record the phase difference between v_1 and v_2.

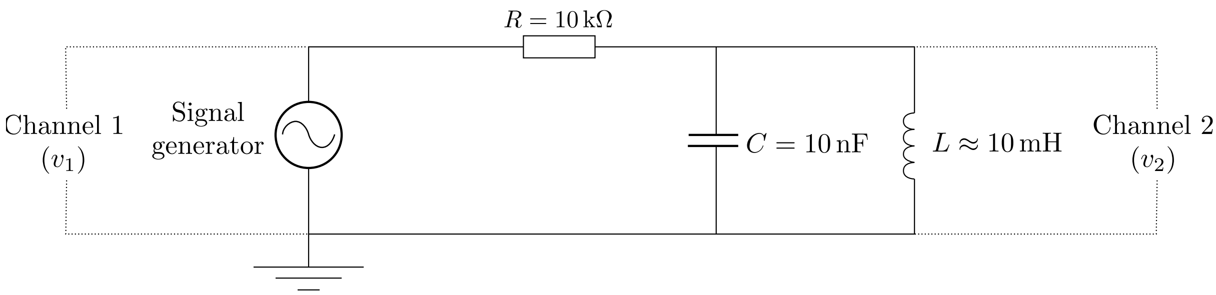


Figure 1: Circuit for the resonance experiment.

- You will be measuring voltages v_1 and v_2 using CH 1 and CH 2 of the oscilloscope.
  - v_1 is the 'input' signal supplied by the signal generator.
  - v_2 is the 'output' signal across the ***parallel combination of the capacitor and inductor***.
- Scan through the frequency range from 1 kHz to 50 kHz, looking for any significant features in the behaviour of v_1 and v_2. In particular, a resonant peak in v_2 should be apparent at a frequency close to your calculated f_0.

Logbook 1.3 Record the frequency f_0 at which resonance occurs and compare with your theoretical estimate.

At this frequency, v_1 and v_2 will be *in phase*. What does this tell you? [*Hint: recall what you found in Experiment 2, Logbook 3.1, when comparing the phase relationship between voltage and current for a resistor.*]

Record the peak-to-peak voltages of v_1 and v_2 against frequency in an Excel table spanning the range $f_0 \pm 2.5\,\text{kHz}$ in steps of $0.5\,\text{kHz}$. Be sure to adjust the vertical scale to keep v_2 as large as possible on the screen.

Logbook 1.4 Plot v_2/v_1 versus frequency. [If v_1 is constant over the range $f_0 \pm 2.5$ kHz, you can plot v_2 versus frequency instead.]

Check that your graph shows a clear peak at f_0 and a symmetric decline on either side. Remeasure any anomalous points.

➢ C1

4 Measurement of Q

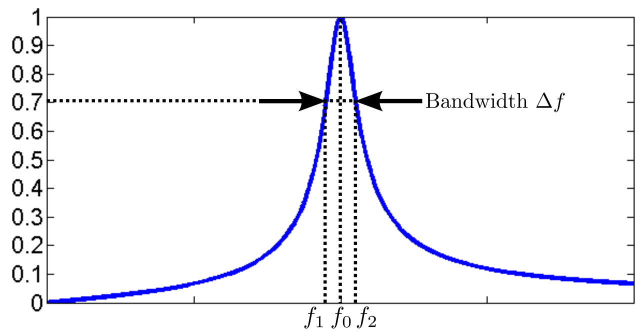


Figure 2: A resonance curve for the parallel LC circuit, showing how bandwidth is defined.

A general resonant peak (from many different physical situations) might look like the one illustrated in Figure 2. The frequencies f_1 and f_2, at which the signal has dropped to $1/\sqrt{2} = 0.707$ of its maximum value, are called the $-3\,\text{dB}$ points (remember a similar terminology for the high and low-pass filters). The bandwidth Δf is defined as the difference in frequency between these points and is given by

$$\Delta f = f_2 - f_1 = \frac{f_0}{Q}\,, \tag{2}$$

where Q is known as the Quality Factor, or simply the Q of the circuit.

Q is a measure of the 'sharpness' of the resonance. If Q is large, the peak is sharp and the bandwidth is small. An LCR resonant circuit acts as an energy reservoir, storing energy in the magnetic field of the inductor and the electric field of the capacitor, and dissipating it in any resistance in the circuit. Q measures the ratio of energy stored to energy lost per cycle.

For the circuit shown in Figure 1, assuming L and C are ideal, the Q is given theoretically by the equation

$$Q = \omega_0 CR = R\sqrt{\frac{C}{L}}. \tag{3}$$

Logbook 2.1 From your resonance graph, estimate the bandwidth, Δf. You may find it helpful to add a (constant) line to your graph at the -3 dB level, and add minor gridlines in frequency. Hence use Eq. (2) to determine the Q of your resonant circuit, along with an estimate of the uncertainty.

Logbook 2.2 Now make use of the fact that the phase shift between v_1 and v_2 is $\pm 45°$ at the -3 dB points to redetermine f_1 and f_2.

Use your estimates of f_1 and f_2 (the -3dB points) and Eq. (2) to obtain an independent estimate of Q and its uncertainty.

Compare your two experimental estimates of Q with the theoretical value from Eq. (3) and comment.

➤ **C2**

5 Non-ideal Inductor

So far in this experiment, we have assumed that the inductor is an ideal component. However, as an inductor is essentially a coil of wire it will have some resistance, R_L, as we saw in Experiment 3. Moreover, you will have found that your experimental and theoretical values of Q did not agree in Logbook 2.2. In this section, we will investigate the effect that the inductor's resistance has on the circuit in Figure 1.

To account for the non-ideal inductor, we take advantage of the fact that v_1 and v_2 are in phase at resonance, i.e., $\Delta\phi = 0$, so the circuit is purely resistive. This means that at f_0 we can use **Thévenin's Theorem** (see Experiment 2, section 3) to replace the complex circuit in Figure 1 by a single voltage source, v_t, and series resistance R_t, where $v_t = v_2$ at resonance. As in Experiment 2, we then connect a known resistor R across the two-terminal network, which creates a voltage divider (as shown in Figure 3) and allows us to determine the Thévenin equivalent resistance, R_t. It is *this* resistance, R_t, that we should use to calculate the theoretical Q via Eq. (3).

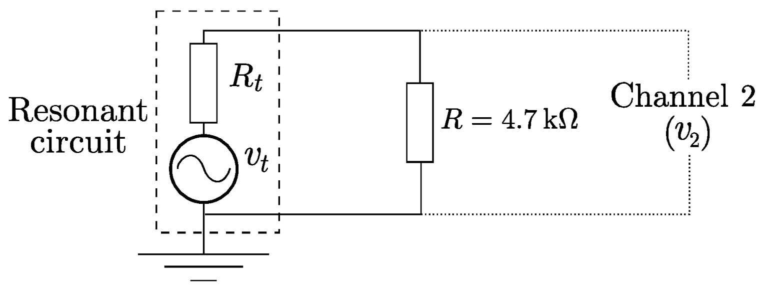


Figure 3: Circuit for Logbook 3.2, showing the equivalent circuit of Figure 1 at resonance.

Logbook 3.1 To emphasise the simplification afforded by adopting the Thévenin equivalent, draw the full circuit of Figure 1, including the series resistance of the inductor. Remember, however, that this simplification applies only at resonance.

Logbook 3.2 Ensure that the LCR circuit is at resonance, i.e., $\Delta\phi = 0$, and record voltage $v_2 = v_t$. Now connect a $4.7\,\mathrm{k}\Omega$ resistance R across the resonant circuit, as shown in Figure 3, and record the new value, v_R, of v_2.

By creating a voltage divider we can now determine the value of R_t, as you did previously in Experiment 2 to measure the internal (Thévenin) resistance of the signal generator.

Using Eq. (2) from Experiment 2, determine the value of R_t and its uncertainty.

Logbook 3.3 Use R_t and Eq. (3) to determine the theoretical Q of the resonant circuit, and compare this with your experimentally measured values from Logbook 2.2.

6 Conclusion

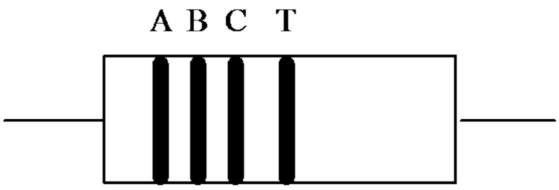
Logbook 3.4 List the main properties of an LCR resonant circuit that you have learnt in this experiment.

➤ C3

When you've finished and your work has been marked by a tutor, please remember to turn off all equipment and dismantle your circuit.

RESISTOR COLOUR CODE

Orient the resistor so that the band nearest the end is on your left. Then read the bands from left to right according to the following scheme.



A: first significant figure

B: second significant figure

C: power of 10 (number of zeros)

T: percentage tolerance

The resistance can be read as

$$R = (10\text{A} + \text{B}) \times 10^{\text{C}}\ \Omega \pm \text{T}\ \%$$

where the colours have the following significance.

Colour code for bands A, B, C

black:	0	green:	5
brown:	1	blue:	6
red:	2	violet:	7
orange:	3	grey:	8
yellow:	4	white:	9

Other colours for band C only

gold:	-1	silver:	-2

Code for T

no colour:	±20%
silver:	±10%
gold:	±5%

Closer tolerances are marked in figures.

Examples

1.

yellow	violet	orange	silver
4	7	10^3	10%

means $47 \times 10^3\ \Omega$ or 47 kΩ ± 10% (or ± 5kΩ).

2.

green	blue	black	no colour
5	6	10^0	

means 56 Ω ± 20% (or about ± 10 Ω).

3.

orange	white	gold	silver
3	9	10^{-1}	10%

means 3.9 Ω ± 10%.

LABORATORY PROJECTS

PHYS 1003 TEC
PHYS 1004 ENV
PHYS 1902 ADV

1 Junior Physics Laboratory Projects

So far all the experiments you have been performing in the laboratory have been carefully designed and provided with an aim, procedure, background theory and necessary equipment. This type of experimentation has served well to introduce you to various skills that are essential for carrying out a scientific investigation. By now you should be familiar with a diverse range of instruments and measuring techniques, have a good understanding of the relevance of uncertainties and how to estimate them, and have acquired some knowledge of computers and their use in analysing experimental data. All these skills will be called upon as part of your work in this final Module. During the last four weeks of lab you will be asked to conduct an investigation on a topic that interests you, and report on the results you find.

1.1 Objectives

This Project Module is designed to provide you with the opportunity to:

- Undertake independent research and encourage natural curiosity.
- Design and carry out a simple scientific investigation.
- Work effectively in a team.
- Improve your general experimental skills, including careful measurement, analysis of experimental data (including graphical analysis) and critical interpretation of your results.
- Gain experience in written and oral communication of your experimental procedures and findings.

1.2 Independent Research

No detailed aim, experimental procedure or relevant theory will be provided. It will be left to you to discuss as a group what it is you wish to investigate and how you intend to go about it!

Of course, your tutors will be available to make suggestions and help guide you **but they will not tell you what to do or how.** This means part of the work you do may include simply exploring and testing several methods to find a successful procedure. This is how most of the progress is achieved in scientific research. Rarely does a physicist write down an aim and procedure and then simply record data. A necessary part of any successful experiment includes designing the experiment, refining the experimental procedure and exploring unexpected or 'interesting' results.

1.3 Help!

To help you, a tutor will be assigned to your project group. You should think of this tutor as a member of your Group. Your session supervisor will also be available to offer advice as well as the laboratory manager.

1.4 Design of experimental procedure

Turning a general idea into a specific proposal with all procedures outlined is essential to the successful completion of your investigation. One of the most important aspects of the project is to specify exactly *what* physical quantities you are going to measure and *how*. Planning of the method of analysis of results to show relationships between particular quantities is also important. Although you are encouraged to propose your own project on any topic, for practical reasons you are largely limited to investigations that can be performed using the equipment available in the First Year laboratories or which you can 'scrounge' yourselves.

You will be given a list of potential projects. You do not have to choose only from this list. Some other ideas for projects and an indication of the equipment readily available can be found by going to

http://www.physics.usyd.edu.au/teach_res/projects/projects.htm

or following the link from the Experimental Physics Lab page on the eLearning page for this unit. In any case, you must discuss your choice of project with your tutors and your lab supervisor.

1.5 Working as a team

Throughout the year you have been working in teams of 2 or 3. For this last Module two such teams will amalgamate to form a group of 4 to 6. To make effective use of everyone's time you will have to carefully plan the various tasks and responsibilities of each group member. For example, in a group of 6, you may decide to split into 3 pairs. One pair may head to the library and do some background reading and research on your topic. Another pair may procure the experimental equipment and the final pair could be responsible for analysing the data and writing the report. All the team members should participate in planning the experimental procedure and making some of the measurements.

All members of your group can access your results from home to work on their aspect of the experiment. To do this, save your work to directory (E:\STUDATA) after your lab session. It will be available for downloading from the Laboratory Download Site at the end of the day. This can be accessed by following the link from the Experimental Physics Lab page on the eLearning page for this unit. You can then work on the data at home and mail it to your University account which can be read from computers in the lab.

1.6 Presentation skills

Another aim of this Module is practice in presenting experimental work using two approaches. Firstly, the work performed will be written up in a ***Report.*** This report should follow the guidelines given below. In addition to this, your work will also be presented as a ***talk*** in front of your lab class during the final week of the module.

2 Timetable for Project Work

To be able to commence work on your project after the first Module requires some preparation and decision making. In the 1st week of laboratory (week 2 of semester) you will be placed in your Project Group. There will be meetings of your Project Group during your Lab sessions in Week2, 3, and 4. At some point during these weeks a tutor will be assigned to your Group to mentor you during your project. In Week 5, after another Project Group Meeting, you will need to submit a detailed ***Project Proposal*** for consideration and marking. In this you will indicate both the experimental procedure you plan to follow and the various roles and responsibilities of all the group members. Working as a team will require group members to briefly meet on a number of occasions outside of normal lab hours to discuss the Project work. Tutors will be available during the weekly lab sessions for advice and guidance.

Your Project Proposal, marked with comments, will be returned to you in Week 6.

Since the final week is devoted to the talks, you really only have 3 laboratory sessions to complete your experiment, prepare the (Powerpoint/Keynote) presentation and write your report.

In that time you will have to set up your apparatus, test your procedure and collect the relevant data. You should aim to do as much of this as possible during the first two sessions to allow analysis and writing in the third session.

Project timetable for second semester:

Semester Week	**Activity**
Week 2	Placed into **Project Groups** and assigned a tutor
Week 3	Preparation of Project Proposal
Week 4	Preparation of Project Proposal (continued)
Week 5	**Final Proposal due**
Week 6	Final Proposal returned
Weeks 9, 10 & 11	Lab sessions for project work
Week 12	Oral Presentation
Week 13	Submission of Report

3 Assessment

A total of 28 marks is allocated to the work in the Project Module. This represents 14% of the total assessment mark for the entire semester. The marks are based on the written Report, the Oral Presentation, a mark given by Tutors, your Project Proposal, and your Weekly participation in the Project work during the lab sessions. All group members will receive the same mark for work handed in and the oral presentation (provided they have signed the appropriate forms and made a contribution) but not necessarily the same mark for laboratory work.

Each week your Project Group will be required to fill out a ***Progress Report*** that summarises what you have accomplished and the contribution of each member. It should also contain your plans for next week.

The ***Progress Report*** has to be pasted into your logbook and signed by each member of your Project Group. Your assigned tutor will check and discuss your Progress Report with your Group.

Project mark allocation:

Activity	**Mark**
Project Proposal	4
Weekly Progress Reports (3)	3
Project Mark	5
Oral Presentation	6
Written Report	10
Total	**28**

3.1 The Project Proposal

Submitting proposals for work you intend to carry out is a very important and necessary skill that will be called upon throughout your working career, whether that be in scientific research or not. The purpose of a proposal is to demonstrate to a supervisor or funding body that you know what you want to do and have a good understanding of how to achieve this. You should also be able to argue why it is desirable or important that you carry out such work. These are issues you will have to consider in writing a proposal.The Project Proposal Form must be signed by each Group member for them to be awarded any marks. Sample forms are shown at the back of the lab manual. The actual forms you need to complete will be distributed during your laboratory classes.

As part of everyday research (and in fact all types of work) money, equipment and labour will be required to carry out some proposed investigation or task. In order for these to be supplied you must convince the person(s) in charge of funding that the task you have proposed is worth carrying out, that you know what is required to complete the task and that you are capable of carrying it out. These are just some of the aims of the project proposal that you should keep in mind when completing it. To help us provide you with the equipment necessary to conduct the investigation you have chosen, you must complete this form carefully.

- Please give the complete details of all students in your Project Group. Marks will ***only*** be awarded to members of the team who have signed the forms.
- ***You*** must clearly indicate your project team number eg 6TECB (you must know this number to identify your team).
- ***You*** have to make sure that the tutor who is mentoring your team has signed the form.
- ***Project Title*** — gives us some idea of what you are going to investigate. Do not leave it blank. The title should clearly indicate what your project is about.

- ***Equipment*** — in order to carry out your investigation you will have to determine exactly what equipment you will require. There will not be sufficient time to find other more suitable equipment or build some special apparatus as it is needed. If the equipment exists in the laboratory, refer to it. If you require a voltmeter, how sensitive and accurate must it be, to measure millivolts, or to 1%? Check the various models of multimeters that exist in the lab and ask for the particular model appropriate for your measurements. The School of Physics will be able to supply certain equipment e.g. tubes suitable for standing wave experiments. However, you must tell us what you want, the shape and dimensions of the tube (or range if particular values are not crucial) and the material. Clearly indicate what equipment you will provide e.g. mobile phone (the School of Physics will not provide any mobile phones). You are then responsible for bringing this equipment when the Project begins.
- ***Summary*** — give a clear and precise summary outlining your project.
- ***Description*** — descriptions of measurements to be made and how they will be made should be clear and concise (for example, ...the voltage supplied by the various batteries will be measured as a function of time for constant load resistance; the service time and power supplied will then be calculated using the equations. . . ; the voltage across the battery terminals is to be measured by a Yokogawa DMM Mode17532-02 using the circuit shown below. . .). Use diagrams to clarify what you are doing. Indicate what is interesting about the work you will perform, basically the motivation for carrying out the investigation. Assuming all goes to plan, what do you hope to learn? What questions or puzzles do you want to answer? Remember you are to work as a team and share the workload evenly. There are many tasks to be completed as part of the Project. Apart from actually designing and performing any experiments there will be data that must be analysed, research to compare with or justify your results, the written report and the oral presentation. Plan these carefully and everyone will do their equal share, e.g. divide the group into 2 teams, one responsible for the report and the other for the talk.
- ***References*** — to show that you are familiar with the relevant theory and know what you want to do, list any references you have used in designing your Project. These can include textbooks, journals, magazines, newspaper articles, the internet, etc.

3.2 Weekly Progress Reports

Your group must fill out a weekly progress report form on each of the three project weeks (weeks 9, 10 and 11). Forms will be provided in the laboratory. A sample of the form is on page P.33 of this lab manual; it's just a sample, don't use it.

Please note: The weekly progress report must be signed by each team member, pasted into your logbook and checked off by your tutor before you leave the laboratory each week. Only team members who have signed this form will be eligible for the weekly attendance mark.

3.3 Project Mark

Your tutors and supervisor will meet after the project presentations and will give you a mark out of 5 for your project. The tutor assigned to mentor you in your project will act as your advocate at this meeting.

Initially, the Project Mark will be given to the entire group. But the mark you are given as an individual will be scaled according to your participation in the project. If you contributed to the project proposal, contributed for the three weeks of project work, and attended the project presentation you will receive the full Project Mark. If you missed any of these your mark will be scaled in proportion to your participation. For this purpose the Project Proposal will carry double weight to the other elements. Please that it is very important that you complete and sign each of the forms during the project. It is the presence of your signature on these forms that will be used to determine your scaled project mark.

3.4 Oral Presentation

A maximum mark of 6 is awarded for your Group's Oral Presentation. YOU have to be present at the time of the talk to receive this mark.

Groups should use *PowerPoint* to prepare their talk. If you use *Keynote or OpenOffice* please Export your presentation as a PowerPoint file (.ppt or .pptx) and then *check* that it works correctly on a Windows PC before you give your talk.

We recommend that no more than three Group members give the talk. This will help the presentation flow. A talk should not be less than 8 minutes and no more than 12 minutes. You may be asked questions at the completion of the talk. It is advisable to present any information in point form. People are not likely to read large blocks of information and nor do you want them to, they should be listening to you. Use the points on the transparencies as cues for your talk. About 4-6 PowerPoint slides are all that you will require.

3.4.1 How to give a good oral presentation

Your results should be presented clearly and concisely. Assume the audience, your peers from the First Year Laboratory Class, know nothing about your work. Most groups will be doing a completely different topic. In order for them to understand your work you will have to:

- Clearly state the aims of your project.
- Describe the experimental apparatus and techniques used.
- Present the important results.
- State your conclusions.

3.4.2 Structuring your presentation

There should be a logical progression or structure in your talk. This is best achieved by dividing the material into separate sections.

Introduction A concise summary of the aims of the Project - what you intended to achieve during the course of the Project.

Theory A brief summary of the ***physics*** relevant to the Project.

Experimental A clear, brief description of the equipment and the techniques you used. Diagrams are ***essential*** here.

Results Keep this section short — it could be as simple as a graph or a value obtained from that graph. Large tables in Powerpoint cannot be read by the audience.

Discussion How good are your results? Why do they differ from what you expected? (Be prepared to say so if you don't know — this is much more convincing than waffling on). Could you possibly improve the experiment? Above all, keep this section short... it is easy to get carried away.

Conclusion A succinct summary of your results — a number (with associated uncertainty), an equation or a couple of lines of text.

3.4.3 Preparing PowerPoint slides

Nearly all students will use PowerPoint (or Keynote or OpenOffice).

- Slides should be clear and simple — avoid clutter. (Advertisers know how to get their message across: check out some billboards.)
- Use colour.
- Use LARGE letters — 24 point type is a good size. Never use less that 18 pt. type. Photocopies of printed text are too small.
- Use a **maximum** of 8 lines of text on each overhead — fewer lines are acceptable and point form is a good idea.
- Diagrams of equipment and graphs should fill the slide/overhead.

3.4.4 Speaking in public

- ***Look*** at the audience.
- Practice, practice, practice, in front of each other, your friends or family
- Keep to the allotted time, practice will greatly help, here. There is a strict limit of 12 minutes. DO NOT shorten the talk by speaking more rapidly, glossing over points or assuming "it will be OK on the day".
- Don't try to present ALL your results. It is much better to concentrate on what you found interesting or important.
- Avoid blocking the audience's view of the overhead screen or other visual aids.
- Point to information on the screen as you discuss it but spend most of your time looking at the audience.
- Memorise your talk. This is not difficult if you use your slides as prompts — they will give you clues as to what comes next.
- Remember you are communicating by speaking, not reading. Read presentations are painfully boring!
- Avoid speaking in a monotone — try to change the loudness and speed of your speech during the talk
- Do NOT use long words or sentences. Don't waffle, keep your talk crisp and concise.
- Do NOT speak too rapidly. Aim at speaking at HALF the speed you would in a normal conversation.

Presentation of the results of an investigation or research project is an essential skill to have acquired, no matter what your future career.

Here are a few words of advice from the experts. The editors of Nature probably have sat through more conference presentations than is good for them. Nature can lay claim to being the worlds most prestigious multidisciplinary scientific journal. Your project presentations should be just like what happens at a scientific conference. This editorial appeared in Nature Methods, vol. 5 no. 5, May 2008, p. 371.

"Talking Points

Presenting at a conference is a unique opportunity to broadly communicate your work.

Here are ten suggestions to make the most of it.

"I know this is a busy slide, but ..."

"You probably cant see this, but ..."

"Im gonna go through these last slides really quickly ..."

As editors, we attend many conferences. Having already heard these staples too many times this year, we decided to put together our top 10 list of presentation rules. We may not address an audience often, but we have plenty of opportunity to build up our pet peeves about presentation skills. There is of course more elaborate advice available, and this short list may sound like common sense to many. Nevertheless, we hope it helps beginner speakers get off on the right foot for the summer meeting season. Perhaps even some seasoned speakers may appreciate the reminder.

1. **Plan for the allotted time.** There are few things more annoying than a speaker who rushes through slides without leaving any lasting impression about the substance of the work. The key to a good presentation is to present the minimum amount of information that is necessary to make your point. A maximum of one slide per minute is a good rule of thumb, but the exact number should be determined by rehearsing.

2. **Know your audience.** There is no such thing as a one-size-fits-all speech. Knowing the level of specialty and diversity of your audience will help determine how much background and detail you need to present. Do not expect everyone to be an expert in your particular body of work but avoid patronizing the audience.

3. **Define your goals** . As you must limit your material, it is important to deliberately decide which points you want the audience to remember. Once this is clear, build your talk around these points and make sure that each slide has a purpose toward your goals.

4. **Structure your talk.** Whatever the audience, it is worth setting the stage by stating the general importance of the work and your specific objectives. To place the work in perspective, mention related efforts and what is unique about your approach. Only then, delve into experiments and results. An outline slide at the beginning is seldom necessary for short talks but it can help if you will be discussing substantially distinct topics. In contrast, there is no way around the summary slide; the all-important take-home message that should capture the key points in a way that both experts and non-specialists will remember.

5. **Keep your slides simple (content).** The slides should be a visual support for your talk rather than the talk itself; they should help convey the essence of your talk rather than the details. Prefer bullet points to paragraphs of text. Avoid complete sentences because the audience will not resist reading them, creating a distracting disparity with what you

are actually saying. Such economy of text means you must choose the words judiciously, making sure you highlight key notions. Prefer schematics and cartoons to words but keep them simple, limiting them to the essential elements. Finally, prefer graphs to tables, and label them adequately.

6. **Keep your slides simple (design).** There is nothing wrong with a good old solid background and an appropriate colour contrast. Use a legible typeface for all text (do not forget about cartoon labels and graph axes) and make it large enough to be legible once projected. If you have to resort to a font size below 20 points, you have too much information on your slide. Sans-serif fonts (in which letters do not have little tails) tend to work best.

7. **Beware of animations and multimedia.** There are cases in which a simple schematic animation will convey a concept better than a still cartoon. But think twice and use animations sparingly as they can be awfully distracting if overused. As for dynamic data representations, such as live microscopy movies or rotating three-dimensional protein structures, they can be invaluable to convey critical observations. Our advice, however, is to keep them to a minimum and make sure they run properly. If you are using someone elses computer, chances are the movie will not play. So do not plan your talk around it, or else, have a contingency plan such as a few slides with representative still frames.

8. **Watch your delivery.** Be attentive to the speed and volume of your speech. If you are a non-native English speaker, pay particular attention to the pronunciation of key terms and use words on the slide to convey key concepts. If you are a native English speaker, keep in mind that many in the audience are not. In addition, using transition words and phrases between slides will help make the talk flow smoothly. To use them effectively, you must know which slide is coming up next.

9. **Choose your words.** Avoid jargon and acronyms. Uncommon abbreviations cannot always be avoided on the slides, but it is important to spell them out as you speak. As much as possible, match key words in your speech to the written words on your slides to maximize the visual support they offer. Explain the graphs and schematics as soon as you bring up a slide. If people do not know what is plotted against what, or what the red arrow is supposed to represent, they will not follow your explanation of the results.

10. **Rehearse!** Most of the points above will become apparent if you give a practice talk. With or without a friendly audience, the key to rehearsal is to make it real. Problems with timing, abrupt transitions and confusing explanations will become obvious only if you try it out loud and not in the comfortable environment of your own head. Some oral presentation instructors film their students giving mock talks in class, a potentially excruciating experience but one that is very informative about bad habits. For a real talk, practice runs will give you the opportunity to fix problems in the presentation design and to keep track of time effectively during the talk. Practicing is also the only proven way to reduce anxiety.

This is our advice, for what it is worth. Perhaps there is one more pet peeve that sums up all the others: **do not make excuses for things you could have addressed before your talk.** If you have prepared well, you will do a great job."

3.5 The Report

The Report will form the main basis for presenting your project work. Your report is worth one third of your project mark. It should not be a copy of your laboratory logbook. It should be a clear and concise presentation of the work you performed. Long tables of results and complicated calculations should not be included. Graphs should be used to present results and a clear explanation of how calculations were performed is more than adequate.

As a guide, the Report will typically be 8 pages in length including diagrams and graphs. But longer, or shorter, reports are fine provided the length is justified by the content (i.e. NOT long filled with waffle; or short missing important aspects of the Project).

We encourage cooperation between students and Groups in completing the Report. However simple copying is not acceptable, whether from other students or any other source (such as the web). Copying the work of another person or group without acknowledgment is contrary to University policies on Academic Honesty in Coursework.
(see http://www.usyd.edu.au/ab/policies/Academic_Honesty_Cwk.pdf).
Allowing your work to be copied is unfair to other students and ultimately does not help the student copying your work.

The Report must be submitted with the ***Cover Sheet*** as the first page, which contains the names, SIDs and signatures of all members of the Project Group. **Students who do not sign the cover sheet will NOT be awarded marks for the Report**. You may have to scan or make a high quality image of the front cover if you do not have the ability to sign the cover sheet electronically, for example by using a tablet.

All Project Group members are expected to keep a copy of the Report.

The Report must be submitted electronically via eLearning/Blackboard before midnight on Friday the 30th of October. It is preferred that you submit the report as a PDF file, although a report written in Word is acceptable.

The marking criteria for your Report are:

Criterion	**Mark**
Effort and presentation	3
Experimental data collected and Scientific presentation of data	3
Scientific analysis and conclusions drawn	4
Total	**10**

The style of a Physics Lab report is that of a scientific journal paper. Our intention is that you obtain some practice in the concise and accurate style of writing that scientists use. This is an essential skill for any science graduate.

To gain an idea of the structure of a scientific paper, we recommended you visit some journal webpages (preferably Physics, but Biology, Medical or Chemical journals are OK), and look at some recently published papers. Alternatively, have a look at recent journals in the SciTech library. Don't worry too much if you don't understand all of the article. For the purposes of this exercise we are more concerned with structure and style than content.

Using a University of Sydney account to do your web-browsing will give you access to papers from sources such as http://www.sciencedirect.com/. Physics enthusiasts could also check out http://journals.iop.org/ and http://journals.aip.org/.

The following is the general structure of a paper, but as you will find from browsing the published literature there are wide variations that depend on the content of the paper. Use the following as a basis from which to work but remember that it's not a template. Your report should be understandable to a scientifically literate person, e.g., another junior physics student.

Abstract This is a paragraph at the beginning of a paper that summarises briefly the experiment, the main quantitative results and their implications.

Introduction This section is where the paper starts. It does not rely on the abstract. It usually includes some background or history to the area of research. It is very rare for an idea to arise by itself since there is always some precedent that has led to the ideas being tested in an experiment. It might also include some application of the principle behind the experiment.

Theory If there is some background mathematical theory or qualitative ideas that need to be introduced so that the experimental results can be understood, then this is the place to do it. The section itself doesn't have to be called "Theory". In many cases the theory is not extensive enough to place it in a dedicated section and is simply incorporated into the Introduction.

Experimental Procedure Since the paper is about an experiment or experiments, then there must be some description of the apparatus used. A reader can only gain confidence in the results if they are confident that you had appropriate apparatus and were able to describe its function and limitations (every piece of apparatus has its limitations, no matter how expensive it is!). In many cases you need to describe in some detail those parts of the apparatus that are critical to the understanding of the experimental results. A diagram goes a long way in helping the reader understand your description of the setup.

Results and Discussion A discussion of the results is best placed along with the presentation of the results. It breaks up the flow of a report to separate the results and discussion into two different sections. The analysis of your results should be quantitative (with uncertainties) and honest: attempt to explain discrepancies in physical terms, don't dismiss them.

Conclusions A conclusion is really an extended abstract, summarising the results in more detail and maybe suggesting ways this experiment or future experiments might be improved or extended.

References We expect you to read relevant material when preparing your report. All references, including web references, must be acknowledged. References should be cited by number, either as a superscript or within square brackets, with a numbered list at the end of your report. The extent of your outside reading can make a big difference to the scientific impact of your report.

Acknowledgments An *essential* part of the Acknowledgments section will be the team members' contributions, where the work of each member is outlined.

3.6 Common mistakes and helpful hints

- Remember to write in the *correct tense*. You have already completed the experiments that you are reporting about. So they WERE done . . . they are NOT being done now as you write the report.

- Do not write instructions as if you are writing a laboratory manual.

- Do not write in dot point format. The writing must be in a narrative style.

- Do not derive formulae or include intermediate steps in calculations.

- Equations and figures should be numbered, with symbols defined in equations and informative captions included for the figures. Figures should be referred to in the text, e.g., as shown in Fig X.
- Do not do join-the-dots plots for your graphs; they do not convey any extra information. However, if you have more than one plot on the same graph, then it may be appropriate to join the points or, better, use different plot symbols or colours to distinguish the points.
- Explain how you determined your uncertainties. There must always be a reason for an uncertainty estimate.
- Always compare experimental and accepted values. Examine the assumptions that may underpin an accepted or theoretical value before writing off your own results.
- Express discrepancies in terms of uncertainties, not as small, large or 5%!
- Exclude any waffle when trying to explain discrepancies. Show physical insight.

SAMPLE WRITTEN REPORT

TESTING COMMERCIALLY AVAILABLE BATTERIES

by

Albert Einstein, Max Planck, Marie Curie, Robert A. Millikan, Isaac Newton and Archimedes

Abstract

A large range of batteries is commercially available these days some claiming superior performance but at a significant cost. This report details tests conducted to measure the service time and rated capacity of 4 such AA batteries manufactured by Eveready under the names: General Purpose, Heavy Duty, Super Heavy Duty and Energizer. The alkaline based Energizer is shown to have a significant performance advantage but the best performance per cost was displayed by the General Purpose battery. Measurement of the open circuit voltage and internal resistance are shown to be good indicators of the battery condition.

Introduction

In recent years the market place has been saturated with various types and models of small electrical batteries. These range from the standard primary dry batteries to the high power alkaline primary batteries and the relatively new rechargeable secondary batteries. Despite their very similar appearance and apparent ability to fulfil most uses the prices per unit range from less than \$0.25 for general purpose batteries to over \$10 for rechargeable batteries. This means the comparison of performance per price and the question of appropriateness of the various batteries for particular uses are very important issues.

This report contains a description of experiments undertaken on various types of AA cells (the common Zn-C and newer alkaline batteries) to test their performance. The tests included simulated continuous use under high and low power demands. This allows not only a direct comparison of the various models and types of batteries but also their appropriateness for high and low power demands. The results obtained are also compared to the manufacturer's technical data where available.

Theory

All dry cells whether the common Zn-C, alkaline or rechargeable Ni-Cd cell produce a current by a series of electrochemical oxidation-reduction reactions. In the Zn-C battery a zinc can forms the anode and serves as the mechanical container for the cell. This is usually covered by protective and insulating layers of plastic and paper. The cathode consists of a mixture of powdered manganese dioxide and carbon moulded onto a central carbon rod. The anode and cathode are separated by an electrolyte made from a paste of ammonium chloride and zinc chloride. A complicated sequence of reactions occurs both at the cathode and in the electrolyte: the overall reaction can be considered as the oxidation of zinc at the anode and the reduction of manganese at the cathode.

In the case of alkaline cells the reactions can be thought of as similar and in fact both a zinc can and manganese dioxide are used. The main difference is the use of potassium hydroxide as the electrolyte. This is a much better conductor than the ammonium chloride and zinc chloride paste and allows the cell to generate much higher currents. It is usually recommended by the manufacturers for high power applications.

An ideal battery (or voltage source) can supply a given voltage independent of the load resistance. A real battery, however, has an internal resistance and hence the voltage measured across its terminals depends on the load. As such a simple model for a battery is an ideal battery with a resistor in series, as indicated in Fig. 1

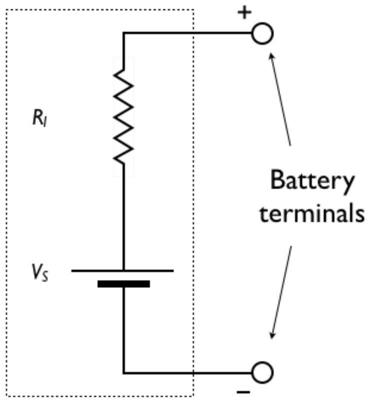


Figure 1: *Equivalent circuit for a real battery.*

Experimental

Tests were performed on a selected range of batteries. The following batteries were included in the tests. EVEREADY General Purpose, EVEREADY Heavy Duty, EVEREADY Super Heavy Duty, ENERGIZER Alkaline.

All the batteries were purchased brand new in packs of 4.

Two series of tests were conducted. In Series 1 the open circuit voltage (OCV) and internal resistance of each battery were measured using a voltmeter (Yokogawa DMM Model 7532-02) and a known resistor. The OCV was measured by simply placing the voltmeter across the terminals of the battery as indicated in Fig. 2.

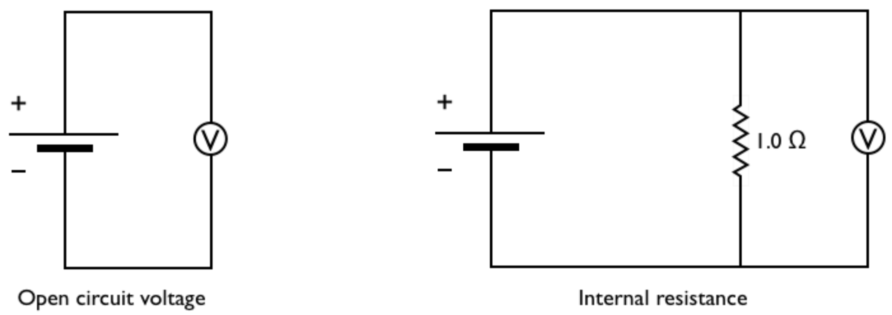


Figure 2: *Circuits used to measure the OCV and internal resistance of batteries.*

This measurement was used along with a measure of the voltage drop across a 1 Ω resistor to calculate the internal resistance of each battery. Considering the model of a real battery discussed earlier and the circuit shown in Fig. 2 we obtain the following relation,

$$V_s - IR_I - V = 0 \tag{1}$$

$$V = V_s - IR_I \tag{2}$$

where V_s is the ideal voltage of the battery, V the measured voltage drop across the resistor, I the current through the resistor and R_1 is the internal resistance. From the measurement of V across the 1 Ω resistor the corresponding value of I was calculated while for the measurement of the OCV I was assumed to be zero (the internal resistance of the voltmeter was given as 11 $M\Omega$). The internal resistance of the battery was then calculated using the following expression

$$V = \frac{V_{OCV} - V_{1\Omega}}{I_{1\Omega}} \tag{3}$$

In the second part of the experiment, Series II, the batteries were tested under operating conditions. The voltage applied by each battery was monitored as a function of time for 2 different fixed load resistor values, 2 Ω and 100 Ω (corresponding to nominal currents of 0.75 A and 15 mA respectively). A different battery of each type was used for each test. The tests were designed to represent different power requirements, high and low respectively. The voltage was monitored until it dropped to 0.9 V. In the case of the high power tests the data was collected by hand using a voltmeter and wrist watch. For the low power tests the time taken for the voltage to drop to the required level meant that a computer controlled data acquisition system had to be used. This allowed the collection of data around the clock for long periods of time. The PC-26 data acquisition card was used and a program written in Pascal to collect and store the required data. This data not only allows a quick comparison between the various batteries but also a calculation of the ampere-hour capacity.

At the conclusion of the Series II experiments the OCV and internal resistance of the batteries were measured once again.

Results

The OCV for each battery used in the tests is shown in Table 1.

Table 1 : *Measurements of OCV for the various batteries.*

Battery	$V_{1OCV}(V)$	**Uncertainty (V)**	$V_{2OCV}(V)$	**Uncertainty (V)**
General Purpose	1.473	± 0.008	1.471	± 0.008
Heavy Duty	1.527	± 0.009	1.527	± 0.009
Super Heavy Duty	1.753	± 0.010	1.752	± 0.010
Energizer	1.581	± 0.009	1.579	± 0.009

Since 2 batteries of each type were going to be used for the Series II tests the results in Table l indicate the measurements for 2 batteries. The uncertainties indicated were calculated using the manufacturer's specifications for the calibration uncertainty in voltage readings.

Equation 3 was used to calculate the internal resistance of the batteries. The resistance was measured accurately using a Keithley 160B meter. The uncertainties indicated were

Table 2 : *Calculation of the initial internal resistance for the various batteries.*

Battery	$R_{1I}(\Omega)$	**Uncertainty (Ω)**	$R_{2I}(\Omega)$	**Uncertainty (Ω)**
General Purpose	0.49	± 0.02	0.47	± 0.02
Heavy Duty	0.51	± 0.02	0.52	± 0.02
Super Heavy Duty	0.47	± 0.02	0.45	± 0.02
Energizer	0.53	± 0.02	0.51	± 0.02

obtained by combining the uncertainties in the voltage measurements. The uncertainty in the resistance was neglected since it was so small. The results for the internal resistance are presented in Table 2.

The results for the Series II tests are indicated in Fig. 3 and Fig. 4 showing how the voltage supplied varies with time. Voltage readings from the PC-26 card have a resolution of 0.0025 V and calibration uncertainty of 0.5% of reading. The time was obtained from the computer's clock and is accurate to within a few seconds. Measurements were taken every 10 minutes. For quick reference the time taken to reach the cut-off voltage of 0.9 V is presented in Table 3 for both sets of graphs.

Table 3: *Service times for high and low power tests to end voltages of 0.9 V.* Cost of 4-packs also indicated.

Battery	**High Power Time(hrs)**	**Ratio**	**Low Power Time(hrs)**	**Ratio**	**Cost($)**
General Purpose	0.504	1	33.2	1	0.99
Heavy Duty	0.648	1.29	59.7	1.80	2.25
Super Heavy Duty	0.759	1.51	65.3	1.97	3.35
Energizer	2.64	5.24	160	4.82	5.69

The capacity in ampere-hours of the batteries during the tests was also calculated using the expression

$$\textit{Rated capacity} = \int I dt = \int \frac{V}{R} dt \tag{4}$$

This was obtained by taking the area under the graphs in Fig. 3 and Fig. 4 divided by the load resistance. The capacity for both high and low power uses is presented in Table 4. Typical uncertainties in the capacities are less than 0.5 %.

At the end of the Series II tests the OCV and internal resistance of the batteries was determined once again. The results are indicated in Table 5. Note that the batteries labelled 1 were used in the high power tests and those labelled 2 in the low power tests.

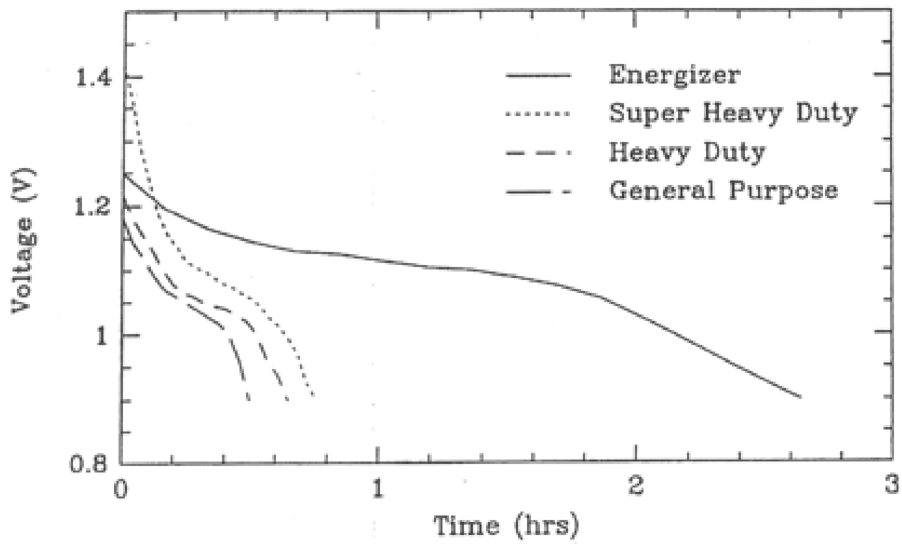


Figure 3: *Measurements of voltage supplied as a function of time for a constant load resistance.*

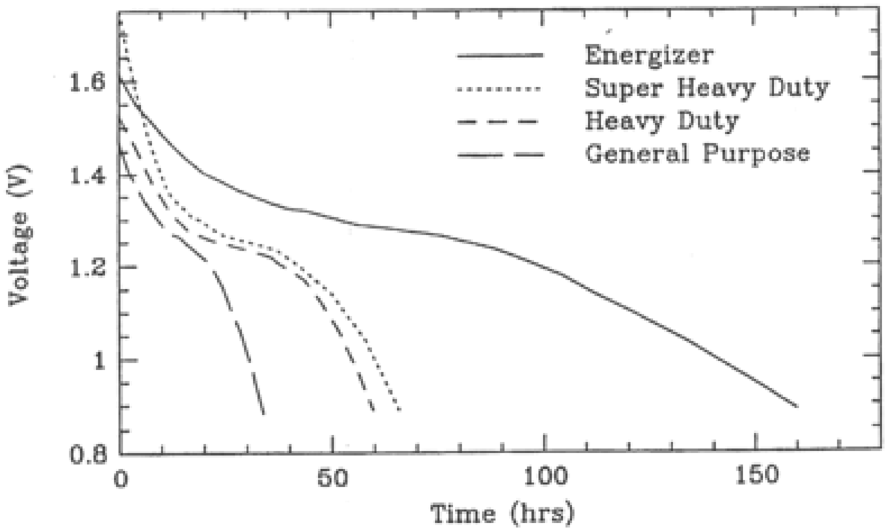


Figure 4: *Measurements of voltage supplied as a function of time for a constant 100 Ω load resistance.*

Table 4: *Calculated values for the capacity to a voltage of 0.9 V. for both the high and low power tests. Manufacturer's values are also included for comparison. The range indicates differences due to high and low power demands.*

Battery	**High Power Capacity** ($mA.hrs$)	**Low Power Capacity** ($mA.hrs$)	**Manufacture's values**
General Purpose	265	402	240-400
Heavy Duty	341	733	320-75
Super Heavy Duty	423	817	400-800
Energizer	1450	1890	1440-1850

Discussion

The AA batteries used in these tests are rated by the manufacturer at a nominal voltage of 1.5 V. Initial measurements of the OCV for the various batteries available indicate a significant range in values from 1.47 V to as much as 1.75 V. These values seem to be consistent between batteries bought in the same packets. One possible explanation for low readings could be deterioration of the batteries due to shelf life. Although they were purchased brand new the time and conditions under storage may vary. Such factors have been shown to influence battery characteristics (Cahoon and Heise, 1976). It has also been noted that the presence of artificial manganese dioxide tends to increase the OCV (Muller, Tye and Wood, 1965). Based on our measurements of OCV it is highly likely that the Eveready Super Heavy Duty batteries used had a significant proportion of artificial manganese dioxide. However, this is only one possible explanation.

The internal resistance of the various batteries also shows a significant variation and strong correlation with batteries from the same packet.

Comparison of the initial and final measurements of OCV and internal resistance clearly indicates that OCV drops with usage whilst the internal resistance increases. This means that together the OCV and internal resistance can be used to indicate the relative condition of a battery i.e. whether brand new or used for a significant time. The decrease in OCV can have significant consequences on the apparent battery life time in the case of devices that require

Table 5 : *Measurements for the OCV and internal resistance at the conclusion of the service tests.*

Battery	$R_{1I}(\Omega)$	$V_{1OCV}(V)$	$R_{2I}(\Omega)$	$V_{2OCV}(V)$
General Purpose	1.473	± 0.008	1.471	± 0.008
Heavy Duty	1.527	± 0.009	1.527	± 0.009
Super Heavy Duty	1.753	± 0.010	1.752	± 0.010
Energizer	1.581	± 0.009	1.579	± 0.008

a given minimum voltage to function e.g. logic devices. The increase in internal resistance implies battery efficiency decreases with usage and this effect is even more important for high power applications where the load resistance is comparable to the internal resistance.

Looking at the graphs from the Series II tests we can identify 3 main common features: an initial steady decrease in the voltage supplied; a plateau region of more gradual decrease in voltage; and finally an extended region of greater voltage decrease. The most significant differences are evident in the plateau region. The extent of this region and the voltage at which it occurs depends on the battery type and the application (high or low power demands). This can again influence the apparent life time of batteries depending on the minimum voltage or power required by a device.

In order to use the data collected in the Series II experiments to make a comparison of the various batteries we must select some criteria. Two results have been chosen, the time taken to reach a supply voltage of 0.9 V and the capacity available to that stage. The cut-off value of 0.9 V represents a significant drop in voltage and will probably produce noticeable deterioration in performance, signifying 'dead batteries'. Also since this value occurs well inside the final region of steady voltage decrease the conclusions drawn are equally valid for a range of similar cut-off voltages (0.8 - 1.0 V).

Table 3 indicates the times taken to reach a cut-off value of 0.9 V (the service time) for the various batteries in both the high and low power tests. For ease of comparison these times have been normalised to the smallest time. There is a significant difference evident between the alkaline Energizer and the other normal Zn-C batteries. In addition there is also a difference in relative service time between the high and low power tests. The Energizer clearly displays higher performance gains for high power applications. The cost of a 4-pack of batteries is also included in Table 3 to enable a cost-performance assessment. It is clear that the General Purpose batteries offer the best performance per dollar in both high and low power applications. The Energizer batteries, however, offer the convenience of significantly longer service with a single set of batteries. This means for some applications it will not be necessary to provide additional sets of batteries and no need to change them. It is this convenience that must also be considered. Certain applications require long service times without the possibility of changing batteries e.g. running an experiment in the field. In such cases the Energizer is the preferred choice. The calculated capacity is indicated in Table 4 and the manufacturer's values are also included for comparison. The manufacturer's values are represented as a range that includes results from high and low power applications, continuous and intermittent use. The notes provided state that the lower values correspond to high power demands while the higher values to low power demands. This corresponds very well with our results and indeed the actual rated capacity values also agree with the manufacturer's specifications. Again in terms of cost-performance the General Purpose batteries offer the best value for money.

Calculation of the internal resistance of the batteries after use shows a significant increase of resistance with usage. The batteries used during the low power tests have deteriorated more in that their OCV is much lower than those used in the high power tests. This accounts for their much higher internal resistance. Such measurements suggest that the OCV and internal resistance of a battery are good indicators of the condition of that battery.

Conclusion

In tests conducted to determine the rated capacity and service time of various AA batteries (Eveready General Purpose, Heavy Duty, Super Heavy Duty and Energizer) significant performance differences were evident. In both high and low power tests the General Purpose battery produced the best performance per cost. However, the significantly longer service time and larger rated capacity of the Energizer makes it more suitable for high power applications or where long service times are required. During the tests it was clear that the OCV of batteries decreases with usage while the internal resistance increases. Measurements of these quantities serve as good indicators of the condition of a given battery provided typical values are known.

References

[1] Cahoon N.C. and Heise G.W., (1976) *The Primary Battery: Volume II*, John Wiley & Sons Inc

[2] Muller J., Tye F.L. and Wood L.L., (1965) *Batteries 2* Pergamon Press Ltd.

[3] Halliday D., Resnick R. and Walker. (1993) *Fundamentals of Physics*, 6th Edition John Wiley & Sons, Inc.

Acknowledgements

Albert Einstein and Max Planck	Wrote data acquisition program and set up apparatus for automated Series II experiments. Performed some calculations on rated capacity and internal resistance.
Marie Curie and Robert A. Millikan	Performed Series I experiments and high power tests for Series II experiments.
Isaac Newton and Archimedes	Prepared report and talk. Responsible for research and obtaining manufacturer's data sheets.

Appendices

Pascal Program for data acquisition card Program listing (omitted for sample report). Manufacturer's data sheet - photocopy is sufficient (again omitted for sample report).

SAMPLE FORMS

The forms that you need to complete will be issued to you in Laboratory classes. These are samples of the forms that you will use.

It is VERY important that each member of a project group SIGN each form. It is your signature on the form that determines that you are given a mark for each section of your project.

you do not need to sign this page

SCHOOL OF PHYSICS, UNIVERSITY OF SYDNEY
JUNIOR PHYSICS EXPERIMENTAL PROJECTS
PROJECT PROPOSAL FORM

Please use a black or blue pen when completing this form.

Project Group (eg **6TECG**)	
Project Title	

Project Group Members (* signature required for marks to be awarded)

#	SID	First Name	Surname	Signature*
1				
2				
3				
4				
5				
6				
7				

Project Description

Official use only - Must be completed by Lab supervisor ***Supervisor's name & comments***	***Mark / 4***

Enter your Project Group Number eg 6TECG

Equipment and Resources - It is important that this section is completed fully because it is used to prepare your Project Kits and organise your allocated space. Indicate whether you will supply the item (**S**) or Physics (**P**).

Supply S or P	**Item and comments**	**Model / Range /Specifications**

Description of Project

Project Timeline

Activity	Names and Contributions
Week 1	
Week 2	
Week 3	
Week 4: Oral Presentation	
Report	

What do you hope to learn from project?

References

SCHOOL OF PHYSICS, UNIVERSITY OF SYDNEY

JUNIOR PHYSICS EXPERIMENTAL PROJECTS

WEEKLY PROGRESS REPORT FORM

Please use a black or blue pen when completing this form.

To be pasted into your team's logbook and checked by a tutor

Project Group (eg **6TECG**)	**Date**
Project Title	

Project Group Members

#	SID	Surname	Signature	Task on day
1				
2				
3				
4				
5				
6				
7				

Activity Summary and plans for next week

Official use only: Must be completed by tutor mentoring the Project Group

Tutor's name & comments

can you progress in reverse?

SCHOOL OF PHYSICS, UNIVERSITY OF SYDNEY
JUNIOR PHYSICS EXPERIMENTAL PROJECTS
PRESENTATION MARK FORM

Please use a black or blue pen when completing this form.

Project Group (eg **6TECG**)	**Date**
Project Title	

Project Group Members

#	SID	Surname (ALL members)	Presentation Mark (max. 6)*	Signature
1				
2				
3				
4				
5				
6				
7				

* Presentation Mark is given by your Tutors.

Any member whose name does not appear on this list will be awarded 0 marks for the presentation, therefore, make sure all Group members are listed and have signed this form.

This form must be completed and given to the Supervisor immediately after your Group's Presentation. Your oral presentation mark will also be recorded on this form. To receive the Oral Presentation mark you must be present during the talk and have signed this form.

Official use:- Marks for Oral Presentation awarded to only those students present during the talks.
Record all marks on rollcard - Marks recorded by:

not much of a presentation on this page

Using the Multimeter

1 Objectives

After studying these notes you should be able to:

- Explain what a multimeter is, and what it may be used to measure.
- Understand the operational principles of the major multimeter controls.
- Take measurements of voltage, current and resistance of simple components in direct current circuits.

2 Introduction

2.1 What is a Multimeter?

A multimeter is an instrument used in Physics and many other branches of science and engineering to measure electrical signals or the properties of electrical components, such as voltage, current and resistance. Until the 1920s, separate instruments were required to measure voltage (voltmeter), current (ammeter) and resistance (ohmmeter); the multimeter combines these functions into a single instrument.

Multimeters are most commonly (but not exclusively) used in d.c. (direct current) circuit measurements. For measurements of electrical signals that are rapidly varying in time an oscilloscope is generally preferred.

There are a great number of different types of multimeter, with varying capabilities and accuracy. Many have extra features beyond voltage, current and resistance, for example capacitance, conductance, decibels, frequency, inductance and temperature. Multimeters may be analogue or digital, digital meters usually having accuracy superior to their analogue counterparts. The most common meter in the First Year Laboratory is the Mastech MS8230B digital multimeter. This multimeter has capabilities beyond voltage, current and resistance, but we will not discuss them in this manual. Mastech MS8230B's accuracy for d.c. voltages, resistance, and currents less than 200 mA is ±2% of the reading. For currents >200 mA, the accuracy is ±3% of the reading.

Closely examine the controls, either on the multimeter or in Figure 1. Take your time. Looks complicated? confusing?

But, underneath all that complexity there is order.

1. In the middle of the multimeter is a rotatable knob, labelled (4) in Figure 1, shown here in the "off" position. Rotating this knob switches the multimeter on and selects the type of measurement and the range.

   Here is a list of the functions and ranges, turning the knob **clockwise** from its "off" position at 12 o'clock. If you look closely at a Mastech MS8230B (a real one, not the diagram), the functions are separated by pale green lines. The functions are indicated by green letters.

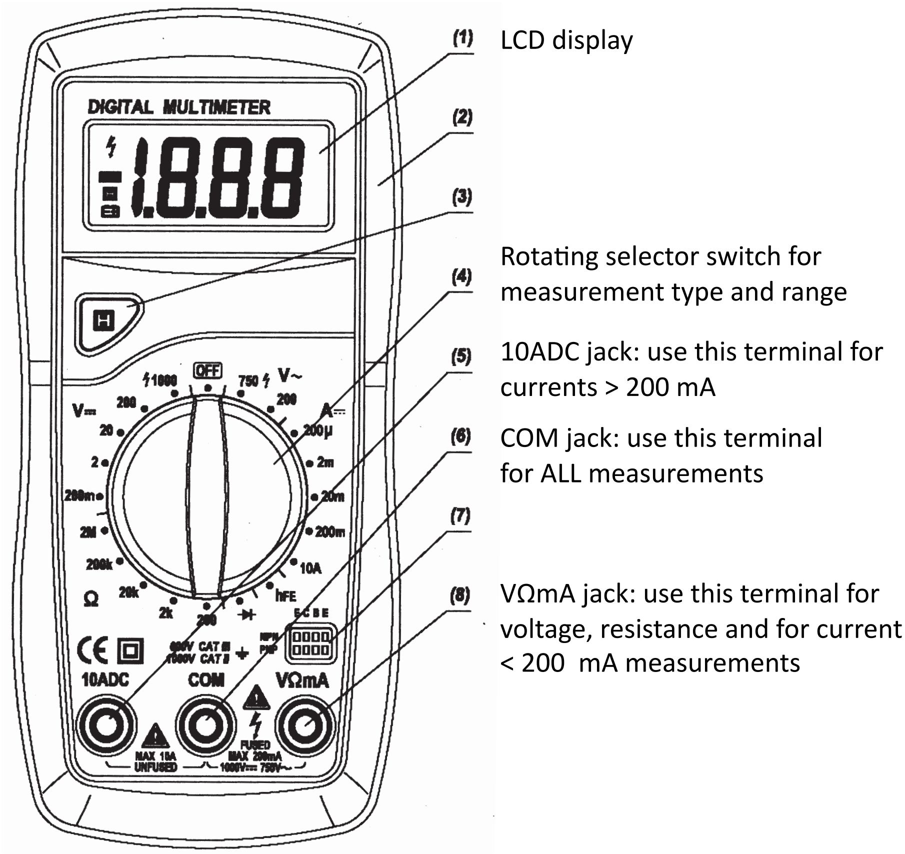


Figure 1: The front panel of a Mastech MS8230B multimeter, showing the arrangement of the controls. Please spend some time familiarising yourself with its layout.

(a) **V~** (at 12 – 2 o'clock). This is the alternating voltage measurement. Use the black lead in the **COM** jack and the red lead in the **VΩmA** jack. It is unlikely that you will use the multimeter to measure alternating voltage in the First Year Laboratory. We would generally use an oscilloscope for this purpose.

(b) **A⎓** (at 2 – 4:30). Use this range to measure DC (sometimes written d.c.) current. Use the black lead in the **COM** jack and the red lead in the **10ADC** jack. For currents of 200 mA (milliAmpere) or **less**, in order to obtain a more accurate reading, you may use the black lead in the **COM** jack and the red lead in the **VΩmA** jack. If there is **any** possibility that the current is greater than 200 mA, **always** check the measurement first with the red lead in the **10ADC** jack, otherwise you may damage the multimeter.

(c) **Ω** (at 6 – 8:30) Use the settings in this range to measure resistances. Use the black lead in the **COM** jack and the red lead in the **VΩmA** jack.

(d) **V⎓** (at 8:30 – 12 o'clock). This the direct current (DC or sometimes d.c.) voltage. Use the black lead in the **COM** jack and the red lead in the **VΩmA** jack.

2. The three plug holes, "jacks", along the bottom of the multimeter, **10ADC**, **COM** and **VΩmA**. In Figure 1 the jacks are labelled (5), (6) and (8).

(a) The **COM** jack (middle) is used in ALL measurements. Connect the black lead to this jack.

(b) The **10ADC** jack (left) is used for most current measurements. Use the red lead. For ALL current measurements start with this jack. **If and only if** the current is <200 mA, may you swap the red lead across to the **VΩmA** jack to obtain a more accurate reading.

(c) The **VΩmA** jack (right) is used for ALL voltage and resistance measurements. Use the red lead.

3. The LCD display, labelled (1) in Figure 1.

4. The other items, labelled (3) and (7) in Figure 1 are beyond the scope of this manual and will not be described.

3 Taking measurements with a multimeter

3.1 Current and Voltage

At its simplest, current may be (loosely) defined as a flow of electrons along a conductor (such as a piece of wire, or the ionised gas in a fluorescent tube). An electrical current of one ampere is a flow of approx. 6.24×10^{18} electrons per second. The S.I. unit of electrical current is the ampere (sometimes shortened to amp), A.

It is the voltage that drives the electrons along the conductor. For a given conductor, the higher the voltage, the more current will flow, analogous to a pressure difference driving liquid flow through a pipe. For a given pipe, the greater the pressure difference the greater the flow rate through the pipe. An old term for voltage (a good description, but no longer in use) is "electrical pressure". The correct term is "electromotive force" (emf). The S.I. unit of voltage is the volt, V.

Consider the following electrical circuit, made up of a battery, three pieces of wire, a switch and a light globe. We connect one terminal of the battery via a piece of wire to one side of the switch, and with a second piece of wire from the other side of the switch to one side of the globe (for example the metal base). We then join the third piece of wire to the connector at the bottom of the globe to the other terminal of the battery. When we close the switch, current begins to flow from one terminal of the battery, along the first wire, through the closed switch, through the filament of the light globe, and back along the wire to the other terminal of the battery. The flow of electrons through the light globe filament heat it up and the filament begins to glow.

We can draw a circuit diagram of our arrangement using simple symbols (Figure 2) for our battery, switch, the light globe and the wires and the two multimeters (Figure 3). To make the diagram easier to understand the multimeter leads are drawn as dotted lines.

3.1.1 Measuring electrical current

To measure current, we have to connect the multimeter in such a way that the

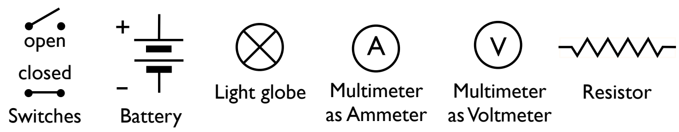


Figure 2: Symbols used in the circuit diagram (Figure 3).

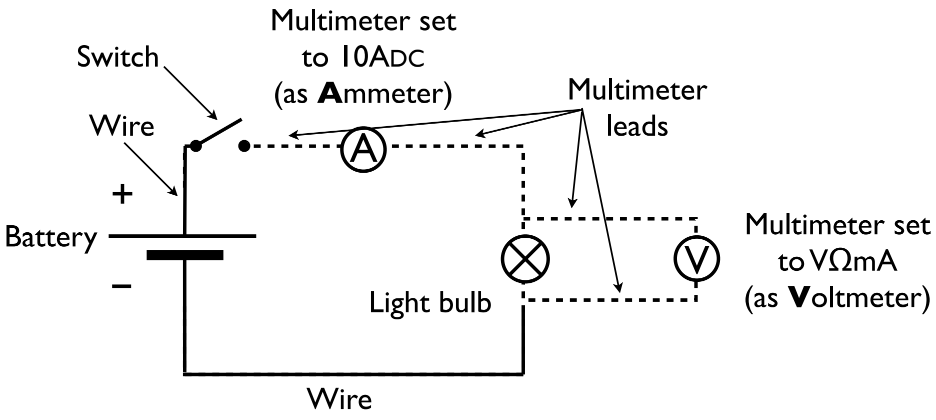


Figure 3: Circuit diagram of the battery, light globe, wire and two multimeters, one connected in series as an ammeter (A) and the other connected in parallel as a voltmeter (V). Note that the switch is shown in the open position. It would need to be closed (i.e. "switched on") before current will flow and measurements made.

electrons that constitute the current have to flow through the multimeter. This is called connecting the multimeter **"in series"**.

With the black lead in the **COM** jack and the red lead in the **10ADC** jack, rotate the centre knob of the multimeter clockwise to the 10A position (4 o'clock). Connect the red lead to the positive (+) battery terminal (or to the switch connected to the battery terminal) and the black lead to the light globe. Connect the other light globe terminal to the other (negative (-)) battery terminal. When the switch is closed should flow through the circuit, the light globe should glow and the ammeter (multimeter) should show the current in amperes. If the value shown by the multimeter is negative, check that you have not reversed the connections to the battery terminals.

3.1.2 Measuring voltage drop

To measure voltage drop of an electrical component in a circuit, we have to measure the "electrical pressure difference" on either side of the component (such as a light globe). This is usually referred to as the voltage drop or potential difference across the component. We measure the potential difference by connecting the multimeter (voltmeter) leads on either side of the component. See Figure 3. This is called connecting the multimeter **"in parallel"**.

With the black lead in the **COM** jack and the red lead in the **VΩmA** jack, rotate the centre knob of the multimeter anticlockwise to the appropriate position for the voltage being measured. For voltages between 2 V and 20 V this is the 20V position (10 o'clock).

1. **To measure the potential difference across an electrical component**, connect the red lead to the terminal of the light globe that is connected to the positive terminal of the battery (via the ammeter if it's already connected as in 3.1.1 above) and the black lead to the terminal of the light globe connected to the negative terminal of the battery. The voltmeter (multimeter) should now display the voltage drop across the light globe.

2. **To measure the emf (voltage) of a battery**, connect the red lead from the multimeter to the positive (+) terminal of the battery and the black lead to the negative (–) terminal.

The measurement is the number displayed on the LCD within the selected range. For example, if the LCD display had a reading of 1.5 and the 20V range was selected, the voltage is 1.5 V.

3.2 Resistance

For any particular conductor, we may define a quantity called the **resistance** that is a measure of how hard it is to push charges through the conductor.

We define resistance, R by

$$R = \frac{V}{I} \tag{1}$$

where V volt is the potential difference across the conductor and I ampere is the current flowing through the conductor.

The S.I. unit of resistance is the ohm, Ω.

There are two ways of measuring resistance:

1. of an individual object or component.

2. of a component within an electrical circuit.

3.2.1 Resistance of a separate object or component.

NOTE: This method is suitable only for a single object or component. It **will not give a correct measurement** of resistance if the component is part of a circuit.

Can you think why?

With the black lead in the **COM** jack and the red lead in the **VΩmA** jack, connect the other ends of the leads to each end of the resistor. Rotate the centre knob of the multimeter anticlockwise to the 2M (i.e. 2 MΩ) setting in the **Ω** range (at about the 8 o'clock position). If the resistance is greater than the range selected a "1." will appear at the left edge of the display. If the resistance is much lower than the range selected, the display will read "0.00" (or similar). Select a lower range (e.g. 200k = 200 kΩ, at 7 o'clock) and repeat the measurement. Keep stepping down the range until a satisfactory reading is obtained.

The measurement is the number displayed on the LCD plus the selected range. For example, if the LCD display had a reading of 4.7 and the 20k range was selected, then the component would have a resistance of 4.7 kΩ.

3.2.2 Resistance of a component in an electrical circuit

To measure the resistance of the light globe (or any other component in a simple electrical circuit) we need two multimeters: one set up as an ammeter (**10ADC**) and the other set up as a voltmeter (**VΩmA**).

As shown in Fig. 2, we measure the voltage drop V volt with the voltmeter leads connected on either side of the light globe, and measure the current I ampere with the ammeter connected in series with the light globe.

Using Eqn (1) we may then calculate the resistance of the light globe R ohm.

Using the Digital Storage Oscilloscope

These notes are a short introduction to the digital storage oscilloscope. A complete operating manual for the oscilloscope is available from any computer in the First Year Laboratory. Open Computer from the Start Menu, select D: drive, and then look for **Agilent Oscilloscope Manual**.

If you want to access the manual from any computer outside the laboratory, the URL is `http://www.home.agilent.com/agilent/facet.jspx?c=153298.i.1&to=80039.k.1&cc=AU&lc=eng&sm=g`. Click on **"1000 Series Oscilloscopes User's Guide"** in the language of your choice.

1 Objectives

After studying this section you should be able to:

- Explain what an oscilloscope is, and what it may be used to measure.
- Understand the operational principles of the major oscilloscope controls.
- Adjust the low frequency compensation on an oscilloscope probe.
- Transfer data from the oscilloscope to an Excel spreadsheet.
- Briefly describe some of the automated measurements available on the oscilloscope.

2 Introduction

2.1 What is an Oscilloscope?

An oscilloscope is an instrument used in Physics and many other branches of science to visually display an electrical signal. Essentially, the oscilloscope is a graph-displaying device – it draws a graph of an electrical signal, usually showing how the signal changes over time. On the displayed graph, the vertical (Y) axis represents voltage and the horizontal (X) axis represents time. Most oscilloscopes are able to have several graphs on their displays at the same time. With a few exceptions, the oscilloscopes in the First Year Physics labs have two channels, i.e. they can display two graphs or signals at the same time.

Until recently, oscilloscopes displayed their signals in the same manner as an analogue TV, hence the common abbreviation "CRO" (Cathode Ray Oscilloscope). A modern oscilloscope uses an LCD display (like a computer laptop), and is often referred to as a "DSO" (Digital Storage Oscilloscope).

2.2 What's it used for?

Oscilloscopes may be used to measure any quantity (temperature, pressure, force, distance, velocity, acceleration) that may be converted into an electrical voltage proportional to that quantity, especially if the quantity under measurement is changing in time. For an unchanging electrical signal we would more commonly use a voltmeter or an ammeter (often combined into a single instrument, called a *multimeter*).

Here are just four of the uses of an oscilloscope in the First Year laboratory:

- measuring the frequency of sound waves in the Ultrasonic Wave experiment (ADV and REG).
- displaying the frequency of a vibrating string in the Vibration of a Wire experiment (ADV and REG).
- measuring the rate of charging and discharging of an electrical capacitor in the Introduction to the Oscilloscope experiment (ENV).
- measuring the amplitude and frequency of an electrical signal in the AC Circuits experiment (ADV and TEC).

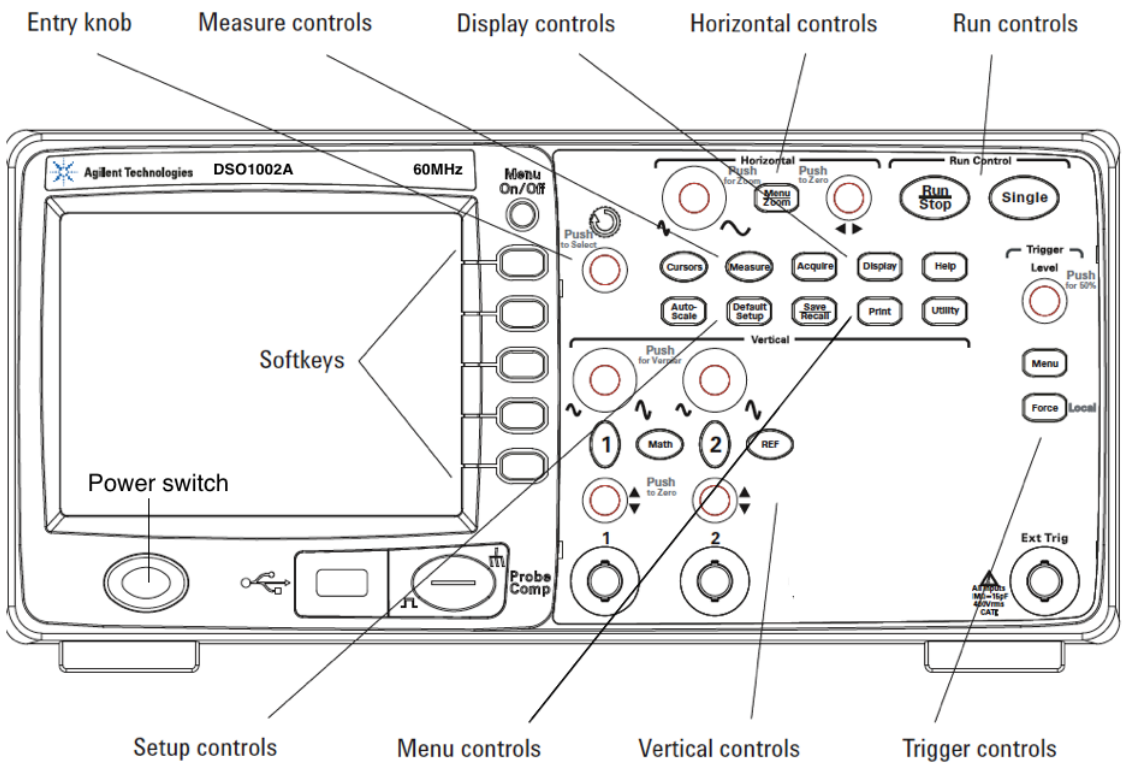


Figure 1: The front panel of an Agilent DSO1002A oscilloscope, showing the arrangement of the controls. Please spend some time familiarising yourself with its layout.

2.3 Oscilloscopes in the School of Physics

Oscilloscopes have been in common use in scientific laboratories for the last 60 years, and there is/has been a plethora of manufacturers and models, with a wide range of capabilities, layout of controls and performance. Much time could be wasted having to work out how to operate an unfamiliar oscilloscope. In order to reduce this unnecessary confusion, in 2010 the School of Physics standardised (most of) the oscilloscopes in the First, Second and Third Year teaching laboratories to a single model, the Agilent DSO1002A.

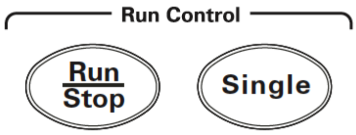
The following operating instructions, whilst generally true for all digital storage oscilloscopes, apply specifically to the DSO1002A. Figure 1 is a diagram of the front panel of an Agilent DSO1002A oscilloscope.

Closely examine the controls, either on the oscilloscope or in the diagram. Take your time. Looks complicated? confusing? All those buttons and knobs!

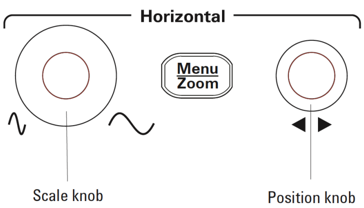
But, underneath all that complexity there is order.

1. In the bottom left hand corner is the [**Power Switch**]. Push it to turn the DSO on or off.

2. In the top right hand corner is the ***Run Control***. Push these to collect data or to stop collecting data. [**Run/Stop**] means "keep collecting until I tell you to stop", and [**Single**] means "just collect one set, please".



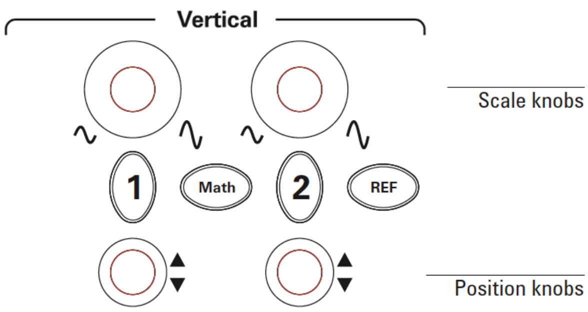
3. Immediately to the left of the ***Run Control*** is the ***Horizontal*** control. The ***Scale*** knob adjusts the horizontal (X-axis, time) scale of the display, which is often referred to as the "timebase".



The ***Horizontal Scale*** knob changes the oscilloscope's time per division setting. This setting (often written as sec/div) lets you select the rate at which the waveform or signal is drawn across the screen (it is also known as the timebase setting or sweep speed). It is a scaling factor that allows you to vary the horizontal width of the waveform or signal on the screen. If the ***Horizontal Scale*** setting is 1 ms, each horizontal division represents 1 ms/div then the total screen width represents 12 ms, or twelve divisions. Changing the sec/div setting enables you to look at longer or shorter time intervals of the input signal. On the DSO1002A, the time per division setting may be varied from 2 ns/div to 50 s/div, i.e. the total time shown on the display may be varied from 2.4×10^{-8} s to 600 s.

The ***Position*** knob enables the signal shown on the display to be shifted to the left or right. This knob enables you to change the position (i.e. time) of the trigger point relative to the centre of the screen.

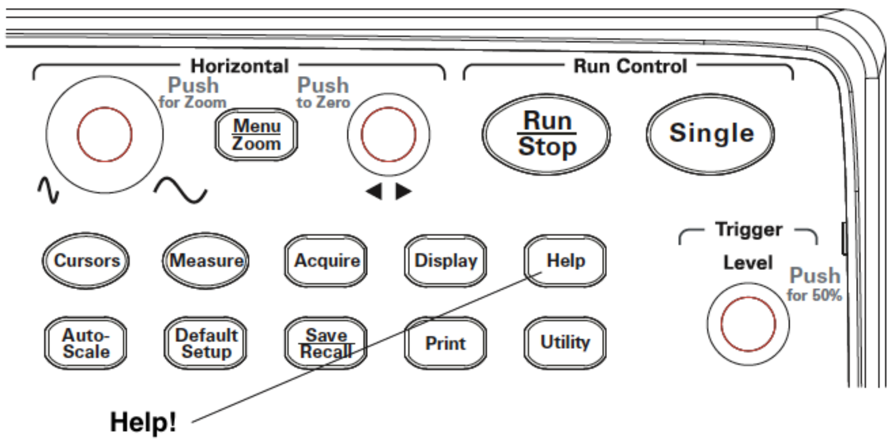
4. There are two ***Vertical*** controls, one for each channel. These channels are colour coded yellow (Channel 1) and green (Channel 2).



The ***Vertical Scale*** knobs change the volts per division setting for each signal. The volts-per-division setting (usually written as volts/div) is a scaling factor that varies the vertical size of the waveform or signal on the screen. If the volts/div setting is 1 volt, then each of the eight vertical divisions represents 1 volt and the entire screen can display 8 volts from bottom to top. If the setting is 50 millivolts/div, the screen can display 0.4 volts (400 mV) from bottom to top, and so on. The most sensitive setting on our Agilent scopes is 20 mV/division. The maximum voltage you can display on the screen is the volts/div setting multiplied by the number of vertical divisions.

The ***Position*** knobs shift each signal up or down the screen.

5. Between the Horizontal and Vertical controls are ten function buttons. At this stage, we need to know only 3 of these: [**Auto Scale**], [**Default Setup**], and, most importantly [**Help**].



- [**Help**]. Press this button, and wait a few seconds. This message will appear on the oscilloscope's screen.

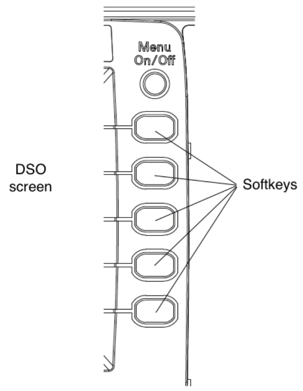
Press this key and then any other button or a menu button to access built-in help information.

For example, if we press **[Help]** then **[Default Setup]** the following message appears:

Press this key to recall the oscilloscope's default setup (that is, its settings when it was shipped from the factory) at any time.

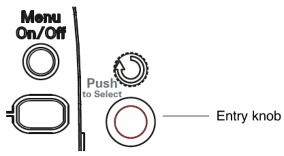
- **[Default Setup]** is useful when you get "lost" and need a "home base" to start again from.
- If you press **[Auto Scale]**, the oscilloscope endeavours to select the settings that best display on the screen your waveform or voltage.

6. The **[Menu]** and **[Softkeys]** are on the left hand side of the oscilloscope's screen. (In case you're wondering, "Softkey" is short for "software key", the keys are not physically softer (or harder) than the other keys and buttons!)

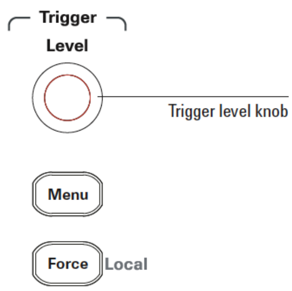


The **[Softkeys]** are used to select items in the screen menu that appears (and disappears) on the left hand edge of the screen.

7. Between the **[Softkeys]** and the ***Horizontal Scale*** knob is the ***Entry*** knob. Use this knob to make adjustments to many of the controls or menu settings.



8. The ***Trigger*** control (on the right hand side of the DSO) enables us to adjust when, and at what signal voltage the oscilloscope will start recording.



For example, we can set a particular trigger voltage; until the signal reaches that voltage, the DSO will not record. We may choose to do this if there is a lot of low level background noise in the signal. Often, however, we use the [**Auto Scale**] button, which sets the trigger mode to "Auto" . This enables the DSO to display, even without a trigger. If there is no signal present, a timer in the DSO causes the the display to "sweep" (draw on screen), so that the display will not disappear if the signal does not provoke a trigger.

We may make a single acquisition, even without a valid trigger, by pressing the [**Force**] button.

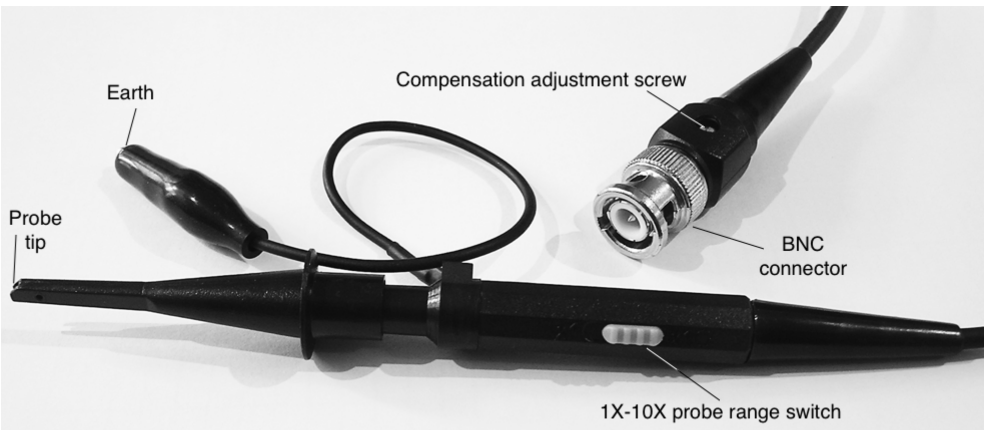
9. At the bottom of the DSO, there are three metal cylinders projecting forwards from the front, and labelled **1**, **2** and **Ext Trig**. These BNC connectors are where we connect probes or other devices whose output we wish to display or measure in the DSO. The **Ext Trig** allows us to trigger remotely (i.e. from a source external to the DSO). Can you think of a situation where we would wish to do this?

3 Using the oscilloscope

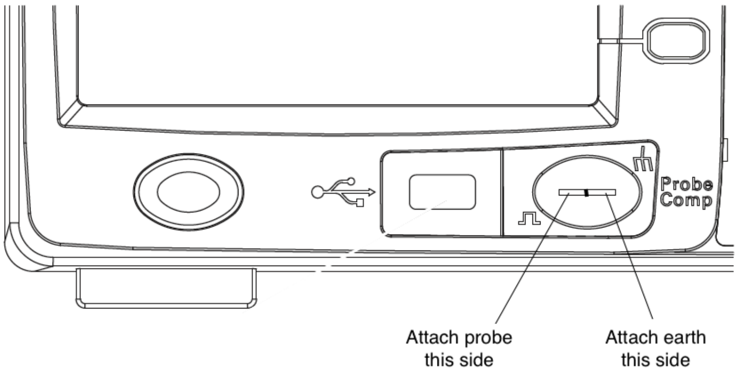
3.1 Frequency compensation of an oscilloscope probe

This is a great way to begin to become familiar with an oscilloscope, and you should always compensate a probe to match the input channel (i.e. Channel 1 or Channel 2) whenever you attach it to the DSO for the first time.

1. Attach the BNC connector of a voltage probe (for example a CP-260) to the Channel 1 BNC on your oscilloscope. Ensure that the range switch on the probe is set to 10X.

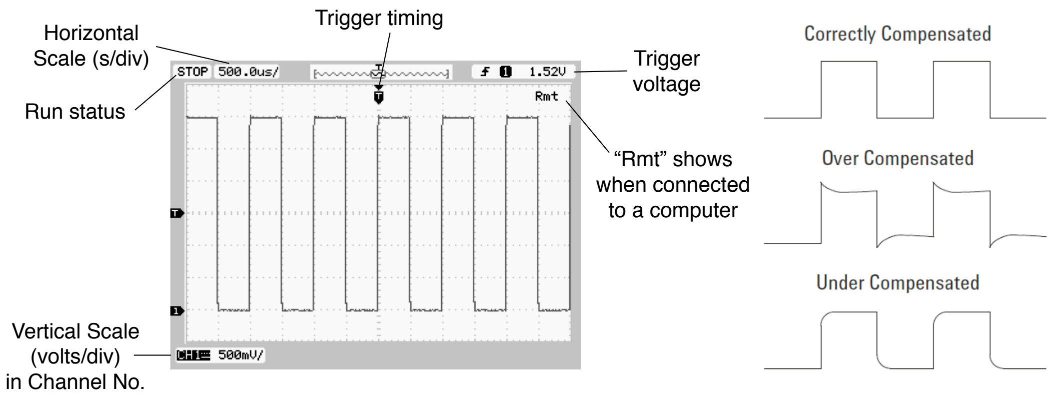


2. Attach the probe tip and the earth lead to the correct parts of the ***Probe Comp*** connector as shown in the diagram below:



The probe tip should be clipped to the left terminal (near the “hat” sign) and the earth should be clipped to the right terminal (near the “fork” sign).

3. Push the ***Power switch*** to start the oscilloscope. Then press the [**Default Setup**] button to clear any previous settings on the DSO.
4. In the ***Vertical*** control, press the oval button with a big “**1**” on it. A menu will appear on the left hand side of the screen. Check that under the word “Probe” on the menu there is a “10X”. If there is, go to step 5. If there is a different value, e.g. 1X or 100X, press the [**Softkey**] next to the value. A sub-menu will now appear. Using the ***Entry*** knob, select 10X from this sub-menu. Push the ***Entry*** knob to load the selection. Press the [**Menu On/Off**] button twice to clear both menus.
5. Now press the [**Auto Scale**] button. You should see a waveform resembling one of the following (colours inverted for easier printing):



6. Using a small screwdriver, slowly adjust the probe compensation screw until your waveform most closely resembles the “square” correctly compensated trace.

Congratulations! You have successfully adjusted your probe. Now it’s time to explore the DSO.

3.2 Exploring the DSO

Setup (or leave) the DSO as in the previous section.

1. **Adust** the ***Vertical Scale*** knob. Observe what happens. Now adjust the ***Vertical Position*** knob: note how the wave is shifted up and down on the screen. Try the same adjustments with the ***Horizontal*** controls.

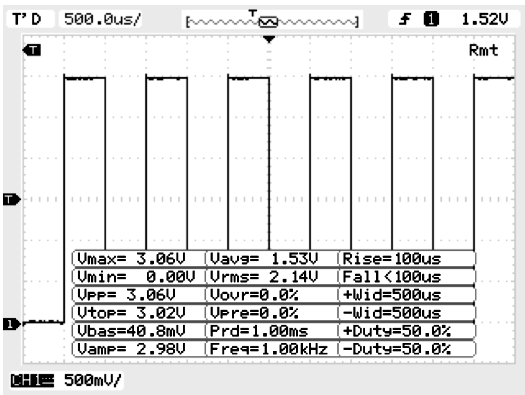
   > Remember, you can always get back to the original settings by pressing the [**Default Setup**] button, followed by the [**Auto Scale**] button.

2. **Measurements**. We may set the DSO to display on screen a wide range of measurements derived from the displayed signal or waveform.

   > **Please note**: To understand the meaning of all the measurements shown on the display, you should consult Ch 4, Making Measurements, in the Agilent User's Guide, by clicking the **Agilent Oscilloscope Manual** icon in the **Start** menu of any of the First Year laboratory computers or via the URL in the text box at the beginning of these notes.

   Setup the DSO as in the previous section. Press the [**Measure**] button. A menu will appear on the left side of the screen with "Measure" at the top. Ensure you are on the second page of the menu (2/2), by pressing the bottom-most [**Softkey**]. Now press the [**Softkey**] adjacent to the "Display All" menu item setting it to "On". To get rid of the menu, press the [**Menu On/Off**] button.

   To remove the measurement display from the screen, repeat the procedure and change "Display All" to "Off".



3. **Do your own explorations**. . . over to you . . .

4. **Channel Coupling** Electrical signals may be extremely complex, containing a mixture of both AC (alternating current, the signal has an oscillation at a particular frequency, e.g. household electricity is 50 Hz) and DC (direct current) components. The oscilloscope may be set up to make it easier to measure the relevant part of the signal. By "Coupling", we mean the method used to connect an electrical signal from one circuit to another. In this case, the input coupling is the connection from your test circuit or measuring instrument to the oscilloscope.

   - **DC**. Passes both DC and AC components of the input waveform to the oscilloscope. You can quickly measure the DC component of the waveform by simply noting its distance from the ground symbol.

- **AC**. Blocks the DC component of the input waveform and passes the AC component. This lets you use greater sensitivity (amplitude/div settings) to display the AC component of the waveform.
- **GND**. The ground setting disconnects the input signal from the vertical system, which lets you see where zero volts is on the screen. With grounded input coupling and auto trigger mode, you see a horizontal line on the screen that represents zero volts. Switching from DC to ground and back again is a quick way of measuring signal voltage levels with respect to ground.

When you press the [**Default Setup**] button, **DC** coupling is selected.

If you need to change the channel coupling, in the ***Vertical*** control, press the relevant oval channel button (big "**1**" or "**2**" on it). A menu will appear on the left hand side of the screen. Select "Coupling" with the adjacent [**Softkey**]. A sub-menu will now appear. Using the ***Entry*** knob, select AC, DC or GND from this sub-menu. Push the ***Entry*** knob to load the selection. Press the [**Menu On/Off**] button twice to clear both menus.

3.3 Noise reduction

Often the signal we are wishing to display will suffer from random noise (rapid random voltage spikes and fluctuations) which may make the data difficult to read. We may reduce the noise in the signal in a variety of ways, two of which are:

- Signal averaging
- Bandwith limiting

Digital filtering may also be used to remove selected frequencies, for details please see p. 49 of the Agilent 1000 Series Oscilloscopes Users Guide.

3.3.1 Signal averaging

A simple way of reducing random noise is by signal averaging, in which the displayed signal is the average of the last several measurements. The Agilent DSO1002A may be set to make 2, 4, 8, 16, 32, 64, 128, or 256 averages.

1. **Normal acquisition mode.** The default acquisition mode of the oscilloscope is the **Normal** mode (averaging turned off). To select or to return to **Normal** acquisition,
   (a) Press [**Acquire**].
   (b) In the Acquire menu, press the softkey adjacent to **Acquisition**.
   (c) Continue pressing the **Acquisition** softkey or turn the ***Entry*** knob to select **Normal**.

2. **Average acquisition mode**
   (a) Press [**Acquire**].
   (b) In the Acquire menu, press the softkey adjacent to **Acquisition**.
   (c) Continue pressing the **Acquisition** softkey or turn the ***Entry*** knob to select **Average**.
   (d) Press **Averages** and turn the ***Entry*** knob to select the desired number (2, 4, 8, 16, 32, 64, 128, or 256).

3.3.2 Bandwidth limiting

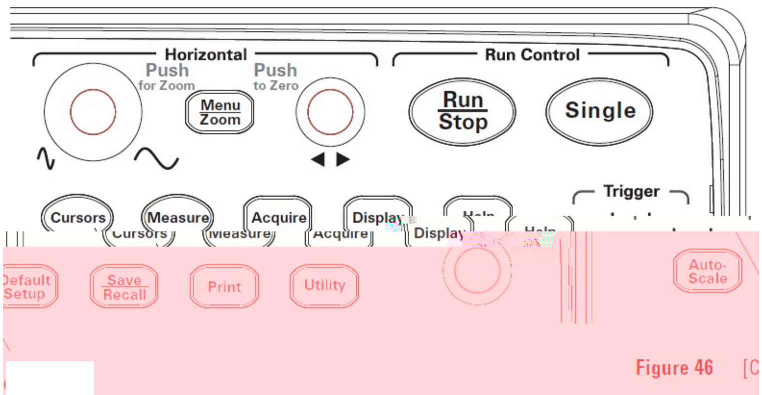
When the high frequency components of a waveform are contributing to the noise and are not important to the analysis of the signal, the bandwidth limit control may be used to reject frequencies above 20 MHz.

1. Press the channel key for the relevant channel [**1**] or [**2**]

2. In the **Channel** menu, press [**BW Limit**] to toggle the bandwidth limit setting to **ON** or **OFF**.

3.4 Using the Cursors

You can use the [**Cursors**] front panel key to select between these cursor measurement modes:



- **Manual**: Gives you manually adjustable, parallel cursors for measuring time or amplitude between cursors.

- **Track**: Gives you one or two manually adjustable, cross–hair cursors that track the points of a waveform, measuring time and amplitude.

- **Auto**: Gives you automatically adjusted cursors for the most recently displayed voltage or time measurement.

- **OFF**: Cursors are tuned off.

3.4.1 To use tracking cross-hair cursors

(The most useful) You may set up one or two manually adjustable, tracking cross- hair cursors to make amplitude (vertical) and time (horizontal) measurements at different points of a selected channels waveform.

1. Press [**Cursors**] .

2. In the [**Cursors**] menu, press [**Mode**].

3. Continue pressing the [**Mode**] softkey or turn the ***Entry*** knob to select **Track.**

4. Press **Cursor A**, and continue pressing the softkey or turn the ***Entry*** knob to select the channel on which to make the measurement (or **None** to turn off the cursor).

5. Press **Cursor B**, and continue pressing the softkey or turn the ***Entry*** knob to select the channel on which to make the measurement (or **None** to turn off the cursor).

6. To adjust the cursors:

   - Press **CurA** and turn the ***Entry*** knob to adjust the **A** cursor.
   - Press **CurB** and turn the ***Entry*** knob to adjust the **B** cursor.

   (a) The **A** cursor values displayed are:
      - A -> X (i.e. the x-axis or time value)
      - A -> Y (i.e. the y-axis or amplitude value).

   (b) Similarly, the **B** cursor values displayed are B -> X and A -> Y.

   (c) If both **A** and **B** cursors are used, these values are also displayed:
      - ΔX difference between **CurA** and **CurB** time values.
      - 1/ΔX shows the frequency associated with the time value difference.
      - ΔY difference between **CurA** and **CurB** amplitude values.

4 Exporting data from the DSO

The are three ways of doing this:

1. To a computer, directly into an Excel spreadsheet using the Agilent 1000 Add-Ins in the Excel 2007 (Add-Ins) and Excel 2003 (Tools/Add-Ins) toolbars.

2. To a computer, using the Agilent “Intuilink” software.

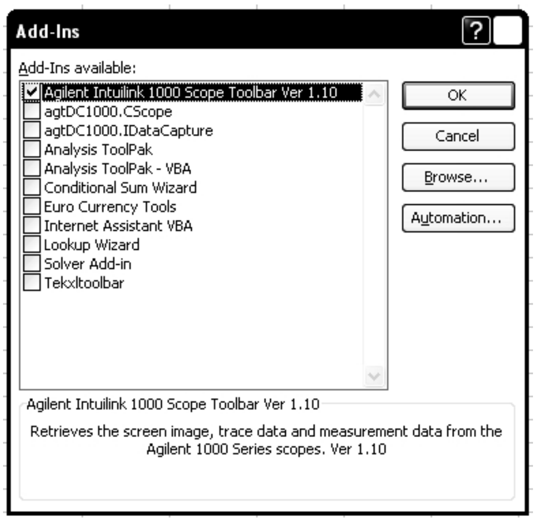
3. To a USB stick, via the USB port on the front of the DSO - slow and fiddly, not recommended, saving directly to a computer is much simpler.

4.1 Excel spreadsheet using Add-Ins

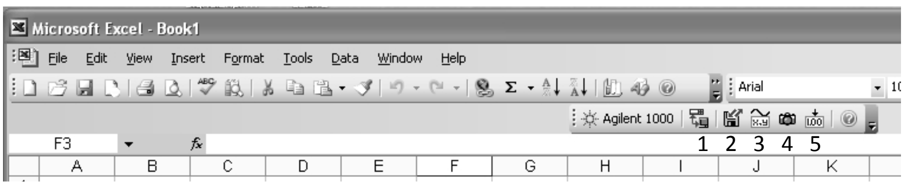
(This requires the Agilent Excel Add-In to have been installed on your PC.)

1. Ensure that the DSO is connected to the USB port of your PC via the square "USB Device" port at the rear of the DSO.

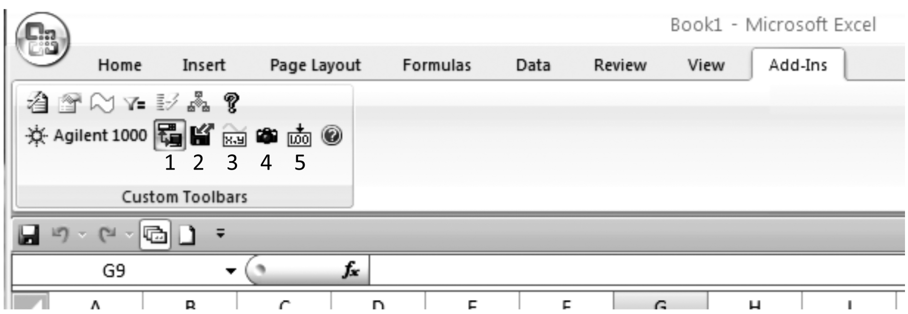
2. **In the First Yr Lab, please use Excel 2003.** Open Excel 2003. Click on the "Tools" menu and then "Add-Ins". Make sure that "Agilent Intuilink 1000 Scope Toolbar" is ticked.



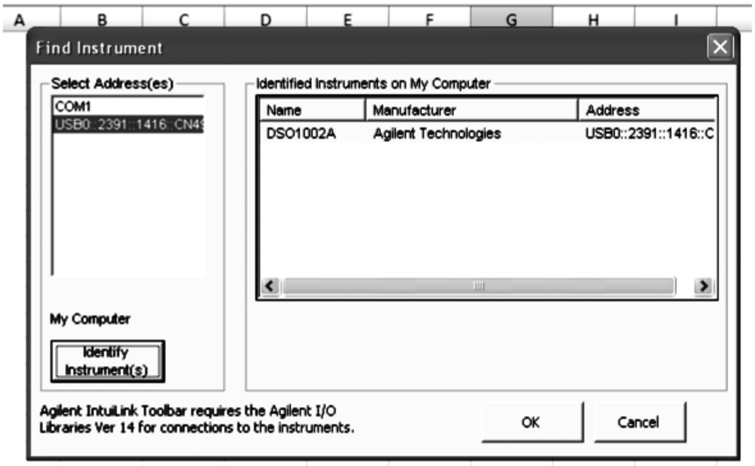
3. A toolbar with the words "Agilent 1000" with a row of six icons next to the words should appear as shown below. The numbers 1 - 5 below the icons **will not** appear; I have inserted them to make these instructions easier.



4. If your are using Excel 2007, click on the Add-Ins menu. The Agilent 1000 toolbar should now appear.



5. Click on the first icon (1), next to the words "Agilent 1000". Excel will search for the DSO. A "Find Instrument" dialogue box should appear like the one shown below.



6. Select the USB address. Click “Identify Instrument”, and the words “DSO1002A Agilent Technologies” should appear as an “Identified Instrument”.
7. Click “OK”. Now click on the “get waveform data” icon (3), and a dialogue box will open. You may need to change the number of data points in the dialogue box, depending on how much of the DSO signal you wish to display in Excel.

> **Please note**: Time zero on the Agilent is the middle of the screen, so your saved waveform will have *negative* time values (!) in the x-axis column. The simplest way to deal with this in Excel is to insert a new column between the x-axis column and the other Ch1 (and/or Ch2) column. Label it “Time” (or similar). Assuming the x-axis data, Time and Ch1 are in columns A, B and C, type **exactly** this (without the brackets) in cell B2, (=A2-A2). Select cell B2 and drag-fill column B. “Time” will now start at zero.

8. The camera icon (4) downloads a picture file of the screen (colours are inverted). The “get measurement” icon (5) downloads selected measurements to the Excel spreadsheet.

4.2 Agilent “Intuilink” Software

(This requires the Agilent “Intuilink” to have been installed on your PC.)

1. Ensure that the DSO is connected to your PC via the square “USB Device” port at the rear of the DSO.
2. On your PC, double click the **Intuilink Data Capture** icon.
3. Click on the **Instrument** menu. Make sure **Agilent 1000 Series** is “ticked”, then click on it. A dialogue box **Agilent 1000 Series Add-In** will appear. In most cases, the default settings in the dialogue box will be suitable
4. Click, “OK” and a screen shot (a bmp picture file) and a “waveform” will appear on your PC screen. The waveform may be saved as a csv file (which Excel or other spreadsheets may open), the default is as a text file, so you will have to select csv in the “Save” dialogue box. Remember to check the “Include X-axis data on save” box on the waveform if you want to graph the data in a spreadsheet.

5. There are two ways of saving measurements via Intuilink:

   (a) Click on the **Instrument** menu. Make sure **Agilent 1000 Series** is "ticked", then click on it. A dialogue box **Agilent 1000 Series Add-In** will appear. Click the **Measurement** tab. Click "Select All" and "Save Data". The measurements will be saved as a csv file.

   (b) Set up Measurements on the DSO screen as in the Measurements section in **3.2 Exploring the DSO**. Then click on the **Instrument** menu as before. The on-screen measurements will now appear in the screen shot bmp file.

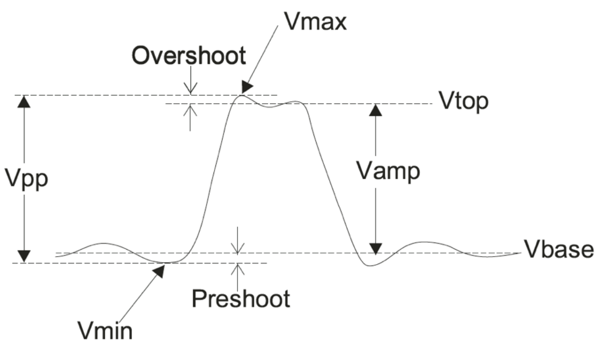
> **Please note**: When connected to the PC, the DSO is locked and the [**Run**] button will be red. If you want to make changes to any of the settings on the DSO, first press the [**Force**] button in the Trigger controls, and then the [**Run**] button. The [**Run**] button should now be green, and you can make your adjustments.

5 Measurements: A brief summary

Please remember: To understand the meaning of all the measurements of which the DSO1002A is capable, you should consult Ch 4, Making Measurements, in the Agilent User's Guide, by clicking the **Agilent Oscilloscope Manual** icon in the **Start** menu of any of the First Year laboratory computers or via the URL in the text box at the beginning of these notes.

5.1 Voltage Measurements

There are 10 automatic voltage measurements available on the Agilent DSO1002A:



- **Vmax** (Maximum Voltage).The maximum amplitude. The most positive peak voltage measured over the entire waveform.

- **Vmin** (Minimum Voltage). The minimum amplitude. The most negative peak voltage measured over the entire waveform.

- **Vpp** (Peak-to-Peak Voltage). Peak-to-peak voltage.

- **Vtop** (Top Voltage). Voltage of the waveform's flat top, useful for square and pulse waveforms.

- **Vbase** (Base Voltage). Voltage of the waveform's flat base, useful for square and pulse waveforms.

- **Vamp** (Amplitude Voltage = Vtop - Vbase). Voltage between Vtop and Vbase of a waveform.

- **Vavg** (Average Voltage). The arithmetic mean over the entire waveform.

- **Vrms** (Root-Mean- Square Voltage). The true root-mean- square voltage over the entire waveform.

$$RMS = \sqrt{\frac{\sum_{i=1}^{n} x_i^2}{n}}$$

  Where x_i = the value at the x^{th} point, and n = the number of points in the waveform.

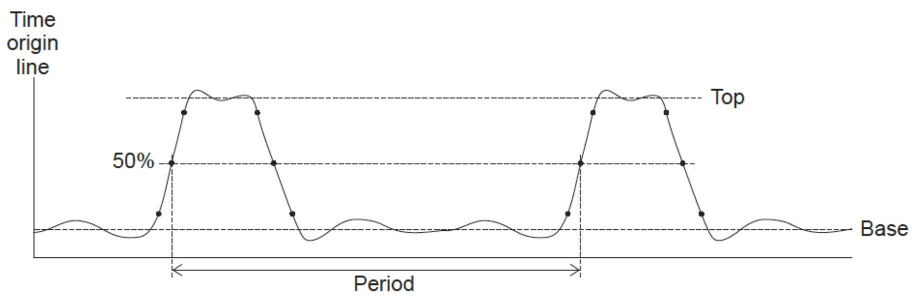
- **Overshoot.** Defined as (Vmax-Vtop)/Vamp, useful for square and pulse waveforms.

- **Preshoot.** Defined as (Vmin- Vbase)/Vamp, useful for square and pulse waveforms.

5.2 Time Measurements

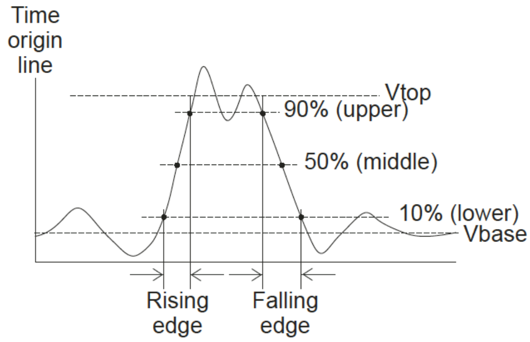
Some of the available time measurements are:

- **Period**. Measures the period of a waveform.

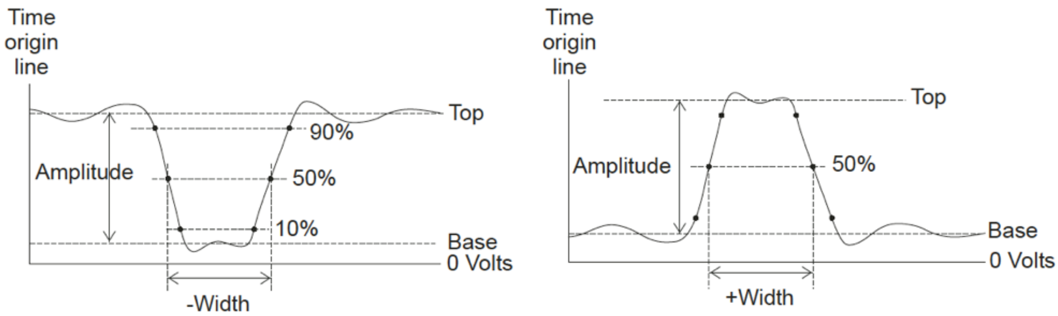


- **Frequency**. Measures the frequency of a waveform.

- **Rise Time** or **Fall Time**. Measures the time taken for a waveform to rise or fall from 10 % above Vbase to 10 % below Vtop.



- **Positive or Negative Pulse Width**. Measures the width of a pulse at the half maximum or half minimum position. Often referred to as **FWHM** (Full Width at Half Maximum).



For other available measurements, please see the Agilent 1000 User's Guide.

EXPERIMENTAL ANALYSIS

1. UNCERTAINTIES IN MEASUREMENT

Whenever scientists measure a quantity, whether directly or by calculation from more basic measurements, it is necessary to have an idea of how accurate the result is. Some instruments give very accurate readings and the uncertainties in our measurements are negligible (but not zero); other instruments or measuring techniques give substantial uncertainties, and we need to know about this. And in some experiments where we count discrete randomly occurring events (such as decay of radioactive atoms), there is inherent scatter or uncertainty present.

Gaining a working knowledge of how to handle uncertainties in measurement (i.e. 'what to put after the ± sign') will be an important part of your Experimental Physics course.

Knowing the uncertainty in the result of a physical measurement greatly enhances the value of that measurement, for then we know how far it can be trusted. We can make full use of the measurement, without pushing it too far. For example, some estimates give the age of the oldest stars as greater than the time since the Big Bang, which is impossible. Perhaps there are inadequacies in the theory of evolution of stars and/or the cosmological theory giving the age of the universe. But before reaching that conclusion, it is vital to have good estimates of the uncertainties of the two age values, to see whether the disagreement is really significant.

For a more familiar example, suppose you use a ruler to measure the length of a steel rod and find a value of 190.1 mm. You can't be certain of the last figure - maybe the length is really 190.2 mm or even 190.3 (or 190.0 or 189.9). In this case the uncertainty (about 0.1 to 0.2 mm) is clear from the number of figures used to quote the result. We would not give any more because we cannot read them from the ruler. Now you ask someone to calculate what the length will be when the rod has been cut into three equal pieces. The answer comes back as 63.3666667 mm. Do you believe that? Quite apart from the limited cutting accuracy and the width of the cuts, clearly those extra figures (...66667) have just been read off a calculator display. Does this matter? Yes, because the extra figures are misleading. They are not valid; they are pure fiction, in fact, and we should report results that are true within their known and stated limitations.

Common sense (and a bit of thought) tells you what to expect in the above example with the ruler. The same combination of common sense and consideration of the system you are measuring is the most important ingredient for handling uncertainties in physics. There are also some formulae for calculating and combining uncertainties, which we will deal with in a later section.

1.0 Indicating uncertainty

There are two different ways of indicating the uncertainties in the numerical values of scientific quantities.

1. **Explicit** - using ± followed by a number. This is often used for results derived directly from experimental quantities. Using the example of the ruler, the steel rod's length is 190.1 ± 0.1 mm.
2. **Implicit** - restricting the number of significant figures so that *only* the last digit is uncertain. Using the example of the ruler, the steel rod's length is 190.1 mm. *This convention should be used for the final answers in all Physics tests, assignments and examinations.* The intermediate steps of any calculation should usually have one or two more significant figures to prevent the accumulation of 'round-off' effects.

Each of these methods is covered in more detail below, but first we will clarify the distinction between decimal places and significant figures.

1.0.1 Decimal Places and Significant Figures

Decimal places are not the same as significant figures.

The following numbers all have 3 **decimal places** (the number of digits to the right of the decimal point):

1.231   0.100   423.756   0.012   0.003

The following numbers all have 3 **significant figures** (working from the left, start counting at the first non-zero digit and continue to the far right, including all subsequent zeros):

1.23   0.100   0.000340 4.00×10^{3} 0.0741×10^{-6}

Note that powers of 10 can be employed to avoid the use of excessive significant figures. Assume for instance that, for a calculated length of 3800 m, the last two digits happen to be very uncertain (the true value might be anywhere between 3700 m and 3900 m). Then the result would be better stated as 3.8×10^{3} m or 3.8 km or even 0.0038×10^{6} m. On the other hand, if you measure a length of exactly 1 m, it should be recorded as 1.00 m or 1.000 m depending how reliable the measurement was. Don't just use 1 m.

In Physics tests and exams you should assume, in the absence of other information, that numerical data have an appropriate number of significant figures.

1.0.2 Use of ±

Unless the uncertainty is derived from a large number of high quality measurements, the uncertainty itself is often very uncertain - probably by at least 10% and maybe up to a factor of 2. Thus it is usually written with only one *significant figure*. The actual answer is then rounded to have the same number of *decimal places*.

For example, assume a calculator gives a result of an averaged measurement as:

mean = 1.37415 mm with an SEM (defined in section 1.3) = 0.0438 mm.

Uncertainty to 1 significant figure

Then the final answer is quoted as $\underline{(1.37 \pm 0.04)\ \text{mm}}$.

Answer limited in decimal places to match uncertainty

'Rounding' consists of removing unwanted digits from the right hand end of a number (e.g. 1.413 rounded to two significant figures is 1.4). If the digits being removed are ≥ 0.5 in the last remaining digit then that digit is increased by one. For example, both 1.45 and 1.463 rounded to two significant figures are 1.5.

1.0.3 Combinations of values

How do you use decimal places and significant figures in calculations?

Key Point

- For calculations involving addition or subtraction, the answer should have the same number of *decimal places* as whichever number in the calculation has the *least* decimal places - e.g. 1.324 + 1.5 = 2.8 (to 1 decimal place).
  If using scientific notation, all the quantities should first be converted to the same power of 10.
- For calculations involving multiplication or division, the answer should have the same number of *significant figures* as whichever number in the calculation has the *least* significant figures – e.g. 3.2 / 2.871 = 1.1 (to 2 significant figures).

These rules apply even if the result happens to be an integer – e.g. 8.0000 / 2.00 = 4.00 (to 2 significant figures).

These rules are a bit rough but to get better results you would need to know the actual uncertainty of each quantity (see section 1.5).

1.1 Sources of uncertainty in measurements

In this section we discuss the five principal sources of uncertainty in the measurements we make. In general more than one source will affect each measurement, but we often find that one such source dominates and the corresponding uncertainty is the one quoted as the uncertainty associated with the measurement.

1.1.1 Calibration

Suppose you use a magnifier to help you read a ruler more accurately. You could certainly read to 0.1 mm quite well in this way. But what if the ruler is one of those cheaply made plastic ones - how well do its markings actually represent real millimeters? Such rulers may be wrong by about 0.5 mm or even 1 mm along a 300 mm ruler, when compared with a high-quality scale. This would be what we call a *calibration error* of the measuring device. All measuring instruments have a calibration uncertainty at some level. It is usually stated by the manufacturer. For example, some of the digital multimeters in the laboratory have a quoted limit of inaccuracy of 0.5% of the reading.

1.1.2 Resolution

Readings you make are usually limited to a certain number of significant digits. For a ruler, the reason for this limit is obvious. In the case of instruments with a digital readout it depends on the number of digits displayed and for analog instruments on the number of divisions indicated. The smallest amount by which the quantity may vary before you can actually detect this change is termed the resolution of the instrument. For digital instruments it is safe to quote ± 1 in the least significant digit. For analog instruments it depends somewhat on the experimenter's skill in reading the scale (there is no hard and fast rule of half the smallest scale division).

1.1.3 Experimental technique

Some errors arise from the physical process involved in making the measurement. Parallax error is one such uncertainty. This occurs when the observer's line of sight, the scale pointer and the scale are not properly aligned. Another example is using a stopwatch to measure a time interval. There will always be some delay due to the observer's reaction time. A part of good experimental design is to be aware of such problems, and to minimise their effects.

1.1.4 Statistical fluctuations

In some physical processes and experiments the outcome is governed by the probability of randomly occurring events. For example take the radioactive decay of Rn-222. If we count for 1 minute and obtain 103 decays then we know that from the statistical theory of such processes (the Poisson distribution) there is an uncertainty associated with this result of approximately ± 10 counts (i.e. $\pm \sqrt{103}$). This statistical uncertainty is also true for other counting experiments where a random process is involved in generation of the events.

1.1.5 Variation in the quantity itself

Some quantities we may need to measure are not as well defined as we might think at first sight. For example say we want to measure the thickness of a wire. We may find that the thickness is not constant along the length of the wire. So the ‘diameter’ of the wire is not a single number at all, but really a function of distance along the wire, and probably the angle around the wire too. Whether this matters or not will depend on the extent of the variations and the accuracy required for our particular application. You have to use your judgement, based on all the facts available.

1.2 Random versus systematic uncertainties

Most uncertainties, including those discussed above, can be classified as either random or systematic.

1.2.1 Random uncertainties

Random uncertainties produce scatter in observed values, about either a single value being measured or a fit to some predicted behaviour (eg a straight line). Random uncertainties can arise from statistical fluctuations, variations in the quantity being measured, resolution effects and some types of errors due to experimental technique. For example, if we use a ruler to make three measurements of the length of a rod (being careful not to let our memory of a previous measurement influence the next one), and get 190.0, 190.1, 190.1 mm, the scatter in these readings is a random error. The effect of random uncertainties can be reduced by taking more readings and averaging.

Most times when we repeat experiments we obtain slightly different results. This may be due to different conditions or fluctuations in human error such as parallax or observer's reaction time. In electronic instruments it may be due to the electrical ‘noise’ in the circuit or the instrument.

1.2.2 Systematic uncertainties

If the measuring instrument used is not calibrated properly, all values may be consistently low or high. This leads to systematic uncertainty. It is no help taking more readings - since all readings are similarly affected, the error will not be reduced by averaging the results.

In one type of systematic uncertainty all readings may be simply offset by a given amount. A common example is the zero error on a micrometer screw gauge. When the micrometer is shut the scale may not read zero. This reading is termed the zero error and should be determined and then subtracted from all values to correct for the systematic error. Another type of systematic uncertainty is where all readings are consistently low, by say 2%, due to calibration error. In such cases we are likely to know the maximum magnitude of the error (eg the manufacturer says that the scale is accurate to $\pm$ 2 %), but we do not know the *actual* error unless the instrument has been specifically checked against a more accurate one. If we did know the error, then we could adjust the reading to allow for it (as for the zero error of a micrometer screw gauge). (Removal of errors in this way is never possible in the case of *random* uncertainties, precisely because they are random – i.e. unpredictable from one measurement to the next.)

Systematic uncertainties are not always obvious to discover, and it is an important experimental skill to be able to spot possible sources of systematic errors.

1.2.3 The borderline between random and systematic uncertainties

In some cases it is not obvious whether the uncertainties are random or systematic. As an example consider the parallax error associated with a measurement. If the magnitude and sign (i.e. direction) of the error varies with each reading then the uncertainty is (almost) random. However, if the experimental technique is such that the parallax error causes the reading to be too high or low by about the same amount each time then the error is mostly systematic. Again, some thought should always be used, rather than blind application of rules.

Many physical quantities vary with temperature, pressure or other conditions. If we cannot ensure that these remain constant throughout our experiment then we are introducing a further uncertainty in the quantity we are measuring. The error introduced is likely to be partly random and partly systematic. Similarly the error due to variation of a quantity itself (such as the diameter of the wire mentioned above) may be neither fully random nor fully systematic. All these factors should be taken into account in your 'common-sense' appraisal of the uncertainties in a measurement.

1.3 Repeated measurements

We now discuss in more detail how we can reduce random uncertainties by taking repeated measurements. If repeated measurements of the same quantity give slightly different results (that is, a scatter of results about some preferred value), what should we do about it? There are two things to consider - firstly, how shall we get a single 'best' result from the set of readings, and secondly, how can we quantify (measure) the actual degree of scatter of the readings? Let us consider both those tasks in turn.

1.3.1 Why we use the mean of a set of readings

Suppose we have measured the height of water in Sydney Harbour relative to a fixed mark, and that we made 10 measurements over a period of 5 minutes (short enough that tidal variation will not introduce a systematic trend). We obtained readings of 0.78, 0.76, 0.73, 0.74, 0.90, 0.76, 0.85, 0.87, 0.84, 0.79 m. The main cause of scatter, i.e. differences between the readings, will be ripples going past the height gauge (an example of a variation in the quantity itself).

To get the best possible single estimate of the desired quantity from the set of data, the procedure is simple - just take the **mean** (i.e. average) of the readings. This is 0.802 m. It is intuitively clear that the mean is in some way more accurate than any one of the individual readings. It has averaged out much of the scatter. In a later section we will show precisely *how much* better the mean is than a single measurement.

By the way, note that our primary aim in taking the mean of a set of data is to average out *random* errors. If there is some systematic trend, eg the numbers keep getting bigger as the tide comes in, then the mean is going to tell us about the average of the trend at the time of the measurements, and is not going to effectively remove random measuring errors. Again, be observant, note all relevant aspects of the situation, and think about what you are doing.

1.3.2 Quantifying the scatter in measurements

Now let us consider the ways we might measure the degree of scatter in the readings of the water height in Sydney Harbour. In other words, what should we put after the ± sign.

We could use the difference between the smallest reading (0.73 m) and the largest (0.90m). Although the difference, 0.17 m, does give some indication of the scatter, it is not the best method because it ignores all the other readings. And if we took a larger number of readings we would tend to get a higher maximum and lower minimum, even though the actual characteristics of the scatter did not change.

We could calculate the *difference* of each reading from the mean. That difference tells us how far from the mean the individual reading is. Since we have 10 readings, we could then average the differences. That would make use of all the readings, but would it work? Satisfy yourself that in fact the sum of the positive differences will cancel out the sum of the negative differences, so this will not do what we want. We could cure that problem by instead averaging the absolute values of the differences; that would be a valid method but is not used much because its theoretical properties are difficult to analyse.

The preferred method to quantify random scatter is:

- (i) Calculate the difference of each reading from the mean (as above)
- (ii) *Square* the differences, so that they are all positive
- (iii) Average the squared differences
- (iv) Take the square root, so that the result has the same physical dimensions as the original measurements.

The result is called σ the rms (or <u>r</u>oot <u>m</u>ean <u>s</u>quare) deviation of the results about their mean. It is also called the **standard deviation**. For the water level measurements above, we get

0.059 m. Note that this is *not* an absolute upper limit to the deviation of readings from the mean. On the contrary, according to statistical theory we expect about 32% of readings to be further than this from the mean, and the other 68% to be less than one standard deviation from the mean.

There is one minor complication that you should be aware of, although we will not deal with its theoretical basis: If the mean has been found from the *same data* as we are using to find the scatter, as is usually the case, then after totalling the squared deviations we should divide by n-1 to find the mean square deviation, rather than dividing by n (n is the number of readings). Most calculators have a button to find the standard deviation, labelled σ (a Greek sigma) or s. If the calculator offers a choice of σ_{n-1} or σ_n you should choose σ_{n-1}.

Now let us consider further what the standard deviation tells us. Suppose that instead of 10 readings of the water height, we were able to obtain 100 readings (again with only random errors, i.e. with no systematic trend). We could then calculate the standard deviation (rms scatter or error) from this larger set of readings. Would that standard deviation be greater than the value from 10 readings, about the same, or less? Remember that the standard deviation is a measure of how much individual readings scatter about the mean. Convince yourself that the two standard deviations will be about the same because they are measuring the same thing.

Although the standard deviation is an estimate of how much *individual* readings scatter about the mean, nevertheless we must have a number of measurements before we can estimate it. This is intuitively clear; with one reading, for example, we have some idea of what the mean might be, but absolutely no information on the scatter. In practice we should have at least 5, preferably 10 points before we calculate σ. The reason is that with too few points the estimate of σ will itself have an uncertainty that is unacceptably large.

To summarise our discussion of mean and standard deviation, we give the relevant formulae. Let x_i be a series of repeated measurements of a quantity, with i = 1...n.

$$\text{Sample mean} = \bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$$

$$\text{Sample standard deviation} = \sigma_{n-1} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}$$

These are most easily evaluated using the function buttons on your calculator or using the Excel functions AVERAGE and STDEV (see Section 3.5).

1.3.3 Mean and SEM

So what should we put after the ± sign? Is it just σ_{n-1}? No, not if our result is the average of several readings. We know that using the mean helps to average out random scatter in our measurements. We now consider precisely how much more accurate the mean is than any one of the individual readings. From statistical theory it can be shown that when we use the mean of n measurements, the uncertainty is reduced by a factor of $\sqrt{n}$ from σ_{n-1} to the **standard error of the mean (SEM)** which is given by

$$\text{SEM} = \frac{\sigma_{n-1}}{\sqrt{n}}$$

In our water level example, with n = 10 readings, mean $\bar{x}$ = 0.802 m and standard deviation σ = 0.059 m, we find SEM = 0.019 m. We would write the result as h = (0.80 ± 0.02) m. So we obtained a very useful improvement (reduction in uncertainty) by averaging the 10 readings.

To better understand the meaning of SEM it may help to consider the following: suppose that we repeated the entire water level experiment 20 times - so we would have 20 sets of 10 readings. From each set we could calculate a mean. Those means would not all be quite the same; they would have a scatter, which we could find by calculating the standard deviation of the 20 means from the overall grand mean. But we do not need to go to all that trouble; from just the one set of readings, with its mean and standard deviation of the individual readings about the mean, we can estimate what the rms scatter of the mean is. This is just the SEM, and since it gives us the scatter of any one of the means about the grand mean, that is exactly what we want as the uncertainty estimate of the one mean that we did actually find in our experiment. So it is the SEM that we should put after the ± sign.

For a given experimental setup the standard deviation of the readings is fixed, so the SEM can be reduced by taking more readings. The above formula shows explicitly how much the rms scatter is reduced by taking the mean of a number of readings. (*Provided* they really are randomly distributed - here you need to use common sense to check that this condition is satisfied.)

In the example above (with 10 readings), we found the standard deviation σ = 0.059 m, If the data are random, then 68% of the readings are expected to fall within the range from 0.74 to 0.86 m. We also found the SEM = 0.019 m. If the data are random and we take a new set of data, there is a 68% chance that the new mean will be in the range 0.78 to 0.82 m.

1.3.4 What if there are discrepant points?

Sometimes what is supposed to be a consistent set of repeat readings measuring the same quantity, or data that are expected to lie along a linear relationship, will instead contain one or more very discrepant values. We sometimes call these ‘outliers’.

For example, suppose the above set of water level readings had been 0.78, 0.76, 0.73, 0.74, 0.90, 0.76, 0.25, 0.87, 0.84, 0.79 m. The lowest reading, 0.25, seems incompatible with the rest. The mean has dropped to 0.742 m, but the standard deviation has more than tripled, to 0.182 m. We use the *squared* deviations in calculating the rms deviation, so it is very sensitive to outliers, because they have large deviations which get even larger when squared. A single outlier point can dominate the entire total of the squared deviations, as in the example here.

A point (reading) can be classed as an outlier, and hence suspect, if omitting it reduces the standard deviation by a lot, say a factor of two or more (providing that there are still about 6 to 10 or more points remaining). We do *not* like to throw readings out just because they seem discrepant - far better to re-examine the experimental work and the calculations to try to find and correct the cause of the discrepancy. Use your common sense, but ask your tutor for guidance and approval before discarding readings in this way.

1.4 Quoting results

When quoting results we present the best estimate for the quantity itself (generally the mean) and the associated uncertainty. It is usual to quote only one significant figure in the uncertainty (sometimes two figures if the first is 1) and then round the best estimate to the same decimal place as the uncertainty. Consider an experiment in which Planck's constant was determined and we obtained a result of 6.648×10^{-34} J.s and an uncertainty of 4×10^{-36} J.s. We would quote the result as $h = (6.65 \pm 0.04) \times 10^{-34}$ J.s. If an actual uncertainty is not quoted (or not relevant) the number of significant figures is used as a guide to represent the uncertainty. Therefore, when quoting a result based on direct measurements made with a metre rule, 0.342 m is appropriate but 0.34247 m is misleading and incorrect.

1.5 Combining uncertainties

Most experimental results are calculated from measurements of several quantities, each of which has its own uncertainty. For example, to find the density of a brass cube we measure its mass and its volume, both with their own uncertainty, then we calculate *density* = *mass/volume*. How do we find the uncertainty in the density? Here we give the guidelines for combining uncertainties in measured values to give the uncertainty in the final result.

Firstly, we distinguish between uncertainties expressed as **limits of errors** such as calibration and resolution and those associated with **random statistics** (such as standard deviation, SEM and counting experiments). We will only combine limits with other limits and SEMs with SEMs. We also define two methods of referring to uncertainties: (i) *absolute* uncertainties (the actual value) and (ii) *relative* uncertainties in which the absolute uncertainty is divided by the reading and thus expressed as a fraction (usually a percentage) of the reading.

Key Point

For limits, the main rules are as follows:

- **when quantities are added or subtracted, add their *absolute* uncertainties**
- **when quantities are multiplied or divided, add their *relative* uncertainties**

For SEMs (and standard deviations) the same rules apply but you need to use the *square* of the quantities.

These rules are presented in the accompanying Table.

- x and y represent two quantities being measured and the result is u.
- The limits of uncertainty in the respective quantities are represented by Δx, Δy and Δu.
- The SEMs are represented by E_x, E_y and E_u.

Key Point

CALCULATION OF EXPERIMENTAL RESULT u	HOW TO COMBINE LIMITS For a result u, the uncertainty $\pm\Delta u$ is calculated using:	HOW TO COMBINE SEMs For a result u, the uncertainty $\pm\ E_u$ is calculated using:
Multiplying by a constant a (with negligible uncertainty): $u = ax$	$\Delta u = a\Delta x$	$E_u^2 = a^2 E_x^2$
Adding/Subtracting: $u = x + y$ $u = x - y$	$\Delta u = \Delta x + \Delta y$	$E_u^2 = E_x^2 + E_y^2$
Multiplying/Dividing: $u = xy$ $u = x/y$	$\frac{\Delta u}{u} = \frac{\Delta x}{x} + \frac{\Delta y}{y}$	$\left(\frac{E_u}{u}\right)^2 = \left(\frac{E_x}{x}\right)^2 + \left(\frac{E_y}{y}\right)^2$
Raising to a power: $u = x^n$	$\frac{\Delta u}{u} = n\frac{\Delta x}{x}$	$\frac{E_u}{u} = n\frac{E_x}{x}$ (*not* $\sqrt{n}$ as you might expect)
General Function of x: $u = u(x)$	$\Delta u = \lvert u(x + \Delta x) - u(x)\rvert$	$E_u = \frac{\mathrm{d}u}{\mathrm{d}x} E_x$

How to use this Table

Take an example:

Think of u as the area of a rectangular plate and that you have measured the length (x) and the breadth (y) of the plate, each with its own uncertainty. To find the uncertainty Δu in the area u (=xy) you would use row 3 of the table.

- If you take a single measurement of each x and y you would use column 2 (How to Combine Limits) so

$$\frac{\Delta u}{u} = \frac{\Delta x}{x} + \frac{\Delta y}{y}.$$

- If you had taken multiple readings (maybe 10 say) then you would use column 3 (How to Combine SEMs) so

$$\left(\frac{E_u}{u}\right)^2 = \left(\frac{E_x}{x}\right)^2 + \left(\frac{E_y}{y}\right)^2.$$

Often you will have constants in your calculation that have negligible uncertainty. They can be simply included by considering them as a term with zero Limit (or SEM) – i.e. a constant a with Δa (or E_a) = 0.

Extending to 3 or more independent quantities can be made in the obvious way – e.g. if you combine single measurements of x, y and z to produce $u = xy/z$, the uncertainty Δu is calculated as a limit using

$$\frac{\Delta u}{u} = \frac{\Delta x}{x} + \frac{\Delta y}{y} + \frac{\Delta z}{z}.$$

1.6 Examples

A. The voltage and current measurements for a resistor were 12.34 V and 8.25 mA, respectively. If the manufacturer quotes the limits of inaccuracy as 0.5% of the reading plus 1 × the least significant digit, calculate the resistance and its uncertainty.

Answer: The uncertainties are due to calibration and resolution. These are both limits, so we use the appropriate formula from the 'LIMITS' column of the Table. Remember $V = IR$.

ΔV = uncertainty in V = (12.34 × 0.5% + 0.01) V = 0.072 V

ΔI = uncertainty in I = (8.25 × 0.5% + 0.01)mA = 0.052 mA

(note that we are carrying extra significant figures in these two values at this intermediate stage of the calculation)

$R = V/I$ = 12.34V/8.25 mA

= 1495.76 Ω

and $\dfrac{\Delta R}{R} = \dfrac{\Delta V}{V} + \dfrac{\Delta I}{I} = \dfrac{0.072}{12.34} + \dfrac{0.051}{8.25} = 0.0120$

ΔR = 0.0120 × R = 18.0 Ω which to 1 significant figure is 2×10^1 Ω.

Thus the final experimental result is R = $(1.50 \pm 0.02) \times 10^3$ Ω .

(Note the rounding of figures and the use of powers of 10)

B. The following 10 readings for the speed of sound in air at 20°C were taken in $m.s^{-1}$:

341.5, 342.4, 342.2, 345.5, 341.1, 338.5, 340.3, 342.7, 343.5, 339.9

Calculate the best estimate of the speed of sound, and its uncertainty.

Answer: The scatter in the measurements is presumably due to random errors (note there is no obvious systematic drift up or down). Therefore we use the standard error of the mean, calculated using a calculator or computer:

Mean = 341.76 $m.s^{-1}$

σ_{n-1} = 1.978 $m.s^{-1}$

SEM = $\dfrac{1.978}{\sqrt{10}}$ $m.s^{-1}$ = 0.626 $m.s^{-1}$ ≈ 0.6 $m.s^{-1}$ (to 1 sig.fig.)

Speed of sound = (341.8 ± 0.6) $m.s^{-1}$

(Note that the number of decimal places in the uncertainty is matched in the result.)

1.7 Comparing results in the presence of experimental uncertainties

When our results are subject to experimental uncertainties, we cannot expect exact equality when comparing a measurement with a known value or with another measurement. Instead, we have to take the uncertainty ranges into account while making the comparison.

Firstly, we consider how to compare a measurement which has experimental error with an ‘accepted’ value eg from theory or more accurate experiments. We assume that we can neglect the uncertainty of the accepted value in comparison with the larger uncertainty of our measured value. Note that our measured value may well be the mean of a number of separate values, and in this case we would use the SEM as the relevant experimental uncertainty.

If the uncertainty estimate we have is a limit, then the measured and accepted values are in agreement if the accepted value lies within the range defined by the measured value ± its limit. If instead we have a standard deviation or standard error, then the two values are consistent if the accepted value lies less than about 2 standard deviations (or SEMs, for a mean) away from the measured value. There is no hard rule here – large discrepancies *can* occur by chance, but there is only a 5 % probability of a discrepancy of 2 standard deviations or more occurring by chance. If the observed discrepancy is larger than this, the most likely explanation is that the measured and accepted values are *not* consistent.

Secondly, we consider how to compare two independent measurements, both subject to experimental uncertainties. If the uncertainties are limits, we check to see whether the range *1st value* ±*1st uncertainty* has any overlap with the range *2nd value* ± *2nd uncertainty*. The values are consistent if there is some overlap.

If the uncertainties are standard deviations or SEMs, the situation is a little more complex. For your needs here it will suffice to check whether there is any overlap between *1st value* ± 1.5 × 1st SD (or SEM)} and *2nd value* ± 1.5 × 2nd SD (or SEM)}. You use SD or SEM depending on which is the appropriate measure of the uncertainty for the quantities being considered. Again, while it is possible that occasional large fluctuations could produce no overlap even when the values really are consistent, it is far more likely that the values are not consistent if these ranges do not overlap.

2 GRAPHS

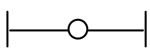
Graphs provide a very clear method of demonstrating relationships between quantities and also for calculating others. For example, plotting the voltage across a component as a function of the current through it will show whether the component has a fixed resistance (graph will be a straight line) and, if so, what is the best estimate of that resistance (the slope of the line).

2.1 Drawing graphs

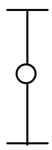
By convention, the **independent variable** is plotted along the x-axis and the **dependent variable** along the y-axis. The independent variable is the one the experimenter controls (varies) and which causes a change in the dependent variable.

Graphs should be clearly labelled with appropriate units. If our current readings were of the order of mA there is no need to convert to A and have labels like 0.001, 0.005 etc. on the graph. The units mA would be preferred (which would be labelled as 'Current (mA)' or perhaps 'Current (10^{-3} A)'). Each graph should also have a descriptive title or caption.

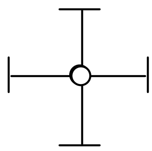
Where appropriate uncertainty estimates should also be included in the graph. These are usually indicated by uncertainty bars as shown below.



Uncertainty in x



Uncertainty in y



Uncertainties in x and y

2.2 Linear graphs

When we plot data it is best to choose the variables on the x and y axes such that a straight line is the expected form. It is easy to discern and fit a straight line to the data but not so clear to fit, say, a parabola. As an example, consider a series of measurements of distance and time for an object rolling down an incline from rest. We want to calculate the acceleration using the formula $s = \frac{1}{2}at^2$. Plotting s against t^2 should result in a straight line and the slope should give half the acceleration, $a/2$. We would fit a straight line to the data such that the line is as close to as many points as possible. If there is some random uncertainty associated with each point we should draw uncertainty bars to indicate this. Our line of best fit should pass within or close to these bars.

In addition to the line of best fit we should also draw two lines that represent the maximum and minimum acceptable slopes. Ideally, these lines should pivot somewhere around the centroid (centre) of the data and extend to the limits of the uncertainty bars. Otherwise, the scatter of the data is used to obtain the two lines of reasonable fit.

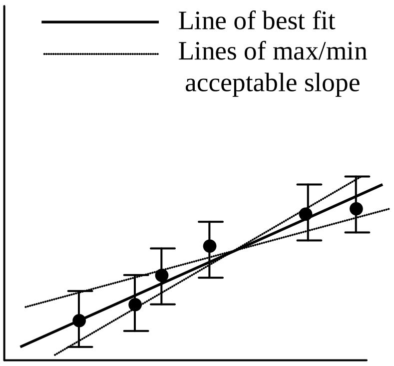
When calculating the slope use two points that lie on the line, not just any two data points that lie close to the line. It is best if the points are well separated. The slope is found from the usual relationship:

$$\text{Slope} = \frac{\text{rise}}{\text{run}} = \frac{y_2 - y_1}{x_2 - x_1}$$

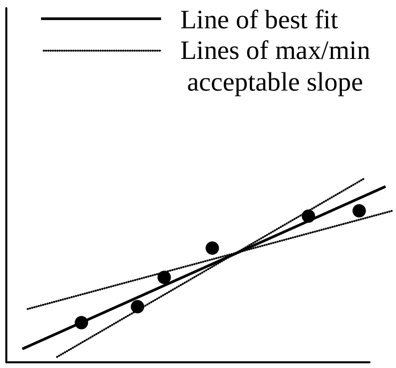
where x_1, y_1 and x_2, y_2 are the two selected points on the line.

Remember that a straight line does not necessarily imply proportionality; there is an intercept too. The two quantities are proportional only if the intercept is zero (or very close to it).

Key Point



Using uncertainty bars to draw lines of best fit and maximum and minimum slopes.



Using scatter of data to draw lines of fit and maximum and minimum slopes

The two maximum/minimum acceptable slope lines can be used to estimate the uncertainty of the slope of the best fit line. The principle behind this is that if we were to take another complete set of data, we would find a new best fit slope. The maximum amount by which it is likely to differ from our existing best fit slope is about half the difference of the maximum and minimum acceptable slopes that we have. So this can be used as an uncertainty estimate:

$$\text{Slope uncertainty} = \frac{\left|(\text{max.acceptable slope}) - (\text{min.acceptable slope})\right|}{2} .$$

If you use Excel to calculate the slope of your best fit line directly from the data, the uncertainty estimate can be obtained in a more objective way (see Section 3.8).

2.3 Log-log graphs

In some cases it is more appropriate to plot the data using logarithmic (log) scales. Many quantities in nature vary as some power law, i.e. the dependent variable is equal to a constant multiplied by the independent variable raised to some power. For example the energy radiated by a hot object per unit time depends on the 4th power of its temperature, i.e. $P = \varepsilon\sigma A T^4$ where ε, σ and A are constants.

Plotting log(*rate of energy radiation*) against log(*temperature*) results in the following

$$P = \varepsilon\sigma A T^4$$
$$\log P = \log(\varepsilon\sigma A T^4)$$
$$= \log(\varepsilon\sigma A) + 4\log T$$

which has the form $y = b + 4x$ representing a straight line with a slope of 4.

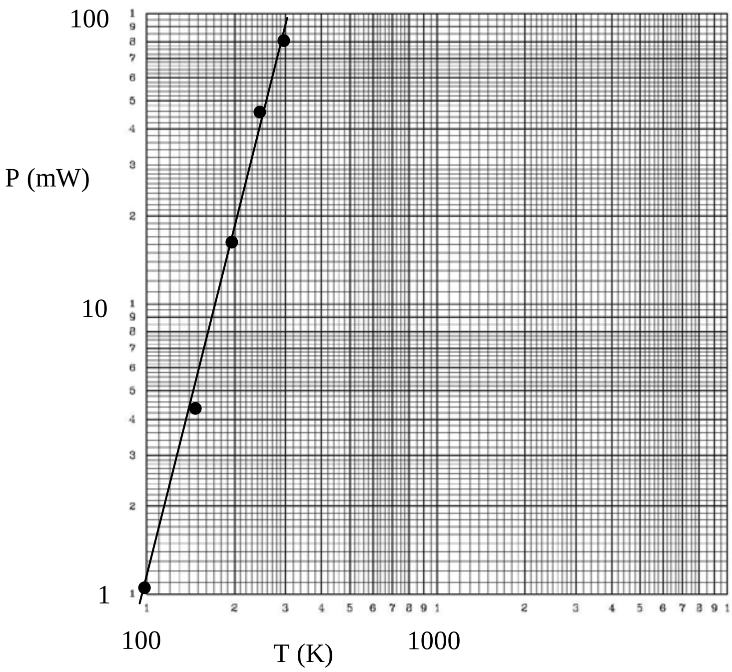
Key Point

To calculate the slope of a log-log graph we need to take the log of the (x, y) values. So for two points (x_1, y_1) and (x_2, y_2) the slope is

$$\text{slope} = \frac{\log y_2 - \log y_1}{\log x_2 - \log x_1} = \frac{\log\left(y_2 / y_1 \right)}{\log\left(x_2 / x_1 \right)}$$

An alternative and equivalent method is to plot the actual x and y values, but to use log-log graph paper, in which both the x and y axes are marked off in a log scale. The slope is found as above.

For example, the following energy measurements P made at various temperatures T are plotted on log-log paper. Notice how the scales on the log-log plot are labelled with appropriate powers of 10.



Measurements

T (K)	P (mW)
100	1.1
150	4.9
200	17
250	48
300	84

From the discussion above we expect a straight line relationship between these parameters, with a slope of 4. A straight line certainly seems a good fit, although no uncertainty bars are plotted. The first and last points lie very close to the line of best fit (although this will not necessarily be true), so we will use these values to illustrate the slope calculation.

$$\text{slope} = \frac{\log 84 - \log 1.1}{\log 300 - \log 100} = \frac{\log\left(84 / 1.1 \right)}{\log\left(300 / 100 \right)} = \frac{\log(76.36)}{\log(3)} = 3.95 \approx 4.0$$

Thus the equation describing these data is $P \propto T^4$, as expected.

(An alternative method will work if the log scales are the same on both axes - i.e. each decade is the same physical length. In that case we can use a ruler to measure distances since the log values are proportional to the distances. Then the slope can be calculated as

$$\text{slope} = \frac{rise\ (mm)}{run\ (mm)} = \frac{73\ mm}{18.5\ mm} = 3.95 \approx 4.0\ )$$

2.4 Log-linear graphs

Many processes in nature exhibit an exponential dependence, either exponential growth or decay. In such cases it is best to plot the data using logarithms for the y-axis but a linear scale for the x-axis. This can be done by taking logs, or by using log-linear graph paper. The result is then a straight line graph.

As an example consider the attenuation of gamma rays through lead. The flux (rate of arrival) of the gamma rays as a function of the thickness of lead is expected to vary as $R = R_0 e^{-x/\lambda}$ where R is the rate, x the thickness and λ the absorption length. λ and R_0 are constants. Using logarithms for the vertical axis gives

$$R = R_0 e^{-x/\lambda}$$

$$\ln R = \ln(R_0) - x/\lambda$$

which has the form $y = b - \frac{1}{\lambda}x$, so the slope is $-1/\lambda$.

Key Point

The slope of a log-linear graph (when we have used natural logarithms, as here) is given by

$$\text{slope} = \frac{\ln y_2 - \ln y_1}{x_2 - x_1} = \frac{\ln\left(y_2/y_1\right)}{x_2 - x_1}$$

For example, the following rate measurements R made for various lead thicknesses x are plotted on log-linear paper. Notice how the log scale on the log-linear plot are labelled with appropriate powers of 10.

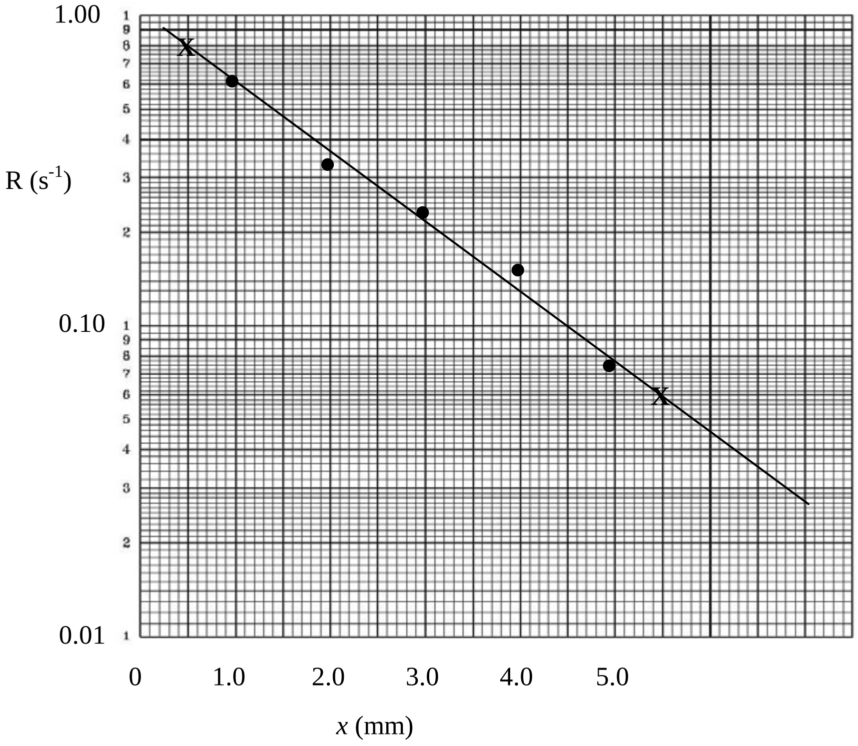
From the discussion above we expect a straight line relationship between these parameters, with a slope of $-1/\lambda$. A straight line with negative slope seems a good fit, although no uncertainty bars are plotted. The line of best fit does not really pass through any data points, so we will calculate the gradient using convenient points on the line read from the graph - (0.5, 0.8) and (5.5, 0.06) (marked by X).

The slope is calculated as follows using natural logs:

$$\text{slope} = \frac{\ln 0.06 - \ln 0.8}{5.5 - 0.5} = \frac{\ln\left(0.06/0.8\right)}{5} = \frac{\ln(0.075)}{5} = \frac{-2.59}{5} \approx -0.52$$

This slope is $-1/\lambda$, thus $\lambda \approx 1.9$ and the equation describing these data is $R = R_0 e^{-x/1.9}$.

Note that the graph is plotted using common [base 10] logs, but the calculation using common logs is slightly more complicated.



Measurements

x (mm)	R (s^{-1})
1.0	0.61
2.0	0.33
3.0	0.24
4.0	0.15
5.0	0.08

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3 USING MICROSOFT EXCEL FOR ANALYSING AND PLOTTING DATA

3.1 Introduction

Excel is the most widely available of the 'spreadsheet' programs for PCs. It provides an easy way to tabulate experimental data, make calculations based on that data, plot the results, and print clearly laid out pages showing the results (and plots). These are important functions in the Physical Sciences and in any other quantitative work.

This note aims to give you enough information to get started and to use Excel for analysis and plotting of results where it is needed in several of the experimental modules.

3.2 Getting Started

If the Windows Desktop screen is showing (coloured background with a 'Start' button at the lower left), use the mouse to place the arrow (cursor) on the Start button and press the left mouse button. This will show a menu; move the mouse pointer to highlight 'Programs', which should bring up another menu, and from this move to the line labelled 'Excel'. Release the mouse button here (or press it again); this should start Excel. If a rectangular grid of lines is on the screen, then the previous users have left Excel running (which they should not do). [1]

If you have problems getting started, ask a tutor.

The basic idea behind a spreadsheet such as Excel is that we have a rectangular grid of 'cells'. They are referred to by their column letters and row numbers, for example the top left cell is A1, the one next to it on the right is B1, the one below B1 is B2, etc. To *select* a particular cell, move the cursor (mouse) to that cell and click the left mouse button once.

Each cell can contain either:

- A *number* you have entered (*eg* an experimental measurement). To do this simply type the number and press Enter or one of the arrow keys.

- A *formula* you have typed in (or copied from another place, see below). A formula takes results from other cells and calculates some new value that you need. For example the formula =26.5+C5/10-A1*2.531 adds 26.5 to 1/10th of whatever value is in C5 and subtracts 2.531 times the value in A1 and puts the result in whatever cell contains this formula. The tricky (and useful) thing is that where the cell appears on the main part of the screen we see the *result* from that formula rather than the formula itself. We can review the formula itself in the little window towards the top left of the screen.

- A *label* consisting of characters you type in from the keyboard. Labels do not take part in the calculations, but are used to make your screen display and printouts clear by indicating

[1] In this case move the cursor to the word **File** at the top left and click the left mouse button on it. Move the cursor down to highlight **Exit** and click on that. This will bring up a box asking whether you want to save the changes to the current spreadsheet. If there is no sign of the previous users, assume they have finished with the file and so click on 'No'. The system will now be ready for you to restart as above.

what the various quantities in the other cells are. You should always label your spreadsheet columns to show the quantity and its units, just as you would if you were writing in your logbook. To enter a label, just type the text. Excel will recognise that it is not a valid number or formula, and so make it a label. (If the label could be misinterpreted as a formula, *eg* /sec, then type '/sec to force interpretation as a label.) You should also type in a general heading at the top of your sheet to identify the experiment and your lab team.

Across the top of the Excel screen is a row of options: **File, Edit, View, Insert,** etc. If you point to one of these and press the left mouse button you will get a drop-down menu giving various options. You will not need to know or use all of these, but you will need to be familiar with the system and to use some of them. Under **File** in particular, are important options for saving your work, printing it, and exiting from Excel. Some items in these menus are shown in a light shade - these are unavailable because they depend on some precondition which has not been satisfied at the moment.

Below the **File, Edit, View, Insert** line there are two rows each containing many icons. These rows are called *Toolbars*, and the icons give access to further useful functions. If you point to any one of these and leave the cursor there for a second or so, Excel will display a label saying what that button does.

To move around inside a large spreadsheet, which will not all fit on the screen at once, you can use the arrow keys or use the mouse to move the grey square in the vertical strip at the right hand side of the screen (press and hold left mouse button, release after moving the grey square).

3.3 Entering Data

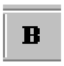
Move the cursor to the desired cell and *select* that cell by clicking the left mouse button. Type in the number, with decimal point if required. Powers of 10 can be entered: *eg* for 3.6×10^{-6} type in 3.6E-6. Press enter (return) key. If you make a mistake, simply reselect the cell and type the new value in - it will replace the old one.

3.4 Editing and Formatting your Spreadsheet

Often you will find you need to insert a new blank row (horizontal) or column (vertical) of cells, to give you more room for headings or another column for calculated quantities, or just to make the sheet easier to read. Select the cell next to where you want the new row or column to be, then from the top row use the mouse to choose **Insert**, and from the menu choose **Rows** or **Columns** as appropriate.

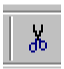
If you make a mistake in editing, you can use **Edit** - the first item in its menu will usually offer to undo the last command you carried out. To erase the contents of one or more cells, select the cells and use **Edit…Clear…Contents**.

In many situations you will need to *select* a group of neighbouring cells – this designates them, ready for some action you want to carry out on the whole group of cells. It is done by pressing the left mouse button with the cursor in the top left cell of the desired group, and then holding the mouse button down while moving to the lower right cell of the group. (This is called ‘click and drag’.)



To make the labels you type above each column stand out clearly it helps to put them in bold type (*eg* **Force**) and in the row directly below type the units (**/ Newtons**). To get bold type, select the cell(s), then click on the **B** button in the lower toolbar.

The labels can be centred in their cells by selecting them and clicking the ‘Centre’ button (shown at left) in the same toolbar.



Sometimes you will want to move a group of cells from one place to another. Select the cells using click and drag, then press the ‘Cut’ button in the first toolbar. Click on the top left cell of the destination area and press the Enter key – the cells will appear in their new location.

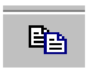
3.5 More about formulas

The usual situation in data analysis is that we have a set of data and we wish to apply the same formula to each number in the set. For example we might have a set a values of mass:

Mass
/kg
0.2
0.54
0.79
1.27
1.91

For each of these we want to calculate the weight, via the equation $W = mg$. The first value (0.20) is in cell A4. Then in the cell beside it (B4) type =A4*9.8 . This calculates mg for that first value and we see:

	A	B
1	**Mass**	
2	**/kg**	
3		
4	0.2	1.96
5	0.54	
6	0.79	
7	1.27	
8	1.91	



Now we do *not* have to type =A5*9.8 in cell B5, etc. Instead, select cell B4 containing the one case where we did type the formula in, and click on the ‘Copy’ icon in the first toolbar, then use click and drag to select all the cells where the same formula is needed. We then see

	A	B
1	**Mass**	
2	**/kg**	
3		
4	0.2	1.96
5	0.54	
6	0.79	
7	1.27	
8	1.91	

Now press the Enter key, and we get (after also adding the labels for the second column):

	A	B
1	**Mass**	**Weight**
2	**/kg**	**/Newtons**
3		
4	0.2	1.96
5	0.54	5.292
6	0.79	7.742
7	1.27	12.446
8	1.91	18.718

Notice that Excel is smart enough to work out that you do not want to copy the formula exactly: in B5 you want =A5*9.8 and in B6 you want =A6*9.8 etc. This is exactly what the above procedure gives.

Key Point

In formulas you can use the arithmetic operators + - * / as in the examples above; there are also numerous functions available. A few you may need are:

SIN(x), COS(x), TAN(x) – take the given trig function of the angle x **in radians**.
LOG10(x) - Base 10 logarithm of x.
EXP(x) - Exponential function of x.
PI() - Returns the constant pi = 3.14159….. The parentheses are needed even though empty.
AVERAGE(x1,x2,x3..) - The average (mean) of all the numbers x1,x2,x3…
STDEV(x1,x2,x3…) - The standard deviation of all the numbers x1,x2,x3…
SUM(x1,x2,x3…) - The sum of all the numbers x1,x2,x3…
SQRT(x) - The square root of x.
POWER(x,n) - Returns the number x raised to the power n. More commonly you can simply use x^n .
ABS(x) - The absolute value of x.

Note that the argument x of any function can be an arithmetic expression itself, *eg* to find Sin(θ) where θ is in cell D6 and is an angle in degrees, we would use the expression

=SIN(D6*PI()/180).

When indicating a *range* of contiguous cells we do not need to write them all out; *eg* to find the average of the values in cells G4,G5,G6….G20 all we need to do is write the function

=AVERAGE(G4:G20) and all the intermediate cells will be included.

3.6 Plotting graphs

Your data for plotting will usually be in columns: the values to be used for the horizontal axis must be in a column somewhere *to the left* of the values to be plotted on the vertical axis. (By the way, if you want other people to be able to understand your graphs, make sure you use the horizontal axis for the independent variable – the one you controlled – and the vertical axis for the dependent variable – the one that you measured and/or calculated.)

First you have to select the columns of x and y data. If they are adjacent, use click and drag to select the block of cells from the top of the x axis column to the bottom of the y axis column (omit the headings). [If the x and y data are not in adjacent columns, select the x column first, then press the Ctrl key while selecting the y column; both should be highlighted.] Then click on **Insert..Chart..**. This begins a multi-step process to create a graph (Chart).

1. Choose the type of Chart you want - choose **XY (Scatter)**. The others are for business applications and use the x data only as labels, with the points plotted equally spaced on the horizontal axis whatever the x values are!

   Choose the type of XY (Scatter) Chart you want - with or without lines or points. You should always have a marker to highlight data points, but you will usually **not** want a line simply joining the points. Choose **Next** to proceed.

2. Confirms the block of data to be used. The ranges look a bit confusing because Excel adds $ signs in the cell references[2]. Choose **Next** to proceed.

3. Add headings and axis labels. Choose ‘No’ for ‘Add a legend’. Use a Chart Title such as Wire Vibration Frequency vs Tension: 6 REG 08 – this describes what the plot is (note this means ‘y variable vs x variable’, *not* the other way around) and gives your team number so you can tell which is your plot on the printer. Note a trap – use the *mouse* cursor to move from one subwindow to the next; if you use the enter key it assumes you are finished and does not let you put in the rest of the labels. Type in labels and units for both x and y axes. Choose **Next** to proceed.

4. Place the Chart **As new sheet** and choose **Finish** and your graph should be done.

5. To improve the screen view of the graph, choose **View, size with window** and change the aspect ratio of the graph so the graph is better proportioned on the page. The default graph in EXCEL has grey background, but you should change to a plain white background. Select (click in) the plot area and choose **Format, Selected Plot Area, Area, None.** Choose **OK** to proceed.

Key Point

Most aspects of the plot can be modified if necessary. Click in the plot area to *select* the plot. Then click something that needs changing: for example Excel may decide to extend the x axis to include zero, and we may not want this. In that case click on one of the values shown on the x axis, and choose **Format** from the top command line. The first item will then be **Selected Axis**.

[2] This has the effect of making the cell references absolute, which means that a copy operation would *not* automatically change cell references when we copy a formula into new cells.

Choosing this will bring up a box offering various options, including setting the minimum of the range to be plotted (click the appropriate tab at the top – in this case **Scale**). Choosing **Chart** from the main menu can also be used to alter the format of your Chart.

3.7 Fitting a Straight Line to Experimental Data

In Physics we often plot data in a way which leads to theory predicting a straight line. (This makes it easy to fit the correct functional form – a straight line – and to see the scatter of the points about that fit.) To get Excel to draw a line of best fit:

Key Point

1. Select the chart window (one click somewhere inside the plot)
2. Use **Chart…Add Trendline**.
3. Choose **Linear** to get a straight line fit; the other options can be appropriate in other situations.
4. Under the tab **Options**, check the boxes for **Display Equation on Chart** and **Display R^2 Value on Chart**. From the equation you can see the slope and intercept of the fitted line. The R^2 value indicates how good a fit you have - 1 for a perfect fit. (The equation and R^2 value can be moved to a more convenient place on the plot using the mouse.)
5. Select the trendline by clicking on it somewhere away from the data points. (It will already be selected if you have just inserted it.)
6. Choose **Format…Selected Trendline**. (If the Format menu does not offer this option, you did not successfully select the trendline.)
7. Under the tab **Patterns** choose the line weight 3rd from the bottom (click the down arrow button to get the alternatives.) Otherwise the default gives a plotted line that looks OK on the screen but is too thick when printed.

The linear 'trendline' or regression line is the straight line which minimises the sum of squares of the deviations of the data from the line (in the *y* direction). This is equivalent to minimising the standard deviation of the points *from the line* rather than from their mean (see Sections 1.3.2 and 2.2)

3.8 Finding Slope and Intercept and their Uncertainties with LINEST

In some cases you will be asked to use the LINEST function; this analyses your x and y data and gives the slope and intercept and both their uncertainties. To use LINEST:

Key Point

1. Note the ranges of cells containing the x and y data (it does not have to be plotted)
2. Find a suitable space on the spreadsheet where you have a vacant block of 2×2 cells
3. Select those 2×2 cells using click and drag

4. Type **=LINEST(y_first:y_last,x_first:x_last,true,true)** where **y_first** is the top cell of the column of y data, **y_last** is the bottom cell, and similarly for x. For example, if the x axis data are in B5 to B10 and the y axis data are in D5 to D10, we would use the form =LINEST(D5:D10,B5:B10,true,true).

5. Note that typing **=LINEST(y_first:y_last,x_first:x_last,<u>false</u>,true)** forces the function to be linear (straight line) with no intercept. The graph passes through the origin.

6. ***Do not just press the Enter key***. Instead, you have to press the ***Ctrl***, ***Shift*** and ***Enter*** keys together.

7. You should get a number in each of the 4 target cells[3], giving:

Slope	Intercept
Uncertainty in slope	Uncertainty in intercept

You can also select a 2×3 block of cells (2 columns x 3 rows), in which case one of the extra values displayed is the R^2 value.

Always review critically the results of any 'black box' calculation such as this! Is the slope about what you expect? Do the uncertainties look reasonable? It is not correct just because it came from a computer - remember 'GIGO' (Garbage In, Garbage Out).

3.9 Printing

To print your 'worksheet' - i.e. the spreadsheet cells with your data and calculated results:

Use click and drag to *select* the area of the sheet you want to print. This is likely to extend from A1 to some cell such as G20 at the lower right. Make sure to include the titles you have put in to describe the sheet and what the columns are.

1. From the top menu choose **File...Print**.

2. In the Print dialog box, for 'Print What' click the circle for **Selection**. Do *not* choose either of the other alternatives - they can tie the printer up printing useless blank cells/pages. Leave the number of copies at 1.

3. Check which printer is specified. It will have a name such as ROOM402, indicating the location of the printer which will be used. If the wrong room is shown, you can change the printer name to the correct one.

4. When all is correct, click on the OK button – once only.

[3] If you only get one number, in the top left cell, then you did not successfully select the 2×2 block.

If the system freezes with the message 'Cannot change part of array', press the ESC key, clear out the 2×2 block (Select, then **Edit…Clear…Contents**) and redo the whole operation carefully – the problem is due to illegal LINEST input.

5. It may take a while for your printout to appear, particularly if a lot of people are using the printer at the same time. Do **NOT** resubmit the print job just because yours did not come out immediately. (A few people doing this a few times causes a printer queue logjam and then jobs really do get delayed.) If you still get nothing when you think the job should have been printed, ask for assistance.

To print your graph:

1. Get the graph on screen (if it is not already) by clicking on the tab (near the bottom of the screen) with a name such as ‘Chart 1’.
2. From the top menu choose **File...Print**.
3. Check printer as in point 4 above.
4. Click OK button.
5. See point 5 above - to help avoid printer queue delays.

3.10 Saving your File

You can save your entire Excel ‘workbook’ (spreadsheet plus any plots) for later retrieval:

1. From the top command line choose **File…Save As**.
2. Select drive e:
3. Give your file a name (maximum 8 characters) based on your team number, so you will be able to find it again later. *Eg* 6REG08A1. (The files from all teams on all days are on the same drive, so this matters.) Write in your team log the filename you have used. The additional characters (A1 in the above example) are chosen by you to distinguish your files, since you may save a number of different Workbooks at different times.
4. Click on **OK**.

3.11 Exiting from Excel

When you have finished using your spreadsheet, make sure you have saved it, then use **File…Exit** to get out of Excel.

3.12 Sample of an Excel spreadsheet

See next two pages.

DATA ANALYSIS WITH MS EXCEL

Oscillating Block - Spring system

Experiment: Determine the spring constant *k*

$$T = 2\pi\sqrt{\frac{m}{k}}$$

Special characters
format / cells/ font

subscript or superscript
format / cells / font / subscript or superscript

Greek letters
select characters - change font to 'symbol'

mass *m* (g)	time interval *t* =5 *T* (s)	± Δ*t* (s)	period T (s)	± Δ*T* (s)	mass *m* (kg)	period² T^2 (s^2)	± Δ(T^2) (s^2)
0	0.0	0	0	0	0.000	0.0	0.0
50	1.6	0.1	0.32	0.02	0.050	0.10	0.01
100	2.3	0.1	0.46	0.02	0.100	0.21	0.02
150	2.8	0.1	0.56	0.02	0.150	0.31	0.02
200	3.2	0.1	0.64	0.02	0.200	0.41	0.03
250	3.6	0.1	0.72	0.02	0.250	0.52	0.03
300	3.9	0.1	0.78	0.02	0.300	0.61	0.03
350	4.2	0.1	0.84	0.02	0.350	0.71	0.03
400	4.5	0.1	0.90	0.02	0.400	0.81	0.04
450	4.7	0.1	0.94	0.02	0.450	0.88	0.04
500	5.1	0.1	1.02	0.02	0.500	1.04	0.04

headings: name, symbol, unit

format / cells / alignment / wrap text

significant figures
format / cells / number
or
increase or decrease # decimal places

copy & paste special values to plot XY data

graph 1

X mass *m* (kg)	Y period T (s)	error bars ± Δ*t* (s)
0.000	0.0	0
0.050	0.3	0.1
0.100	0.5	0.1
0.150	0.6	0.1
0.200	0.6	0.1
0.250	0.7	0.1
0.300	0.8	0.1
0.350	0.8	0.1
0.400	0.9	0.1
0.450	0.9	0.1
0.500	1.0	0.1

graph 2

X mass *m* (kg)	Y period² T^2 (s^2)	error bars ± Δ(T^2) (s^2)
0	0	0
0.050	0.10	0.01
0.100	0.21	0.02
0.150	0.31	0.02
0.200	0.41	0.03
0.250	0.52	0.03
0.300	0.61	0.03
0.350	0.71	0.03
0.400	0.81	0.04
0.450	0.88	0.04
0.500	1.04	0.04

Borders
Format / Cells / Border

Analysis

slope	2.02	0.00	intercept
Δslope	0.03	0.01	Δintercept
R^2	0.998	0.01	

=linest(G33:G43,F33:F43,true,true)

SHIFT+CTRL ENTER

slope	2.03	0	intercept
Δslope	0.01	#N/A	Δintercept
R^2	1.000	0.0136072	

=linest(G33:G43,F33:F43,false,true)

SHIFT+CTRL ENTER
(R^2 = 1 for a perect straight line ft)

slope = $4\pi^2 / k$ Δslope / slope = $\Delta k / k$

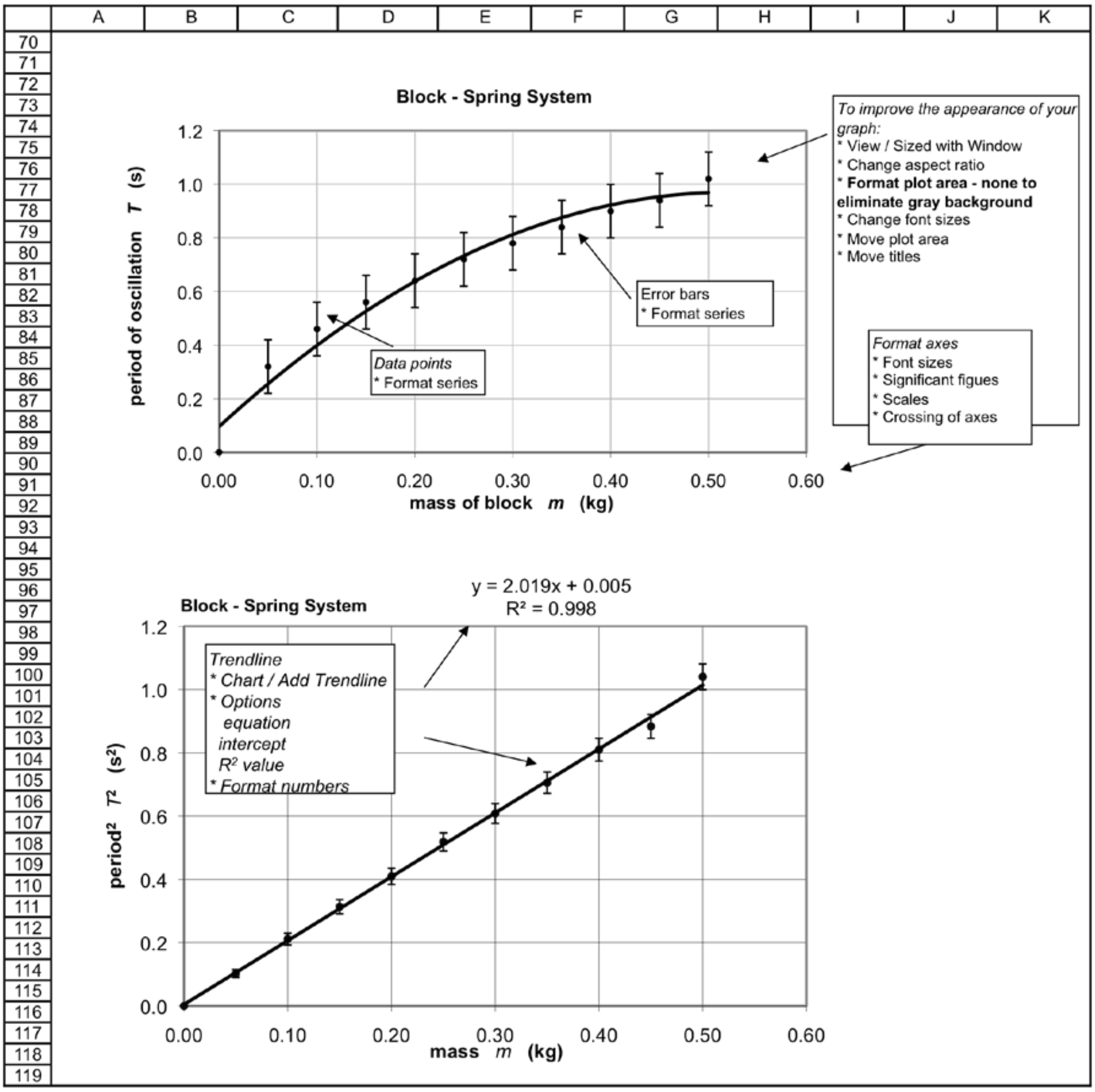
$k = 4\pi^2$ / slope $\Delta k = k$ (Δslope / slope)

k = 19.55292 N.m^{-1} Δk = 0.259961 N.m^{-1}

***k* = (19.6 ± 0.3) N.m^{-1}**

Printing
* Select data to be printed - print only selection
* Page Setup - print to a page, headings, gridlines etc

Significant figures
* uncertainty 1 digit (usually)
* value & uncertainty same no. decimal places


A B C D E F G H I J K
70 71 72 73 74 75 76 77 78 79 80 81 82 83 84 85 86 87 88 89 90 91 92 93 94 95 96 97 98 99 100 101 102 103 104 105 106 107 108 109 110 111 112 113 114 115 116 117 118 119
Block - Spring System
period of oscillation T (s)
mass of block m (kg)
To improve the appearance of your graph:
* View / Sized with Window
* Change aspect ratio
* Format plot area - none to eliminate gray background
* Change font sizes
* Move plot area
* Move titles
Error bars
* Format series
Data points
* Format series
Format axes
* Font sizes
* Significant figues
* Scales
* Crossing of axes
y = 2.019x + 0.005
R² = 0.998
Block - Spring System
Trendline
* Chart / Add Trendline
* Options
equation
intercept
R² value
* Format numbers
period² T² (s²)
mass m (kg)

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A QUICK GUIDE

SOME OF THE KEY PRACTICAL POINTS OF EXPERIMENTAL ANALYSIS

Some of the most important *practical* things you need to know from these *Experimental Analysis* notes are highlighted as a ***Key Point***

Where are they?

Junior Physics Experimental Laboratory Timetable, Semester 2, 2017

Week	Course	ADV	TEC	ENV	PROJECTS
	PHYS	1902	1003	1004	all classes
	Session Number	5 10	2 3 4 6 7 8	2 6 8	
	Location	Check notice signs outside labs 401 and 402			
Week	Dates				
1	31 Jul - 4 Aug	NO LAB			
2	7 Aug - 11 Aug	Circuits 1	Circuits 1	Intro Circuits 1	Initial Project Group Meeting
3	14 Aug - 18 Aug	Circuits 2	Circuits 2	Intro Circuits 2	Project Proposal Preparation
4	21 Aug - 25 Aug	Circuits 3	Circuits 3	Intro Circuits 3	Project Proposal Preparation
5	28 Aug - 1 Sept	Circuits 4	Circuits 4	Intro Circuits 4	**Project Proposal DUE**
6	4 Sep - 8 Sep	Circuits 5	Circuits 5	Intro Circuits 5	Project Proposal returned
7	11 Sep - 15 Sep	Mid-Semester Exam			Project Preparation
8	18 Sep - 22 Sep	NO LAB			Project Preparation
	25 Sep - 29 Sep	Mid-Semester Break - NO LAB			
9	**# 2 Oct holiday** 3 Oct - 6 Oct	Project 1	Project 1	Project 1	Day 1
10	9 Oct - 13 Oct	Project 2	Project 2	Project 2	Day 2
11	16 Oct - 20 Oct	Project 3	Project 3	Project 3	Day 3: Draft Report Review
12	23 Oct - 27 Oct	Project 4: Presentations	Project 4: Presentations	Project 4: Presentations	Day 4: Presentations Report Review
13	**# 30 Oct Monday only**	# Project 4: Presentations	# Project 4: Presentations	# Project 4: Presentations	# Day 4: Presentations Report Review
	31 Oct - 3 Nov	NO LAB			**Reports due online by Friday 3 Nov at 11:59 pm**

 # Monday 2 Oct is a public holiday; Monday class will catch up that day in Week 13

Session Number 1 = Mon 10am-1pm; Session Number 2 = Mon 2-5pm;
Session Number 3 = Tue 10am-1pm; Session Number 4 = Tue 2-5pm;
Session Number 5 = Wed 10am-1pm; Session Number 6 = Wed 2-5pm;
Session Number 7 = Thu 10am-1pm; Session Number 8 = Thu 2-5pm;
Session Number 9 = Fri 10am-1pm; Session Number 10 = Fri 2-5pm;