THE UNIVERSITY OF LEEDS

School of Physics and Astronomy

Module PHAS1000

Laboratory Handbook

1st Semester/2nd Semester

2024/2025

Name ___________________________________

Course __________________________________

If found, please return to: Physics Undergraduate Teaching Laboratory, Room 4.08
Sir William Henry Bragg Building

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PHAS1000 Laboratory Schedule

Semester 1 in 2024:		
Week:	**What's happening:**	**Notes and Deadlines**
Week 0: starting Mon. 23rd Sept.	**Introduction Week lecture** – location, date and time will be announced on Minerva.	Lecture attendance will be monitored. You are expected to attend.
Week 1: starting Mon. 30th Sept.	**Intro Experiment 1: Stokes Law** Part 1	
Week 2 starting Mon. 7th Oct.	Interactive Lab Skills lecture taking place during your scheduled lab session in Bragg 4.08	This interactive lecture will introduce you to some key analysis skills you will use and develop during the module. We will have PCs available, but you are welcome to bring along you own laptop for this session
Week 3 starting Mon. 14th Oct.	**Intro Experiment 1: Stokes Law** Part 2	Lab Notebook to be submitted online **by 2pm** after the end of your lab session.
Weeks 4 and 5 starting: Mon. 21st Oct. & Mon. 28th Oct.	**Intro Experiment 2: Electrical Circuits** Week 4: Part 1 Week 5: Part 2	You will be allocated to either 9am until 11am or 11am until 1pm for these two weeks. You will complete these tasks in workbooks which will be handed in at the end of each session.
Week 6: starting Mon. 4th Nov.	No lab sessions	You should start **Data Analysis Task 1: Darts and the Gaussian distribution.**
Weeks 7-10 starting: Mon. 11th Nov. to Mon. 2nd Dec.	**Rota experiments**. A schedule for the eight rota experiments will be available on Minerva in week 6 You will complete 8 rota experiments between week 7 in semester 1 and week 17 in semester 2	**These rota lab sessions will start at 9am and finish at 1pm**. Lab Notebook to be submitted online **by 2pm** after the end of each of your lab sessions.
Week 11: starting Mon. 9th Dec.	Catch up Lab and Drop in session	**Deadline** for **Data Analysis Task 1: Darts and the Gaussian distribution.** Submit by **2pm on Friday 13th December 2024.**
Christmas Break		

Semester 2 in 2025:		
Week:	**What's happening:**	**Notes and Deadlines**
Weeks 14-17: starting: Mon. 27th Jan. to Mon. 17th Feb.	**Rota experiments**. A schedule for the eight rota experiments will be available on Minerva in week 6 Weeks 14 to 17 follow on from semester 1	**These rota lab sessions will start at 9am and finish at 1pm**. Lab Notebook to be submitted online **by 2pm** after the end of your lab session.
Week 18: starting Mon. 24th Feb.	No lab sessions	You should start **Data Analysis Task 2: X-ray Diffraction**
Week 19: starting Mon. 3rd March	**Presentation**	Presentations will be done in small groups during your normal lab session. You will be notified of the time and location. This will be marked using Feedback Fruits.
Weeks 20-21: starting: Mon. 10th March & Mon. 17th March	**Group Video Experiment** Attend on your normal lab day.	You will have two sessions to plan, carry out and film your experiments to prepare your 2½ minute video. This assignment will be marked using Feedback Fruits.
End of Week 21		**Deadline** for **Data Analysis Task 2: X-ray Diffraction.** Submit by **2pm on Friday 21st March 2025.**
Week 22: starting Mon 24th March	**Lab Skills Assessment**	You will do six half hour Lab Skills experiments on a rota.
		Deadline for **Group Video.** Submit by **5pm on your normal lab day.**
End of week 22		**Choose your four rota experiments to be numerically marked and notify the lab staff**
Easter Break		
Week 23: starting Mon.28th April	**Employability Session** This time and location of your employability session will be on your timetable.	Deadline for the **Formal Report.** Submit by **2pm Monday 28th April 2025**
Week 24: starting Tues. 6th May	**Employability Session** This time and location of your employability session will be on your timetable.	

PHAS1000 Module Information

The experimental physics component of the PHAS1000 module is designed to start teaching you the skills required by an experimental physicist. Throughout the module you will be tested on these skills rather than on detailed knowledge of the theory underpinning the experiments. These skills will be assessed through a variety of tasks undertaken throughout the year.

Within this laboratory handbook you will find the laboratory schedule as well as important information about each task and how it will be assessed.

General Information

Module Staff: the organisation of the module is overseen by the staff below:

Position	Name	Contact details
Module Lead	Dr Emma Cochrane	e.c.a.cochrane@leeds.ac.uk
Lab Manager & Module Team	Dr Peter Hine	p.j.hine@leeds.ac.uk; Tel: 0113 3438342
Senior Lab Technician & Module Team	Angela Beddows	a.beddows@leeds.ac.uk; Tel: 0113 3438200

Location:

The Physics Undergraduate Teaching Laboratories are located within the School of Physics and Astronomy in **Room 4.08 in the Sir William Henry Bragg Building**.

Laboratory sessions:

Laboratory sessions take place from **9am until 1pm** on **Mondays, Wednesdays and Fridays**. This module covers both semesters. You will be assigned one of these sessions, which will remain the same throughout the year.

Attendance Recording

At the start of each session you must sign in with the Laboratory Technician. This is for health and safety reasons and so your attendance can be logged.

- **If you do not sign in then you will be recorded as absent.**

Absences will be reported each week to Physics Student Support team.

It is important to arrive at each session by **9am**. If you are late you may miss important information given by your demonstrator at the start of your experiment. Latecomers will **not** be allowed extra time and may lose marks as a result.

- **If you arrive late to your lab session you may not be able to start the session and will be recorded as absent.**

Absence

If you miss a laboratory session for any reason then you need to do the following:

- Self-certify your absence via Minerva. (Instructions on how to do that can be found here: https://students.leeds.ac.uk/info/10108/attendance_and_absences/659/absences).

- Email the Lab Technician (Angela Beddows: a.beddows@leeds.ac.uk) and the module lead (Emma Cochrane: e.c.a.cochrane@leeds.ac.uk) to inform them of your absence and request a catch up opportunity.

All lab absences will recorded using attendance monitoring software. Frequent unjustified absences or failure to submit work will trigger an appointment with the Year Convenor.

Please note that you **will be recorded as absent if you do any of the following**:

- If you do not attend a lab session.
- If you do not sign into a lab session.
- If you arrive more than 30 minutes late to your lab session.
- If you have attended the lab session but then failed to submit your lab notebook.

Failure to submit of any work will result in a mark of zero for that assignment.

There will be catch-up opportunities for verified absences throughout each semester.

Should you be experiencing any difficulty that prevents you attending or working happily in the lab, please see your tutor, one of the Lab staff or contact the Physics Student Support office.

Help & Support

You are welcome to drop in to the lab during the two lab sessions that are not your scheduled lab day, as there will always be a member of the Lab team available. The Technician is also available in the Lab at the following times: Monday, Wednesday and Friday mornings (8.30am until 1pm).

You are welcome to email the Lab Team during working hours with any questions or requests for help.

Module Overview:

- **All laboratory VITALs must be met in order to pass the year** and progress to Year 2.
- **All** components of this module are compulsory and you must have made a reasonable attempt at each component.
- **A portfolio of marks will go towards the Year 1 assessment module,** as set out below.
- **Feedback** will be given on all components. During the Easter Break you will be asked to choose **four** of your completed rota experiments to be given a numerical mark. These four experiments will form 60% of the total Module mark, as shown in the table below:

Total mark breakdown of the laboratory component portfolio:

Component/Assessment type	% of Total Portfolio
Introduction Experiments: 2 Introduction experiments: Stokes Law & Electrical Circuits. These tasks are both formative which will allow you to start developing important experimental and analysis skills. You must make a reasonable attempt at both experiments.	
Rota Experiments: 8 Rota experiments: Diffraction and Interference, Inter-atomic Forces in Copper, Adiabatic Expansion, Newtonian Mechanics, Determination of Planck's Constant, Millikan's Oil Drop, e/m of an electron, Stefan's Law. You will choose 4 of these experiments to go towards your portfolio.	60
Data Analysis Tasks: 2 Data Analysis Tasks: Darts and the Gaussian Distribution and X-Ray Diffraction. These tasks are both formative which will allow you to develop important data analysis techniques. You must make a reasonable attempt at both of these tasks to pass the module.	
Presentation	10
Group Video Experiment	10
Lab Skills Test	10
Formal Report	10

- All components are compulsory and you must make a reasonable attempt at each task. **Failure to submit any assignment puts you at risk of failing the year.**
- Throughout both semesters there will be opportunities to catch up missing experimental tasks and achieve each experimental VITAL. Please note that **there is no summer resit for the experimental work**.
- If you fail one or more of the additional compulsory components, a resit opportunity will be provided during the University resit period in **August**.

Learning and Skills Outcomes:

Learning Outcomes for the Experimental Component of the Module

On successful completion of the module students will have demonstrated the ability to:

LO1. use a range of laboratory apparatus safely and competently to obtain results within the time allowed, either by following instructions or using their own experimental designs and risk assessments.

LO2. accurately record experimental details and results, as well as analyse data and determine uncertainties by selecting appropriate analytical techniques, and critically evaluate an experiment.

LO4. use appropriate scientific computing packages, including Python, to employ computer based data visualisation.

LO5. Present scientific content, ideas and data using a range of media and digital tools.

Skills Learning Outcomes for the Experimental Component of the Module

On successful completion of the module students will have demonstrated:

SO1. proficiency in a variety of experimental and programming skills used by physicists and astrophysicists, at a level appropriate to year 1.

SO2. the ability to apply appropriate mathematical and analytical techniques within experimental and computational physics.

SO3. the ability to communicate scientific ideas and results using a variety of media and digital tools.

SO4. the ability to plan and manage time to meet deadlines.

VITALs (Verifiable Indicator of Threshold Ability or Learning)

E1. Experimental work

a. Safely measure and record experimental data
Module Learning Outcomes: LO1, SO1, SO4
To pass this VITAL you will need to demonstrate the ability to take and record measurements by safely and competently using a range of laboratory apparatus.

b. Keep a detailed laboratory notebook
Module Learning Outcomes: LO2, SO1, SO4
To pass this VITAL you will need to demonstrate the ability to neatly and clearly document all aspects of your experimental work; methodology, experimental measurements, uncertainties, data analysis and evaluation.

c. Perform appropriate calculations
Module Learning Outcomes: LO2, LO4, SO2
To pass this VITAL you will need to demonstrate the ability to use appropriate formulae to combine experimental measurements and calculate a final value.

d. Produce appropriate graphs or charts
Module Learning Outcomes: LO2, LO4, SO2, SO3
To pass this VITAL you will need to demonstrate the ability to use graphical software (e.g. MS Excel or Origin) or programming (e.g. Python) to analyse and present your experimental data.

e. Determine the overall uncertainty in a final value
Module Learning Outcomes: LO2, SO2
To pass this VITAL you will need to demonstrate the ability to combine the uncertainties in your data to calculate the overall uncertainty in your final value and to critically evaluate your results.

E2. Design and deliver a presentation
Module Learning Outcomes: LO5, SO3, SO4
To pass this VITAL you will need to demonstrate the ability to design and deliver a visually based presentation using appropriate software (e.g. PowerPoint).

E3. Participate in a group experimental task
Module Learning Outcomes: LO1, LO2, LO5, SO1, SO3, SO4
To pass this VITAL you will need to demonstrate the ability to work as part of a group to design and carry out an experiment, and create a short video to showcase your experiment.

E4. Complete a Lab Skills Test
Module Learning Outcomes: LO1, LO2, LO4, SO1, SO2
To pass this VITAL you will need to demonstrate the ability to perform laboratory skills developed during year 1; taking measurements, recording data, using graphical software, calculating a final value with its uncertainty and critically evaluating an experiment.

E5. Write a formal scientific report
Module Learning Outcomes: LO5, SO3, SO4
To pass this VITAL you will need to demonstrate the ability to present scientific content, ideas and data in a formal written scientific report.

E6. Complete sufficient experimental tasks
Module Learning Outcomes: LO1, LO2, LO4, SO1, SO2
To pass this VITAL you need to have made a reasonable attempt with at least 80% of all the experimental and data analysis tasks including the introductory experiments.

The table on the following page shows which VITALs will be tested in each assessment

Laboratory Component	VITAL	
Experimental work		
Stokes Law	**E1 a:** Safely measure and record experimental data	**E1 e:** Determine the overall uncertainty in a final value
Electrical Circuits	**E1 a:** Safely measure and record experimental data	**E1 e:** Determine the overall uncertainty in a final value
Millikan's Oil Drop	**E1 a:** Safely measure and record experimental data	**E1 b:** Keep a detailed laboratory notebook
Diffraction and Interference	**E1 c:** Perform appropriate calculations	**E1 b:** Keep a detailed laboratory notebook
Inter-atomic Forced in Copper	**E1 a:** Safely measure and record experimental data	**E1 b:** Keep a detailed laboratory notebook
Adiabatic and Isothermal Processes	**E1 d:** Produce appropriate graphs or charts	**E1 b:** Keep a detailed laboratory notebook
Experiments in Newtonian Mechanics	**E1 e:** Determine the overall uncertainty in a final value	**E1 b:** Keep a detailed laboratory notebook
Determination of Planck's Constant	**E1 c:** Perform appropriate calculations	**E1 b:** Keep a detailed laboratory notebook
Measurement of e/m for Electrons	**E1 d:** Produce appropriate graphs or charts	**E1 b:** Keep a detailed laboratory notebook
Determination of Stefan's Constant	**E1 c:** Perform appropriate calculations	**E1 b:** Keep a detailed laboratory notebook
Darts and the Gaussian Distribution	**E1 d:** Produce appropriate graphs or charts	**E1 e:** Determine the overall uncertainty in a final value
X-ray Diffraction	**E1 c:** Perform appropriate calculations	**E1 d:** Produce appropriate graphs or charts
Experimental Component	**E6:** Complete sufficient experimental tasks	
Additional Compulsory Components		
Presentation	**E2:** Design and deliver a presentation	
Group Video Experiment	**E3:** Participate in a group experimental task	
Skills Test	**E4:** Complete a Lab Skills Test	
Formal Report Lab	**E5:** Write a formal scientific report	

- There are at least 3 opportunities to achieve each experimental work VITAL throughout the module. You need to complete a minimum number of tasks to achieve **E6**.
- For the additional compulsory components, if you fail to achieve this VITAL, a resit opportunity will be provided during the University resit period in **August**.

Submitting Your Work

- **If you submit any assignment past its deadline it will be subject to late penalties**; University policy sets this penalty at a deduction of 5% per day late, or part thereof, including weekends and holidays. This is cumulative; e.g. if you submit your work 3 days late, 15 marks will be deducted from your total mark.
- If you need an extension for an individual assignment, **you must apply for Mitigating Circumstances before the assignment deadline** You can apply for Mitigating Circumstances (for either a coursework extension or additional consideration) by completing the online application form. Guidelines can be found at https://students.leeds.ac.uk/info/10111/assessment/860/mitigating-circumstances .

Laboratory Notebooks

- **You must submit your lab notes by 2pm after the end of your lab session**
- Your lab notebook must be digitised and uploaded to Gradescope. This can be done through the Gradescope app or by using the link on Minerva. If you have any issues uploading your work, then contact a member of the lab team as soon as possible.
- Data tables and graphs must be printed out and pasted into your notebook before digitising your work. A printer will be available in both Undergraduate Laboratories up to the submission time. Screenshots or photographs of computer screens will **not** be accepted.
- **Your work must be legible in order for it to be marked.** If the images are too dark or fuzzy and we can't read it, it won't get marked. It is recommended that you use the Gradescope app to scan your lab book and create a single PDF document. Avoid taking photographs as j-peg files are often unclear once uploaded to Gradescope.
- After uploading your work **it is up to you to check your submission** to make sure it has all uploaded correctly and is legible. Guidelines for creating an electronic copy of your lab notebook and submitting it to Gradescope can be found on Minerva in **Assessment and Feedback > Submit My Work folder**.

Assessment Tools and Feedback

Feedback will be given in all experimental work through Gradescope of Feedback Fruits.

Component/Assessment	Feedback Tool	Grading
Stokes Law Experiment	Gradescope	Feedback only
Electrical Circuits	Feedback Fruits	Pass/Fail and Feedback
Rota Experiments	Gradescope	Feedback only. Marks awarded to 4 reports at the end of year
Data Analysis Tasks	Gradescope	Feedback only
Presentation	Feedback Fruits	Numerical Mark and Feedback
Lab Skills Test	Feedback Fruits	Numerical Mark only
Group Video Experiment	Feedback Fruits	Numerical Mark and Feedback
Formal Report	Turnitin	Numerical mark and Feedback

Laboratory Sessions (Weeks 1 – 17)

Each week you will attempt the experiment or assessment indicated in the Laboratory Schedule. You can find out which rota experiment you will be attempting by looking at the rotas available on Minerva in **Experimental Physics: Information**.

Preparation for lab sessions:

Before attending each lab session, **you must prepare** for your assigned experiment by doing the following:

1. Reading the experiment manuscript given in this handbook and any suggested background theory. Most experiments are based on A level knowledge but where additional content is needed relevant sections from Tipler are given.
2. Watching the supporting video for the experiment. These videos are available on MS Stream and the links will be posted in the relevant experiment folders found in **Experimental Physics: Learning Resources** on Minerva.
3. Complete the relevant online Health and Safety Assessment Form. **You will not be allowed to do the experiment until you have completed thje relevant form.**
   To complete the health and safety form you need read the Risk Assessment for your assigned experiment. This is available in the lab handbook along with a QR code for each form. This link is also available in the relevant experiment folder on Minerva.
4. Writing your introduction and drawing your apparatus ready to start recording your experimental method and results.

During the lab sessions

A laboratory demonstrator, a member of staff or a postgraduate teaching assistant, is assigned to each experiment. The demonstrator will be able to answer questions and sort out any problems during the session.

The demonstrator will start each session by recapping the background theory for your assigned experiment and setting out any safety requirements. After the introduction you will undertake the experiment. Most experiments are carried out in pairs but in some cases you may work individually or as part of a group.

You must record important experimental details, experimental measurement and data analysis **directly in your lab notebook**. Do not write on loose pieces of paper! Tables and graphs can be produced electronically, but they must be printed out and pasted into your notebook.

Although you may leave the lab once you have finished taking the data, it is recommended that you stay so you can ask your demonstrator or a member of lab staff for any help with the analysis.

At the end of the lab session

You must submit your work by 2pm after the end of your laboratory session

At least 15 minutes before the end of the session you should start taking images of your lab notebook pages and turn them into a single PDF file. You must submit your lab notebook to Gradescope using the relevant link. It is recommended that you use the Gradescope App to submit your work. The links are available on Minerva in **Assessment and Feedback > Submit My Work.**

Safety in the Laboratory

There will be a short Fire Safety Video shown at the start of your first laboratory session. Please pay attention to this video so you know what to do in event of a fire. You will also need to follow these safety rules:

- **If you need to leave the laboratory, even for a moment**, please tell your demonstrator. If there is a fire, we need to know where you are.
- Food or drink **must not be** consumed in the laboratory. If you want to eat or drink, please do so in the corridor outside the laboratory.
- Smoking is not permitted anywhere on campus.
- Please put your mobile phone on **silent** before entering the lab. If you need to make a phone call then please do so outside the laboratory.
- Headphones, earbuds etc **must not** be worn while in the laboratory and no music players of any kind may be used.
- You must not interfere with any equipment not specified for your allocated experiment.
- You must not use any equipment in ways not specified in the laboratory handbook. In particular you must not attempt to dismantle any part of mains-voltage electrical equipment, including the mains plug.
- You must not bring 'guests' into the laboratory without permission.
- No equipment may be removed from the laboratory.

Good Practice for Experimental Work

Preliminary Measurements

It is good practise to carry out a pilot experiment, or a pilot calculation using initial results, before completing the whole experiment. This is for the following reasons:

- The experimenter 'learns' about the experiment and techniques for taking careful measurements.
- It enables the experimenter to check that the apparatus is working properly and giving sensible results.
- A suitable range for each variable can be determined and an estimate of the uncertainties can be made.
- The procedure can be modified to optimise the final experiment, for example more attention can be paid to quantities which give the largest uncertainties.

Once pilot experiment has been completed, the experimenter should be in a good position to carry out the experiment properly and obtain accurate answers.

Repetition of Measurements

Always repeat measurements at least three times so that:

- You can avoid mistakes in reading instruments or recording numbers.
- You are able to estimate the random uncertainty in the measurement.
- If the results are inconsistent you need to make sufficient measurements to estimate the uncertainty using statistics.

Calculate results as you proceed

It is good practice to calculate results as you proceed. This will stop you making silly mistakes; if the result is obviously wrong you can repeat your measurements and calculations and recheck everything. You cannot do this once the session has ended.

Laboratory Notebooks

You will be provided with a lab notebook in which to record all your laboratory work.

It is important that you develop the skill of making good scientific bench notes. The true value of an experimental notebook can only be realised when you need to refer to it at a later date.

Bench notes should be recorded in such a way that someone should be able to read your notes and repeat the experiment exactly as you did. The reader needs to be able to:

- read your data and know the units and uncertainties in **all** your measurements
- be able to follow your data analysis and understand the reasoning behind your conclusion.

Ask yourself if at the end of the year you could write a Formal Report from your notes, or if you could describe to someone exactly what you did, how you did it and the outcome of your experiment.

✐ Bench notes do not need to be perfect documents! We expect to see some rough notes, bits added in and any mistakes neatly crossed out.

What to Include:

- The title of your experiment and the date it was carried out.
- The aim of your experiment – what you are hoping to find.
- Target value(s) and key physics equations underpinning the experiment.
- A labelled schematic diagram of your equipment.
- A short method written in ‘real time’ as you carry out the experiment, explaining how the apparatus was used.
- The uncertainty in the equipment you are using to record the data.
- A neatly drawn table of results, which includes the uncertainties in your measurements. Data tables produced electronically should be printed out an pasted into your notebook (except for very large sets).
- Graphs can be plotted directly into your lab notebook or produced electronically. Graphs produced electronically must be printed out and pasted into your notebook. Plot graphs as you go along. It is too late to retake measurements once the session has ended.
- All data analysis set out neatly and clearly, example calculations should be shown if carried out using a spreadsheet.
- A conclusion, which must include your final result(s) and associated uncertainty and an evaluation of the experiment

An example **Lab Notebook Report** can be found on Minerva in: **Experimental Physics: Learning Resources > General Resources**.

Experiment Marking Criteria

The first introductory experiment, Stokes Law, and all rota experiments will be assessed and given feedback based on the Criteria shown in the table below, **but these marks will not be awarded until the end of the module**.

In Week 22 **you will be asked to select your four best rota experiments** to go towards your portfolio and these will be awarded a mark out of 100 as shown below.

- **Please note: these marks will be subject to late penalties.** Therefore, you should make sure that you **submit your work on time**.

Section	**% of overall mark**
Experimental Notes: Summary of experimental aims. Target value(s) with references. A brief summary of the background physics and experimental method used, including any key equations, schematic diagrams, electrical circuit diagrams etc. Notes detailing problems encountered during the experiment or techniques used to improve the quality of the data.	20
Data: All data recorded (in tables where appropriate). Filenames clearly recorded for any data taken or stored electronically. Measurement uncertainties recorded for all data. Data table should be printed out and pasted into your notebook where appropriate (electronic attachments will not be accepted).	20
Graphs: Graphs (including diffraction spectra) plotted using MS Excel/Origin Pro or compiled from the data collection software (PASCO Capstone) with clear titles and axis labels. Uncertainty bars and lines/curves of best fit added where appropriate. Graphs should be printed out and pasted into your notebooks where appropriate (electronic attachments will not be accepted).	20
Analysis: Calculations performed using appropriate equations to determine the final values and the uncertainty in these values. Example calculations must be clearly shown. Final values and their uncertainties given to the correct number of significant figures and with appropriate units.	30
Conclusions: A summary of the final results with a comparison to any expected values. A discussion on the quality of the data obtained and possible sources of uncertainties. Suggestions for improving the experimental method or apparatus.	10
Total percentage	100

Ungraded Marking – Rubric Comments

Feedback will be given using a pre-written set of rubric comments available on Gradescope. The assessor will also give you individual comments where appropriate.

- **It is up to you to read your feedback and act on it accordingly.**

Tables containing all the general comments available are available on Minerva in:
Experimental Physics: Assessment and Feedback.

- For each assignment, you should look at which comments have been selected in Gradescope. You can then use the general comments tables to see where these comments fall in relation to the marks available (towards 0 or towards 100).

- Reading the criteria for each comment available and the individual feedback from the assessors should allow you to move from the red/yellow comments towards the green/blue. If you are unsure why a particular comment has been selected, please ask your demonstrator.

As shown, it is possible to achieve 100% for each component, so this is something to work towards. However, please remember that first year labs are designed to introduce you to the skills needed to be successful in final year projects. **It is the skills you develop and improve through feedback which are important, not the marks!**

Ungraded Marking – Marking Codes:

Although you will not be awarded marks for your rota experiments, you will be given a 'mark' of either 0, 1, 10 or 11 in Gradescope which will allow us to assess whether you have passed the relevant VITALs and written suitable bench notes:

Gradescope Mark Code	Code Meaning
11	Both VITALs achieved with bench notes written to a passing standard
10	Both VITALs achieved but bench notes not written to a passing standard
1	Both VITALs not achieved but bench notes written to a passing standard.
0	Both VITALs not achieved and bench notes not written to a passing standard

- **If you achieve a mark of 10 or 0 it means that you have not written bench notes to a passing standard.** You should read your feedback carefully and act on it for future reports.

Electrical Circuits Experiment

The electrical circuits experiments are designed to help you develop different skills needed to build and analyse electrical circuits, as well as evaluate uncertainties. You will record these tasks in workbooks rather than in your notebook. These skills will be evaluated by using Feedback Fruits.

Data Analysis Tasks

Data analysis tasks will be assessed in a similar way to the rota experiments. Information about the data analysis tasks will be provided in week 5 (Data Analysis Task 1: Darts and the Gaussian Distribution) and week 17 (Data Analysis Task 2: X-Ray Diffraction).

Presentation (Week 19)

This **compulsory component** assignment is worth 10% of your overall portfolio mark.

You are required to give a 10-minute presentation on one of the rota experiments carried out this year which will be followed by a 5 minute question & answer session.

You will give your presentation to a small group of your peers and a laboratory demonstrator during your usual laboratory session. A schedule will be available on Minerva in week 17.

An optional lecture outlining good practice for presentations will be given via MS Teams during Semester 2, and the subsequent recoding and slides will be available on Minerva in **Experimental Physics: Learning Resources > Presentation**.

The marking criteria for the presentation is given below. A larger version of this table can be found on Minerva in Experimental Physics: Learning Resources > Presentation

Presentation Marking Criteria

Aspect (Weighting)	Fail (20%)	3rd (45%)	2ii (55%)	2i (65%)	1st – Outstanding (85%)	Perfection (100%)
Scientific Content (40%)	Lacking in university level Physics, or incomprehensible to all but specialist in the subject.	Lacking Physics beyond A level, or some parts too specialised for general 1st year audience.	Some material beyond A level Physics, but not made clear to the audience.	Clearly leads the audience from A level Physics into new material.	Clearly leads the audience from A level Physics into new material, showing evidence of detailed investigation into the subject	Clearly leads the audience from A level into new material showing an exceptional investigation into the subject.
Structure and Slides (40%)	No discernible structure to talk, slides incomprehensible or irrelevant.	Poor structure. Some slides incomprehensibl e or irrelevant.	Reasonable structure with most slides well designed	Good structure, made clear to audience at start. Slides well produced, attractive and clearly conveying desired message.	Excellent structure, made clear to audience at start. Slides very well produced, attractive and clearly conveying desired message.	Excellent structure and quality of slides which cannot be improved
Verbal skills and interaction with audience (10%)	Inaudible, with no attempt to interact with the audience.	Spoken too fast or too slow. Poor engagement with audience. Too reliant on notes	Mostly clearly presented with reasonable engagement with audience. A few hesitations	Clearly presented with good eye contact and engagement of audience.	Clear and confident, engaging and inspiring the audience.	Very clear and confident, perfect interaction with the audience
Timekeeping (10%)	Less than half the time, or close to double the time.	Too long or too short and no attempt to adjust delivery of material	Slightly too long or too short, and some attempt to adjust delivery of material.	Slightly too long or too short, but made good attempt to adjust delivery of material to fit the time.	Very close to allotted time, with smooth steady delivery	Perfect timing

Group Video Task (Weeks 20 and 21)

This **compulsory component** assignment is worth 10% of your overall module mark.

The aim of the group video assignment is to help you develop several key skills required by practising scientists; critical and creative thinking, problem solving, teamwork and scientific communication. All of these skills are highly valued by employers and form part of the IOP accreditation for every Physics degree course. Increasingly scientific communication is done via short videos, which is how this task will be assessed.

Working as a Team

This is a group task with many different roles available, for example;

- designing the experiment
- deriving key equation
- taking measurements
- analysing data
- creating a video storyboard
- filming
- creating graphics/animations
- editing

The members of your group will have a variety of experiences and skills they can bring to these roles. Therefore, everyone should be able to make a valuable contribution to this task. Make the most of everyone's talents!

Part 1: Designing an experiment

For the first part of this task you are required to work as a group to design and carry out an experiment to **measure the acceleration due to gravity 'g'**. This will be done during your normal lab session where you will be provided with a range of equipment including:

- A ramp
- A variety of objects (e.g. toy car, marbles, masses, etc).
- Tape measure
- Lab Timer
- String
- Retort stand, clamp and boss (and G-Clamp)
- Newton Meter
- Pulleys

You will also be provided with a phone holder and should use your own smartphones to record your video. You may also request other basic pieces of apparatus, before or during the laboratory session, which we will try to accommodate. The Lab Technician and module lead will be available during each session if you require any additional basic equipment.

Part 2: Creating a video

As a group you need to create a **2 ½ minute** video to explain your experiment and results to your peers / general viewers with A-Level physics knowledge.

You video should include:

- a description of your chosen experimental technique(s)
- a summary of your results
- a comment on how your measured value of 'g' compares to the expected value
- a description of how you could improve your experiment and reduce uncertainties
- any interesting facts or details which will add interest to your video
- an acknowledgement slide at the end to highlight everyone's contribution.

You **must** complete all of your planning, experimental work and lab footage within the two allocated lab sessions. The equipment and lab space will not be available after the end of the second session. A suggested time-line is given below:

- **Week 20: Lab session 1**: Design and test your experiment. Create a rough storyboard for your video to ensure you include all the relevant criteria. Start filming footage of your experiment.
- **Week 21: Lab session 2**: Finish your experimental work and filming in the lab. Record any additional footage required. Start editing your video
- **Week 22: Submission deadline**: Your video needs to be submitted by 5pm on your normal lab day:

  - **Monday Lab Groups Deadline: 5pm on Monday 24th March 2025**
  - **Wednesday Lab Groups Deadline: 5pm on Wednesday 26th March 2025**
  - **Friday Lab Groups Deadline: 5pm on Friday 28th March 2025**

One member of your group must upload the video to Feedback Fruits by this deadline.

Video Editing: You will have until the deadline in week 22 to edit your video**;** amend footage, add graphics or commentary etc.

- Remember, videos **must not exceed 2 ½ minutes**. This time limit will be rigidly enforced; videos exceeding this limit may not be accepted and be given zero marks.

Assessment of the Videos

This task will be peer marked using Feedback Fruits. Peer marking will help you to learn how to mark against criteria and give appropriate feedback. You are required to watch the 8 videos created by students in your usual lab session. Marking is compulsory and will contribute your overall mark for this assignment. Further details will be provided nearer the time.

You will be assessing the videos on the following criteria:

Criteria	**Acceptable** (1 Point)	**Good** (1 Point)	**Very Good** (1 Point)
Engaging - keeps your attention			
Production Quality - technical and storytelling			
Creativity - experimental design			
Scientific Content - clear information & explanations			

Here are some examples of science videos to give you some inspiration:

- Jim Al-Khalili - Gravity: https://youtu.be/SjCEhdvnj6A
  (Especially from 1:30 onwards, has explanations, but also changes of scenery and some animations of planets with voiceover)
- Helen Czerski - Bubbles: https://youtu.be/XotBYcft_qQ
  (Simple production with talking head, action video and slides with continuous speech.)
- Alex Rosenthal and George Zaidan - Other dimensions https://youtu.be/C6kn6nXMWF0
  (Entirely animation with voiceover. Worth thinking about for parts of your production, or if you are camera shy!)

Reasonable Adjustments

If you need reasonable adjustments for these activities, please email a member of the lab team, in confidence, or come and talk to us in the lab.

Lab Skills Assessment (Week 22)

This **compulsory component** assignment is worth 10% of your overall portfolio mark.

In week 22 of semester 2 you will carry out a Lab Skills assessment. This assessment involves six 25 minute activities which will test the skills you have built up over the year.

These activities will be as follows:

1) Measuring and the Volume of a wire
2) Measuring Potential Difference and Current for a simple DC Circuit
3) Using an oscilloscope.
4) Determining an unknown mass using A level physics knowledge
5) Plotting and analysing data using MS Excel (LINEST).
6) Using a pendulum to determine the acceleration due to gravity.

All the relevant physics equations will be given for each activity.

Each activity will be marked out of 10, giving a total mark of 60 for the Skills Assessment.

Formal Report (Week 24)

This **compulsory component** assignment is worth 10% of your overall portfolio mark.

You are required to produce one formally written report on an experiment you completed for the module. This is a more formal presentation of your experiment designed for an interested reader who might want to carry out the experiment for themselves, check your data or collect their own.

An **electronic version** of your Formal Report must be submitted via the **Turnitin** link on Minerva which can be found in **Assessment and Feedback > Submit My Work**. The **deadline** for the Formal Report is**:**

2pm on Monday 28th April 2025

Your Formal Report **must** be on one of the eight **rota** experiments or one of the two **data analysis** tasks. Choose wisely; it is best to choose one where you understood the experiment, one that worked well or one which you enjoyed doing. All of these factors will make it easier for you to complete your report.

- **The report must be completed electronically; if you submit a hand-written report without an explanation you may lose marks.**

There is an example Formal Report available on Minerva in **Experimental Physics: Learning Resources > Formal Report** , which is also posted in the Lab. This example Formal Report is written about the same experiment as used for the Specimen Lab Notebook so you can compare and contrast the different styles.

- You should read the example report available on Minerva and you will be expected to write your report in a similar style.

- You must pay attention to matters of style, presentation and the correct use of English. Do **not** write in the personal tense (I, or We). **You must use the past, impersonal**

tense, e.g. “the ball bearing was carefully dropped into the fluid”, not “I will carefully drop the ball bearing into the fluid.”’.

- You must show evidence that you have **understood** the physics of the experiment and that you have correctly analysed the results.

- Carefully proof read and spell check your work to ensure there are no mistakes! In published work this correctness is usually assumed as a matter of professional competence.

- Be warned: **do not work with your lab partner on your formal report, or copy and paste any information from external sources**. Your work will be checked against all published works, other students work and the lab handbook. You may be asked to attend an academic integrity meeting if there are concerns over your report. Please see the section on plagiarism given on page 23.

A summary of the key points to include in your formal report is given below.

Formal Report: Summary of key points

- Use flowing text everywhere rather than lists.
- Produce all content electronically (not hand drawn).
- Write in the past, impersonal tense (not ‘I’ or ‘we’).
- Use an equation editor to write all equations.
- Number all equations and align them centrally on the page.

Title Page must include**:**
- The title of your report
- Your name
- The date of submission

Abstract:
An abstract is a very short summary, no more than one paragraph long, which contains:
- The objectives of the experiment
- A brief summary of the experimental methods used
- A summary of the key results obtained along with their associated uncertainty
- A comparison with a referenced value, if possible, and a comment on the agreement (e.g. within the uncertainty or not?) and any discrepancy

Introduction:
This section is a good opportunity to show the depth and breadth of the physics associated with your experiment. The introduction should be written in your own words, **do not copy this section from lab manual.** It should contain:
- An overview of the experiment and why the experiment is important to its field
- The objective(s) for this particular experiment
- A description of the basic principles studied, including any governing equations and derivations

Figures and Captions
- All diagrams, tables and/or graphs should be computer generated
- Each figure must have a caption explaining the figure shows, e.g. a summary of the image shown or key features of a graph, and a citation where appropriate.

Methods & description of apparatus:
This section is a description of how the experiment was carried and should allow the reader to recreate the experiment using their own equipment. This should include:

- A detailed schematic of the apparatus used. This must be produced electronically and should be a diagram and not a photograph.
- A summary of the apparatus explaining to the reader how to put the various components together.
- A description of the experimental procedure followed. This should be written in your own words with no unnecessary details such as instructions on how to use a particular brand of apparatus or software etc; the reader may not have the same brand.
- An description of any sources of uncertainties and how they were minimised

Results
For most physics journals the method and results are in separate sections. However for astrophysics journals experimental results are included alongside the method. This should include:

- Computer generated tables and graphs presenting major results. Data should be shown graphically where possible. Any raw data tables or preliminary results may be put in an appendix if these are to be included.
- For graphs, the axis labels should be clear with units given. A line of best fit line and uncertainty bars should be included where appropriate.
- For charts, such as bar charts and pie charts, a clear legend should be included
- For all data, the uncertainty in the value should be included (or a comment made).
- A discuss of trends found in the results, and any relevant comparisons with theory or reference values

Conclusion (often quite similar to the abstract, but not identical).
This should include:

- A summary of the final results. Numerical results should be clearly stated with an uncertainty, and a comparison given to any expected value.
- A brief discussion on whether the objectives of the were met.
- A discussion on the reliability of the experiment, with comments on the accuracy and precision of the results obtained
- Sensible suggestions for improving the experiment (e.g. ways to reducing uncertainties etc.), which should be justified.

References

- You must include any references, such as sources of reference values or images, which should have a citation in the text. For advice on referencing, please see the Library Referencing Guide: https://library.leeds.ac.uk/info/1402/referencing

Appendices (optional)
An appendix contains information which is too detailed to be included in the main report. The contents of an appendix is optional but may include:

- Original data tables. These should be summarised graphically in the main report (where possible)
- A derivation of important equations used in the data analysis (if appropriate).
- A derivation of uncertainty equations used and a summary of the uncertainty analysis.

An optional online lecture about the formal report will be given during Semester 2. A recording of this lecture and the lecture slides will then be available on Minerva

Formal Report: Assessment Criteria

Aspect	Written Communication	Abstract	Introduction	Method	Analysis, Discussion and Conclusion
Class: 1st* 85-100%	The report is easy to read, highly informative and free from mistakes. All sections have the appropriate length and include sufficient detail to reproduce and extend the work. The list of references is fully comprehensive and in an accepted style.	A very well written abstract that covers the essentials in a clear and brief style, similar to a professional research paper. Describes key results with uncertainties and comparison to accepted values.	Content is correct and draws upon a variety of sources to introduce the experiment clearly demonstrating a thorough understanding of the underlying physics at a level beyond 1st year.	Method described in a clear and insightful way that shows thinking beyond that demonstrated or in the lab Manuel. Figures very clear and put together in a way that highlights significant data with informative figure captions.	Discussion involves critical analysis and placing in context. Full, critical analysis of the results, cause(s) for problems and/or unexpected findings. Independent study leading to a strong conclusion of main points beyond that covered in the lab (if applicable) or by the demonstrator.
Class: 1st 70-84%	Well-structured and well organised. The report shows and explains the main results, conclusions and possible future work. English largely correct with only minor, sparse typographical errors that do not impede understanding.	Abstract is well written, of appropriate length, and includes what they found and if appropriate a comparison (with uncertainties) with accepted values.	Content is correct and written at or beyond a 1st year level, making use of material from appropriate sources to introduce the experiment.	Method clearly described in way that would make the experiment easy to reproduce. Figures clear and well described by figure captions to make understanding the data easy.	Discussion of results and key findings placed in context of expected results, reasonable attempt to synthesise an overall conclusion discussed within the understanding of the physics for the given experiment.
Class: 2.1 60-69%	A standard sectioning and organisation. Some sections are overly long/detailed while others miss important points. Periodic typographical and/or grammatical errors. References correctly displayed and largely complete.	Abstract is of appropriate length, includes what they found and if appropriate a comparison (with uncertainties) with accepted values. May contain minor stylistic errors.	Broadly correct content that at a level expected of a 1st year physics student with minor errors of fact or omissions.	Method and most figures of acceptable quality but could be improved or have better figure captions.	Discussion and evaluation of results mostly following the established facts in the field as explained by demonstrator. Uncertainties not correctly calculated or displayed, lack in critical analysis or work not placed in context.
Class: 2.2 50-59%	Structure as expected but with some errors. Number of citations significantly lower than needed, and/or contain formatting errors. Occasional flaws in English may hinder understanding in places. Conclusions, further work and/or introduction not well defined with clear arguments	Abstract covers the main points, but contains several substantial errors in style/length/presentation of key results	Significant number of substantial and important errors. Background equations wrongly displayed and/or with terms not defined.	Substantial defects in many figures – e.g. illegible/unlabelled axes, uninformative figure captions.	Some discussion and evaluation of results but vague, without original insight, or limited to restating of findings. Missing uncertainties, lack in critical analysis or work not placed in context.
Class: 3rd 40-49%	Structure poor/missing key sections. Referencing incorrectly used (e.g. sole use of Wikipedia; no citations in text), or limited to one reference such as the lab handbook	Abstract present, but badly written, may not contain key information or be overlong	Introduction demonstrates a A-level understanding of physics and contains several substantial errors of fact or is missing important information.	Substantial defects in methodology and many figures – e.g. illegible/unlabelled axes, uninformative figure captions or many figures missing.	Provides little or no discussion, no attempt to analyse data critically or synthesise conclusions. Little or no evidence of thought beyond displaying the data.
Fail <40%	Very Poor structure, missing sections, page numbers or leaving out substantial material. Poor use of English makes it difficult to understand or obscures the meaning of some passages. No references or references missing key aspects that make it impossible to find the work.	Abstract missing or incoherent.	Lacking in even A-level physics content or hopelessly confused/missing	No relevant or useful figures or no data presented in report.	Sections missing or incoherent, no evidence of thought beyond displaying the data.
Writing Threshold	Work that fails to meet this standard must be referred to the module leader.	Paragraphs are used. There are links between and within paragraphs although these may be ineffective at times. There are attempts at referencing. Word choice and grammar do not seriously undermine the meaning and comprehensibility of the argument. Word choice and grammar are generally appropriate to an academic text.			

Plagiarism

The University views plagiarism as a serious offence and any suspicious work will be investigated. Any concerns will not be dismissed lightly. You will be required to do an Academic Integrity Test course before you start your degree course. All students need to complete this test to progress at the University.

Do not copy the Lab Handbook or any other sources without a clear reference.

What is counted as Plagiarism in this module:
- Using sections of text copied from either the Lab Handbook, a previous years Lab report or other references sources (e.g. books or internet).
- Using a diagram from either the Lab Handbook or another source (web link etc.) without a reference.

What is not counted as Plagiarism in this module:
- Using sentences that are common to all reports (e.g. the charge/mass ratio of an electron, x-ray diffraction using Bragg's Law etc.). Turnitin will flag this up but we do check all reports.
- Using sections of your own work from your Lab Notebook.
- Diagrams from the Lab Handbook or other sources may be used as long as they have a clear reference. However, you should work towards using your own diagrams; **we expect you to be able to use your own diagrams from semester 2 onwards.**
- If you need advice on referencing, please see the Library Referencing Guide: https://library.leeds.ac.uk/info/1402/referencing

Student Feedback

You will be given the opportunity to feedback at the end of the module via an anonymous online form. Please give us any constructive feedback; this is very useful as we continue to develop the module for each successive years. You are also welcome to email any member of module team with feedback or concerns before or after this time.

Reading List

Here is a list of recommended books for the experimental component of the module:

1. Experimental Methods by Les Kirkup, John Wiley and Sons (1994)
2. Practical Physics by G L Squires (1986)
3. Writing for Science by Heather Silyn-Roberts, Addison Wesley Longman (1996)
4. Practical Guide to Data Analysis for Physical Science Students by Louis Lyons (1994)

Laboratory Technician

The Senior Lab Technician, Angela Beddows, is available in the first year lab to answer any general enquiries during the following times: Monday, Wednesday and Friday mornings (8.30am until 1pm). Alternately, Angela may be emailed via a.beddows@leeds.ac.uk .

The Lab Technician is responsible for:

- Setting up all the experiments used in the lab for all the first and foundation year lab modules.
- Resetting/checking experimental set-ups for each lab session to ensure they are working when students come to use them.
- Fixing the experimental equipment if it goes wrong.
- Regularly maintaining apparatus and fixing faulty equipment when things break so experiments can be completed by students in the time given.
- Electrically testing all electrical equipment used in the lab so it's safe for students and staff to use.
- Doing a rolling programme of safety check so that equipment is maintained and is safe to use on a daily basis.
- Designing and building new equipment where necessary.
- Setting the lab rotas for all first year and foundation year modules, and ensuring students have the information.
- Reporting absences to the Physics Student Support/Tutors/Lab convenor and arranging catch-up opportunities for students who have missed a lab session.
- Managing student mark sheets.
- Editing and maintaining the Lab Handbooks, in collaboration with the Lab Convenors, to ensure they are up to date and contain all appropriate information.
- Dealing with any other lab-based student enquiries.

Uncertainties in Experimental Physics

All experimental measurements are composed of the value and the uncertainty in the values, along with appropriate units

$$\text{value} \pm \text{uncertainty (plus units)}$$

for example: 42 $\pm$ 1 mm or 42.0 $\pm$ 0.1 mm

The uncertainty gives an indication of how well the value is known. The following sections give information on types of uncertainties in experimental measurements, how to estimate these uncertainties and how to determine the overall uncertainty in final values.

Part 1: Types of Uncertainties

Part 1a: Instrument Resolution (Uncertainty):

The “quality” of the equipment used to take experimental measurements impacts the certainty with which the data are known. In general, the higher the resolution of the equipment, the smaller the uncertainty. During an experiment it is important that the equipment used to take data is properly assessed and the uncertainty noted.

- For all equipment, **first look on the equipment, or read any supporting documentation, to see if the uncertainty is given**. If not, use the rules given below.

For analogue readings:

When increments (i.e. divisions) are present, use half of the increment size as an estimate of the uncertainty.

For example, a ruler with millimetre division is used to measure the width of an object, as shown in in Fig U1(a) below. Here the uncertainty is equal to half a millimetre, 0.5mm = 0.05cm, giving a measurement of: **1.60 ± 0.05 cm**.

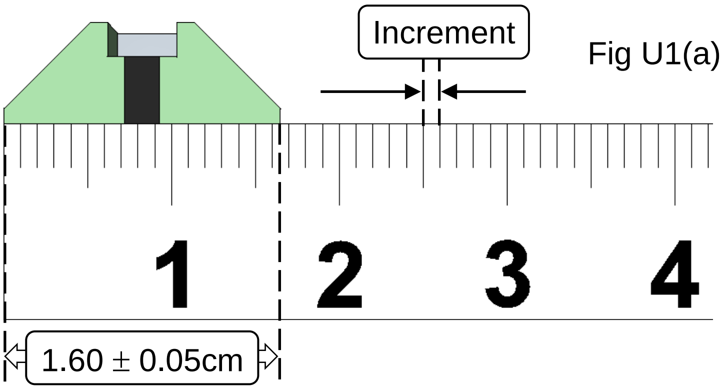
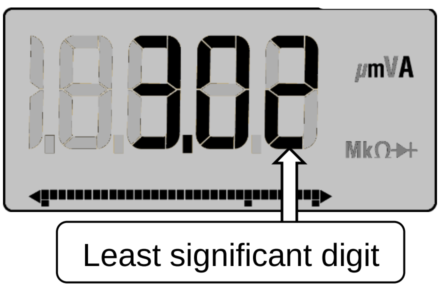


Fig U1(a)

For digital instrument readings:

Digital displays do not have increments so do not convey this same level of precision as analogue equipment. For digital displays, use an uncertainty of 1 in the ‘least significant digit’.

For example, a multimeter is used to measure the current through a circuit, as shown in Figure U1(b). Here a current of 3.02 mA is displayed, where the 2 is the least significant digit. Therefore, the uncertainty would be 0.01 mA giving a measurement of: **3.02** $\pm$ **0.01 mA.**

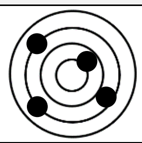
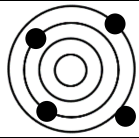
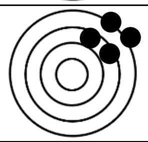
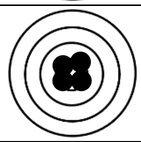
Fig U1(b)


Part 1b: Systematic Uncertainties: Often due to improper calibration or use of an instrument. For example, not zeroing a scale before measurement. These types of uncertainties are not reflected in the uncertainty.

Part 1c: Random Uncertainties: Variations in the result of repeated measurements of the same physical quantity which arise from undetected/unnoticed variations in measurement technique, small changes in experimental conditions, etc.

A **precise** measurement is one where the independent measurements of the same quantity closely cluster about a single value, which may not be the right value.

An **accurate** measurement is one where independent measurements cluster about the true value of the measured quantity.

	Low Accuracy	High Accuracy
Low Precision		
High Precision		

Part 2: Statistical Tools for Repeated Measurements

Taking repeated measurements reduces the overall uncertainty in the final value. When repeated measurements are taken, the mean and standard uncertainty should be calculated. The mean is given by:

$$\bar{x} = \frac{1}{n}\sum_i x_i \qquad \text{equation (U.1)}$$

where, x_i is the value of each individual measurement and n is the number of repeats.

The standard uncertainty, α_n, gives a measure of the random fluctuations in the sample, as shown in part 4. It is defined as:

$$\alpha_n = \frac{\sigma_{n-1}}{\sqrt{n}} \qquad \text{equation (U.2)}$$

where σ_{n-1} is the standard deviation **in the sample** given by:

$$\sigma_{n-1} \cong \left(\frac{1}{(n-1)}\sum_i (\bar{x} - x_i)^2\right)^{\frac{1}{2}} \qquad \text{equation (U.3)}$$

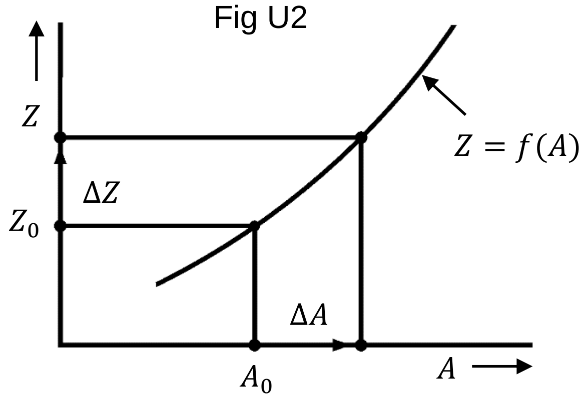
Note: In physics the standard deviation in the sample is always used, never the population.

- If the standard uncertainty is larger than the instrument uncertainty, then the result should be quoted as: $\bar{x} \pm \frac{\sigma_{n-1}}{\sqrt{n}}$
- If the instrument uncertainty is larger than the standard uncertainty, then the result should be quoted as: $\bar{x} \pm \text{Instrument uncertainty}$

Remember to include appropriate units!

Part 3: Uncertainty Propagation

Fig U2



The uncertainty in the final value depends on the uncertainty in each measured variable and the relationship between them.

For example suppose the final value, Z, depends upon variable A such that:

$$Z = f(A)$$

The effect of the uncertainty in A, ΔA, on Z is illustrated in figure U2.

There are two ways to calculate the uncertainty in Z, ΔZ, due to the uncertainty in A; the differential method and the substitution method.

Both of these methods are explained on the following pages. For more detailed explanations please see Practical Physics by G.L.Squires:

Part 3a: The Differential Method:

By considering figure U2 the uncertainty in Z, ΔZ can be found from the gradient of the curve $Z = f(A)$:

$$\text{Gradient} = \frac{\Delta Z}{\Delta A} \qquad \text{equation (U.4)}$$

The gradient can also be determined by differentiating function Z with respect to A:

$$\text{Gradient} = \frac{dZ}{dA} \qquad \text{equation (U.5)}$$

Therefore, the uncertainty in Z, ΔZ can be determined using the formula:

$$\Delta Z = \left(\frac{dZ}{dA}\right) \cdot \Delta A \qquad \text{equation (U.6)}$$

For a general function, Z, which depends on three variables, A, B and C:

$$Z = f(A, B, C)$$

the uncertainty in Z results from fluctuations in A, B and/or C given as, ΔA, ΔB and ΔC respectively, which are determined by differentiating the function with respect to each variable:

$$\Delta Z_A = \left(\frac{\partial Z}{\partial A}\right)_{B,C} \Delta A, \qquad \Delta Z_B = \left(\frac{\partial Z}{\partial B}\right)_{A,C} \Delta B, \qquad \Delta Z_C = \left(\frac{\partial Z}{\partial C}\right)_{A,B} \Delta C$$

Here, for example, $\left(\frac{\partial Z}{\partial A}\right)_{B,C}$ is the **partial** derivative of Z with respect to A.

The question then arises as to how to combine these individual uncertainties to give the overall uncertainty in Z, ΔZ. Statistical analysis shows that simply adding these terms assumes the maximum uncertainty for each variable and hence over estimates the final uncertainty. **Where variables are independent to one another** (uncorrelated), a more realistic estimate is obtained by adding the terms **in quadrature**:

$$(\Delta Z)^2 = \left[\left(\frac{\partial Z}{\partial A}\right)_{B,C} \Delta A\right]^2 + \left[\left(\frac{\partial Z}{\partial B}\right)_{A,C} \Delta B\right]^2 + \left[\left(\frac{\partial Z}{\partial C}\right)_{A,B} \Delta C\right]^2 \qquad \text{equation (U.7)}$$

Therefore, if the function has more than one variable, differentiate the function with respect to each variable in turn (keeping the other variables constant) and then add in quadrature.

Example 1

Consider the function:

$$Z = A.B.C \qquad \text{equation (U.8)}$$

Using equation (U.7), where $\left(\frac{\partial Z}{\partial A}\right)_{B,C} = BC$ etc. the uncertainty in Z is given by:

$$(\Delta Z)^2 = [BC \times \Delta A]^2 + [AC \times \Delta B]^2 + [AB \times \Delta C]^2$$

Dividing throughout by $Z = ABC$ gives the uncertainty in terms of the fractional uncertainties:

$$\left(\frac{\Delta Z}{Z}\right)^2 = \left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta B}{B}\right)^2 + \left(\frac{\Delta C}{C}\right)^2 \qquad \text{equation (U.9)}$$

This is often written as:

$$\Delta Z = Z\sqrt{\left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta B}{B}\right)^2 + \left(\frac{\Delta C}{C}\right)^2} \qquad \text{equation (U.10)}$$

Example 2

Consider the function:

$$\frac{1}{Z} = \frac{1}{A} + \frac{1}{B} + \frac{1}{C} \qquad \text{equation (U.11)}$$

This can be differentiated to give the uncertainty in $\frac{1}{Z}$, written as $\Delta\left(\frac{1}{Z}\right)$:

$$\left[\Delta\left(\frac{1}{Z}\right)\right]^2 = \left(-\frac{\Delta A}{A^2}\right)^2 + \left(-\frac{\Delta B}{B^2}\right)^2 + \left(-\frac{\Delta C}{C^2}\right)^2$$

The uncertainty in Z, ΔZ, can then be found either by considering a function $f(Z) = \frac{1}{Z}$ or by considering the fractional uncertainty in both:

$$\frac{\Delta Z}{Z} = \frac{\Delta\left(\frac{1}{Z}\right)}{\left(\frac{1}{Z}\right)} \qquad \text{equation (U.12)}$$

This then leads to the uncertainty in Z, ΔZ given by:

$$\Delta Z = \frac{\Delta\left(\frac{1}{Z}\right)}{\frac{1}{Z}} . Z = \Delta\left(\frac{1}{Z}\right) . Z^2 \qquad \text{equation (U.13)}$$

Examples to commit to memory:

Consider the general function, $f = f(x, y, z)$, the uncertainty in f, Δf can be found using the formula:

$$(\Delta f)^2 = \left[\left(\frac{\partial f}{\partial x}\right)_{y,z} \Delta x\right]^2 + \left[\left(\frac{\partial f}{\partial y}\right)_{x,z} \Delta y\right]^2 + \left[\left(\frac{\partial f}{\partial z}\right)_{x,y} \Delta z\right]^2 \quad \text{equation (U.14)}$$

which leads to the following general formula:

$f = x + y$ affords $\Delta f = \sqrt{(\Delta x)^2 + (\Delta y)^2}$	$f = x - y$ affords $\Delta f = \sqrt{(\Delta x)^2 + (\Delta y)^2}$
$f = xy$ affords $\frac{\Delta f}{f} = \sqrt{\left(\frac{\Delta x}{x}\right)^2 + \left(\frac{\Delta y}{y}\right)^2}$	$f = \frac{x}{y}$ affords $\frac{\Delta f}{f} = \sqrt{\left(\frac{\Delta x}{x}\right)^2 + \left(\frac{\Delta y}{y}\right)^2}$
$f = x^a y^b$ affords $\frac{\Delta f}{f} = \sqrt{\left(\frac{a\Delta x}{x}\right)^2 + \left(\frac{b\Delta y}{y}\right)^2}$	$f = \sin(\theta) \Longrightarrow \Delta f = \cos(\theta)\, \Delta\theta$ $\Delta\theta$ in radians

Table 1: General formula and their associated uncertainties.

Beware: The differential method is based on the assumption that there is no correlation between the variables. However, this may not be true!

- These general formula should only be used when $\boldsymbol{x}$ **does not depend in any way on** $\boldsymbol{y}$.
- Where the is a correlation between variables, or there if the relationship is known, **the substitution method** should be used.

Part 3b: The Substitution Method:

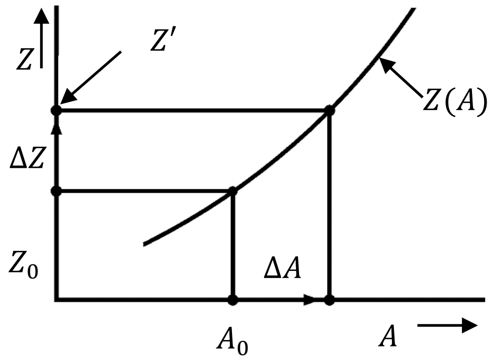
The substitution method works for all functions, even where variables are dependent on one another. It can also be used when function are too difficult to differentiate. For uncorrelated variables, the substitution method gives identical overall uncertainties as the differential method.

Although the outcome is the same as the differential method, here the average value of Z is calculated using the fluctuations (uncertainty) in each variable.

Consider again the function:

$$Z = f(A)$$

Fig U3



Here Z_0 is calculated using the value of A_0, and Z' is calculated using the largest probable value of A, $A + \Delta A$, as shown in figure U3.

The uncertainty in Z, ΔZ, is then calculate from the different between $Z'$and Z_0:

$$\Delta Z = (Z' - Z_0)$$

If the function has more than one variable, the difference is found for each variable in turn and then these differences are added in quadrature.

Example 1

Consider again the function:

$$Z = A.B.C$$

Here Z is calculated using the measured (average) values of A, B and C and largest probable values for each variable calculated as follows:

$$Z_{(A+\Delta A)} = (A + \Delta A).B.C$$

$$Z_{(B+\Delta B)} = A.(B + \Delta B).C$$

$$Z_{(C+\Delta C)} = A.B.(C + \Delta C)$$

The overall uncertainty is then given by:

$$\Delta Z^2 = \left(Z_{(A+\Delta A)} - Z\right)^2 + \left(Z_{(B+\Delta B)} - Z\right)^2 + \left(Z_{(C+\Delta C)} - Z\right)^2 \qquad \text{equation (U.15)}$$

This looks very different from equation (U.12), but substituting in the correct values should give the same overall uncertainty.

Example 2

Consider again the function:

$$\frac{1}{Z} = \frac{1}{A} + \frac{1}{B} + \frac{1}{C}$$

Here $\frac{1}{Z}$ is calculated using the measured (average) values of A, B and C and largest probable values for each variable calculated as follows:

$$\frac{1}{Z_{(A+\Delta A)}} = \frac{1}{(A + \Delta A)} + \frac{1}{B} + \frac{1}{C}$$

$$\frac{1}{Z_{(B+\Delta B)}} = \frac{1}{A} + \frac{1}{(B + \Delta B)} + \frac{1}{C}$$

$$\frac{1}{Z_{(C+\Delta C)}} = \frac{1}{A} + \frac{1}{B} + \frac{1}{(C + \Delta C)}$$

And the overall uncertainty in is given by:

$$\left[\Delta\left(\frac{1}{Z}\right)\right]^2 = \left(\frac{1}{Z_{(A+\Delta A)}} - \frac{1}{Z}\right)^2 + \left(\frac{1}{Z_{(B+\Delta B)}} - \frac{1}{Z}\right)^2 + \left(\frac{1}{Z_{(C+\Delta C)}} - \frac{1}{Z}\right)^2 \qquad \text{equation (U.16)}$$

(Note that this equation can be simplified by substituting in each expression!).

The uncertainty in Z, ΔZ, can then be found using equation (U.13). Again, substituting in the correct values should give the same overall uncertainty calculated using the differential technique.

Part 3c: Worked Example using Differential and Substitution methods

Suppose that during an experiment the area of a plate has to be calculated where:

$$A = lw$$

If $l = 30 \pm 1\ \mathrm{mm}$ and $w = 23 \pm 2\ \mathrm{mm}$, the area is calculated as:

$$A = 30\ \mathrm{mm} \times 23\ \mathrm{mm} = 690\ \mathrm{mm}^2$$

By considering the differential method the uncertainty is calculated using

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

where:

$$\frac{\Delta A}{690\ \mathrm{mm}^2} = \sqrt{\left(\frac{1}{30}\right)^2 + \left(\frac{2}{23}\right)^2} = 0.093$$

Notice that the units cancel on the right hand side.

This leads to an uncertainty of:

$$\Delta A = 690\ \mathrm{mm}^2 \times 0.093 = 64.26\ \mathrm{mm}^2$$

Using the substitution method:

$$A_{(l+\Delta l)} = (l + \Delta l).w = (30\ \mathrm{mm} + 1\ \mathrm{mm}) \times 23\ \mathrm{mm} = 713\ \mathrm{mm}^2$$

$$A_{(w+\Delta w)} = l.(w + \Delta w) = 30\ \mathrm{mm} \times (23\ \mathrm{mm} + 2\ \mathrm{mm}) = 750\ \mathrm{mm}^2$$

Hence:

$$\Delta A^2 = \left(A_{(l+\Delta l)} - A\right)^2 + \left(A_{(w+\Delta w)} - A\right)^2$$

Therefore:

$$\Delta A^2 = (713\ - 690\ )^2 + (750\ - 690\ )^2 = (23^2 + 60^2)\ = 4129$$

And, including relevant units:

$$\Delta A = \sqrt{4129\ \mathrm{mm}^4}\ = 64.26\ \mathrm{mm}^2$$

This is exactly the same result as before.

Remembering that the uncertainty is always given to one significant figure, the area can then be written as:

$$A = 690\ \pm 60\ \mathrm{mm}^2$$

Part 4: The Impact of Repeated Measurements

Let's assume that you have taken n measurements of a quantity x where each measurement has an uncertainty of Δx. The average value of x, $\bar{x}$, is then given by:

$$\bar{x} = \frac{1}{n}(x_1 + x_2 + x_3 + x_4 + \ldots + x_n)$$

Using the general formula shown in table 1, the uncertainty in the average value of x is given by:

$$\Delta\bar{x} = \frac{1}{n}\sqrt{(\Delta x_1)^2 + (\Delta x_2)^2 + (\Delta x_3)^2 + \ldots + (\Delta x_n)^2} \qquad \text{equation (U.17)}$$

where Δx_1 is the uncertainty in x_1, and so on. If the value of each uncertainty, Δx_n, is equal to the standard deviation in the sample, σ_{n-1}, equation (U.17) can be written as:

$$\Delta f = \frac{1}{n}\sqrt{n(\sigma_{n-1})^2} = \frac{\sqrt{n}}{n}\sigma_{n-1} = \frac{\sigma_{n-1}}{\sqrt{n}}$$

Repeated measurements reduces the uncertainty by the square root of the number of repeats

This is equal to the standard uncertainty given in part 2.

Note that the improvement in the precision goes as the square root of the number of measurements taken. Therefore, to improve the precision by a factor of 2, 4 times the number of measurements is required. An improvement of a factor of 10 requires 100 times the number of measurements.

Part 5: Significant Figures

Every experimental value must be written with the precision to which it is confidently known. This is done by using the correct number of significant figures (sig. figs.). In general, all definite digits and the first doubtful digit are significant.

For example, if the length of a piece of wood, L, is measured between 1.55 m and 1.59 m this should be recorded as

$$L = 1.57 \ \pm 0.02 \text{ m}$$

Writing L as 1.570 would imply the 7 was a definite digit when in fact the 7 is the first doubtful digit.

If L is then re-measured with a better ruler to a value of 1.573 metres, writing the new measurement as 1.573 $\pm$ 0.02 m would imply that the 7 is the first doubtful digit rather than the 3. Therefore this new measurement should be recorded as 1.573 $\pm$ 0.002 m.

In general, when values are added or subtracted, the answer should contain **the same number of decimal places as the value with the lowest precision**. For example, in the sum shown below the value with the lowest precision is 150.0 g (one decimal place):

$$\begin{array}{lr} & 150.0 \text{ g} \\ + & \underline{0.507 \text{ g}} \\ & 150.5 \text{ g} \end{array}$$

In general, when values are multiplied or divided, **the answer should contain the same number of significant figures as the least accurate value.** For example, in the calculation shown below the least accurate value is 4.87 which has 3 sig figs. Therefore the answer should be recorded to 3 sig figs:

$$15.03 \times 4.87 \div 1.987 = 36.8$$

The following rules can be used to determine the number of significant figures:

Rule 1: Leading zeros are never significant. E.g. 0.00682 has three sig. figs.
Rule 2: Embedded zeros are always significant. E.g. 1.072 has four sig. figs.
Rule 3: Trailing zeros are significant only if the decimal point is specified. E.g. 300 has one sig. fig. whereas 300.0 has four sig.figs.

In general, **uncertainties should be reported to 1 significant figure**. For practice at using significant figures see: http://science.widener.edu/svb/tutorial/sigfigures.html

Part 6: Rounding

Numbers must be rounded to reflect the correct number of significant figures.

Consider the number 1.784 where 8 is the first doubtful digit. The 4 is insignificant and should not be included in the value. The question is do we report a value of 1.78 or 1.79? Here the following rules should be followed:

- If the insignificant digit is less than 5, it should just be discarded. Therefore 1.784 would become 1.78.
- If the insignificant digit is greater than or equal to 5, discard it and round up the first doubtful digit by one. Therefore 1.785 would become 1.79.

Graph plotting

Graphs are used to give a visual representation of the relationship between two quantities and may be used to obtain information that would be too time consuming or difficult to obtain in other ways.

Part 1: Straight Line Graphs

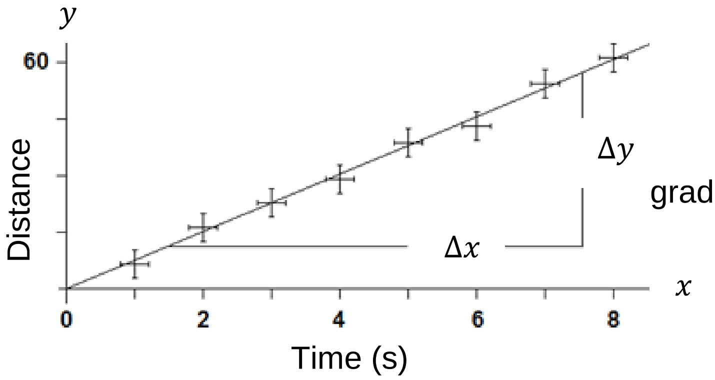
The aim of many experiments is to generate a straight line graph of the form:

$$y = mx + c$$

where x and y are the independent and dependent variables respectively. Here m is the gradient or slope of the line given by $m = \Delta y/\Delta x$ and c represents the intercept on the y axis, the value of y when x = 0. Both the gradient and intercept can lead to of the average value of relevant physical quantities.

Consider the example shown below where the distance travelled by a sprinter is plotted as a function of time.

Fig. G1. Graph of distance of sprinter travel versus time



gradient = $\frac{\Delta y}{\Delta x} = \frac{\Delta s}{\Delta t}$

Here the gradient is equal to the average speed of the sprinter, 10.2 m/s.

Part 2: Guidelines for Plotting Graphs

Graphs may be plotted electronically, using software such as MS Excel or Origin, or plotted by hand. The following guidelines should be used for both electronic and hand drawn graphs:

- Clear data points should be used. For hand drawn graphs use a sharp pencil to draw crosses (+) **not** dots. Dots may be used for electronic graphs as long as they are clearly visible.
- In general, the dependent variable should be plotted along the vertical (y) axis, and independent variable should be plotted along the horizontal (x) axis.
- Graphs should be large enough for information to be accurately determined or clearly seen. For hand drawn graphs, choose x and y scales which use the full page as this will improve the quality of data obtained from gradients and intercepts.
- Each axis should be clearly labelled, and include appropriate units.
- Each graph should have a clear and meaningful title. For formal reports, each graph should also have a figure number and a caption.
- Data points should include uncertainty bars.
- Draw a line or curve of best fit to your data points.

Part 2a: Hand Drawn Graphs

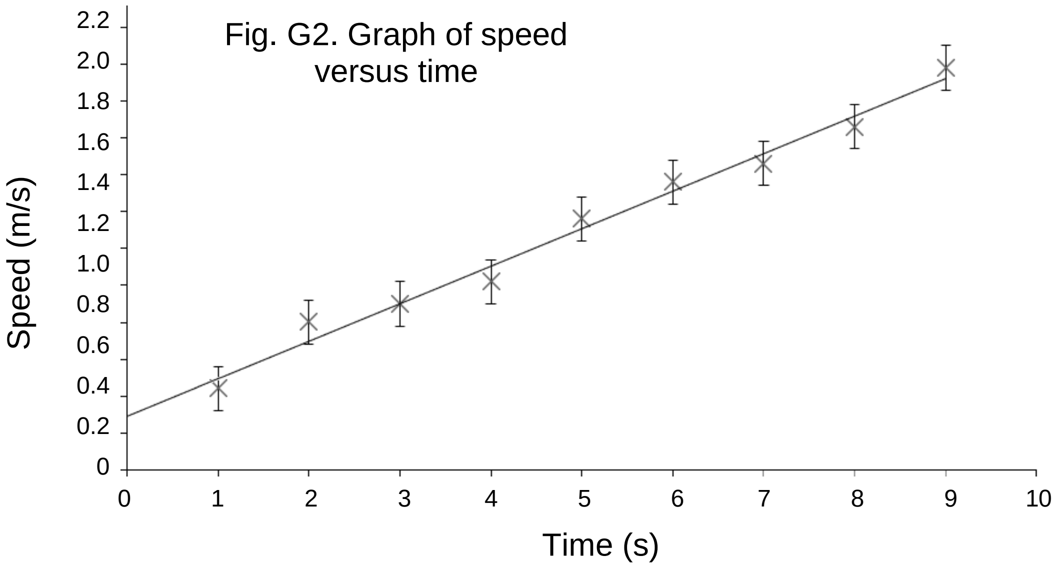
Although software is now commonly used to plot experimental data, knowing how to plot a graph by hand is an important skill for experimental physicists.

Hand drawing lines of best fit:

A line (or smooth curve) of best fit is the one that goes through most of the data points, with an equal number of points above and below the line. Where error bars have been added, the line of best fit should pass through the positive or negative error bar for each individual data point. An example of a good line of best fit is shown in figure G2 below. This also illustrates how the line of best fit provides an 'average' value. Lines of best fit should be drawn using a sharp pencil and a ruler!

Determining gradients from hand drawn graphs

To determine the gradient of a hand drawn graphs, select two points on the line which are well separated and, where possible, cross the intersection between the grid lines. Data points may only be used if they are **exactly** on the line of best fit! The difference between the data points along each axis, Δx and Δy, can then be used to calculate the gradient.



Part 2b: Graph Plotting Exercise

Consider the following data obtained during the study of the speed of an object (dependent variable) as a function of time (independent variable).

Speed (m/s)	Time (s)	Speed (m/s)	Time (s)	Speed (m/s)	Time (s)
0.22 ±0.06	1	0.51 ±0.06	4	0.83 ±0.06	7
0.40 ±0.06	2	0.68 ±0.06	5	0.93 ±0.06	8
0.45 ±0.06	3	0.78 ±0.06	6	1.09 ±0.06	9

1) Use these data to hand draw a graph of speed against time.
2) Add uncertainty bars and a line of best fit.
3) Determine the gradient and the intercept of the line of best fit.

Part 3: Uncertainties in Gradients and Intercepts

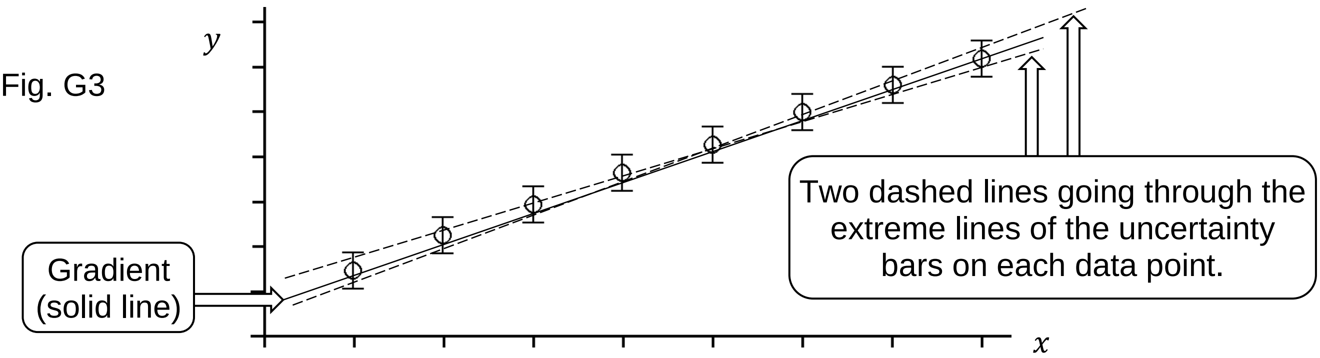
Part 3a: Hand drawn graphs with clear uncertainty bars

For hand drawn graphs, the uncertainty bars associated with each data point can be used to estimate the uncertainty in the gradient as described below:

1) Draw a line of the best fit in the usual fashion using a solid line.
2) Draw two more lines of fit, using dashed lines, which pass through the extreme values of the uncertainties as shown in figure G3 below.
3) Calculate the gradient of each line. The gradient of the solid line will give the 'average' value, and the gradients of the dashed line will allow the uncertainty in this value to be estimated. Always use your judgement, this is not a rule that you should follow blindly.

This technique allows the uncertainty in the gradient and the intercept to be determined.

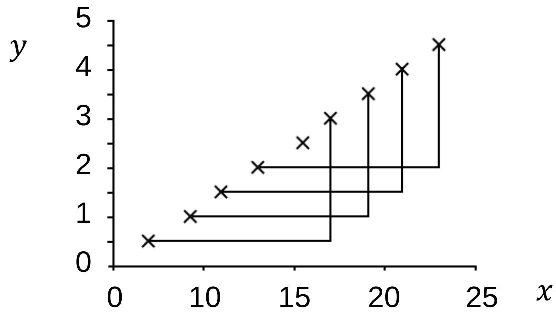
Fig. G3



Part 3b: The multiple gradient method for hand drawn graphs

Sometimes the uncertainty bars are too small to be of use. In this case you multiple gradients from pairs of data points can be calculated, as shown in figure G4 below, and the standard uncertainty in the average gradient determined.

Fig. G4



To determine the uncertainty in the gradient using the multiple gradient method:

1) Choose pairs of data points which have equal precision and are spaced the same distance apart
2) Calculate the gradient using each pair of data points.
3) Calculate the average (mean) gradient and the standard deviation in this value.
4) Use equation (U.2) to calculate the standard uncertainty in the average gradient.

Care should be taken when selecting pairs of points, as shown In figures G5(a) and G5(b). In figure G5(a) the pairs of point have equal spacing but they are not independent pairs. Here only the endpoints contribute to the mean gradient as the rest cancel each other out!

Figure G5(b) shows independent pairs but the spacing is unequal. The central pair of points could have a disastrous effect on the average!

Fig. G5(a)

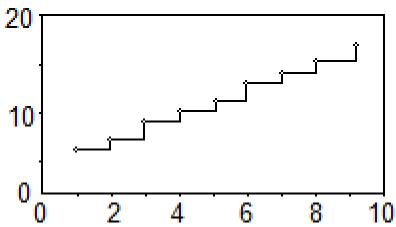
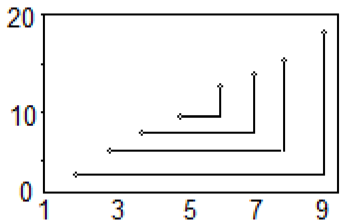


Fig. G5(b)



Part 4: Useful Graph Plotting Functions in MS Excel

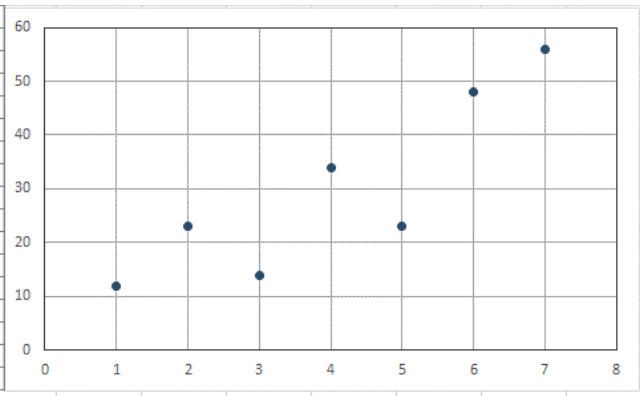
Below are written instructions for some useful MS Excel functions. Screencasts demonstrating different functions in MS Excel are also available on Minerva in **Experimental Physics: Learning Resources > Plotting Graphs in MS Excel**

Part 4a: Adding Custom Uncertainty Bars in MS Excel

1) First create your Scatter graph from your data. An example is shown figure G6 below:

Fig. G6

X	Y	Y Uncertainty
1	12	1
2	23	2
3	14	1
4	34	3
5	23	2
6	48	5
7	56	5



1) Click the graph and then on the **Design Tab** as shown in figure G7 below.
2) Next select **Add Chart Element**. Click on **Error Bars** and then **More Error Bar Options**. These options can also be found by selecting the green + symbol next to the graph.

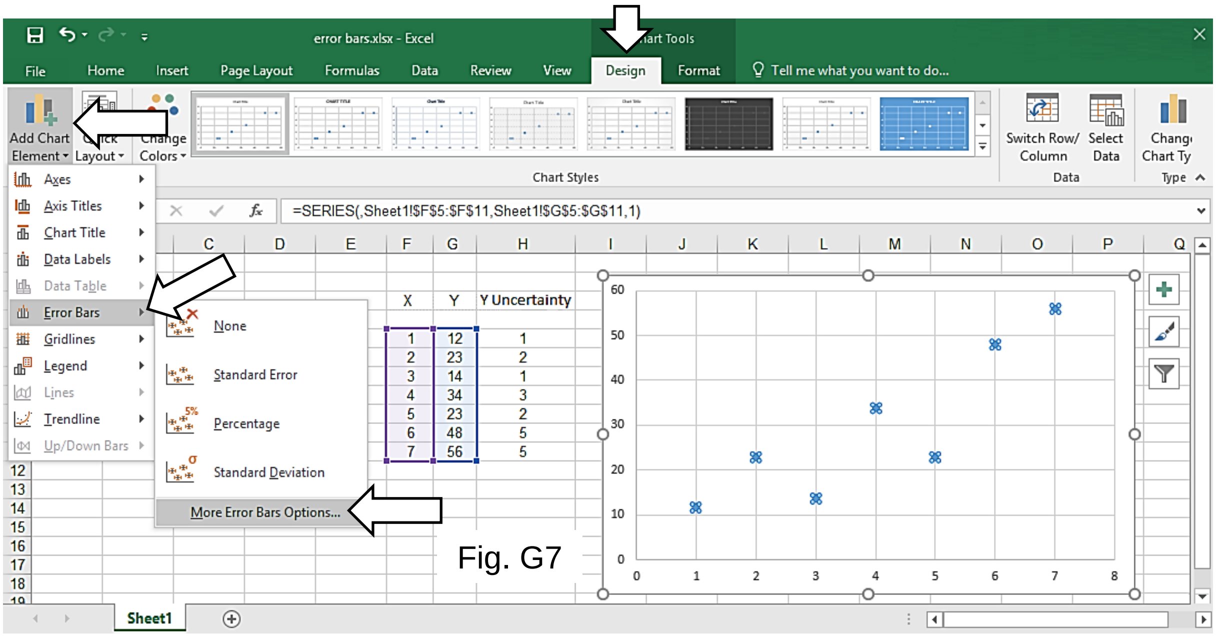


Fig. G7

3) Selecting **More Error Bar Options** with bring up the **Format Error Bars** side tab.
4) First select the Y error bars, by clicking on one of the error bars or using the option on the **Format Error Bars** tab.
5) At the bottom of the **Format Error Bars** tab, click **Custom**, then click on **Specify Value**. This will open a pop up box.
6) Populate the Positive and Negative regions in the pop up box by dragging through the range in the **Y Uncertainty** column (the same data should be used for both the positive and negative error bar values). Then click OK to accept. The graph should now have the correct Y error bars, as shown in figure G8 below.

X	Y	Y Uncertainty
1	12	1
2	23	2
3	14	1
4	34	3
5	23	2
6	48	5
7	56	5

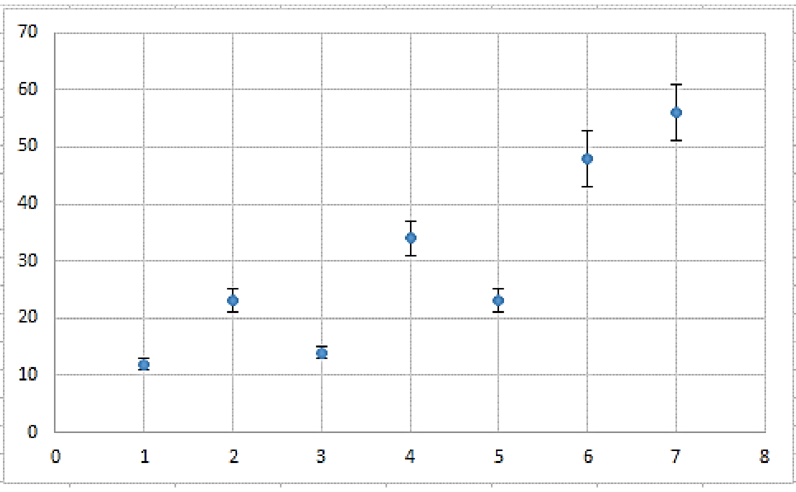


Fig. G8

7) Steps 4 to 6 can then be repeated for the X error bars.

Part 4b: Lines of best fit and the LINEST Function in Excel

In Microsoft Excel, lines of best fit or **Trendlines** are determined using a **linear regression** or '**least square fit method**'. Here the difference between each data point and probable lines of best fit and calculated. These differences are then squared and added together. The total 'squared difference' is then minimised to determine the optimum position of the line of best fit.

The LINEST function also uses this least squares fit method to determine various statistics for a straight line, including the uncertainty in the gradient and intercept and the 'R^2 value'. The R^2 value in a measure of how well the data points match onto the line of best fit. Here a value equal to one indicates that the data point form a perfect straight line.

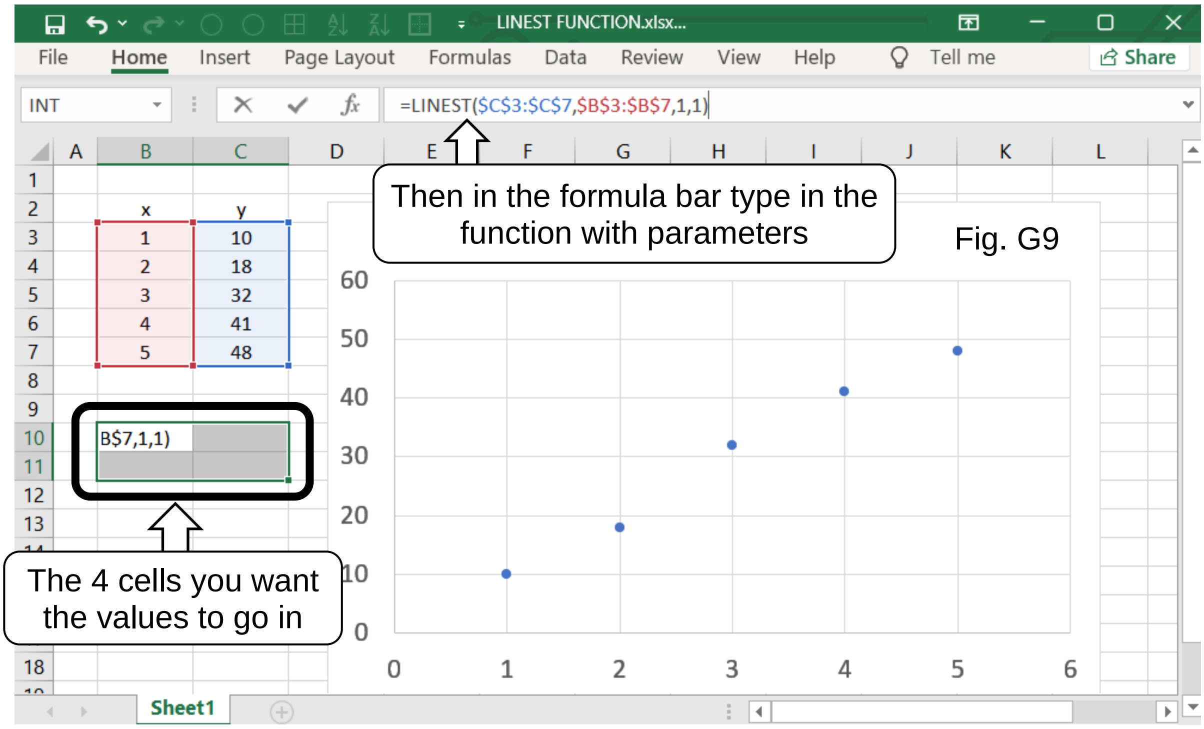
Note that the LINEST function does not take uncertainty bars into account when calculating the uncertainty in the gradient and the intercept!

Part 4c: Adding a Trendline in Excel

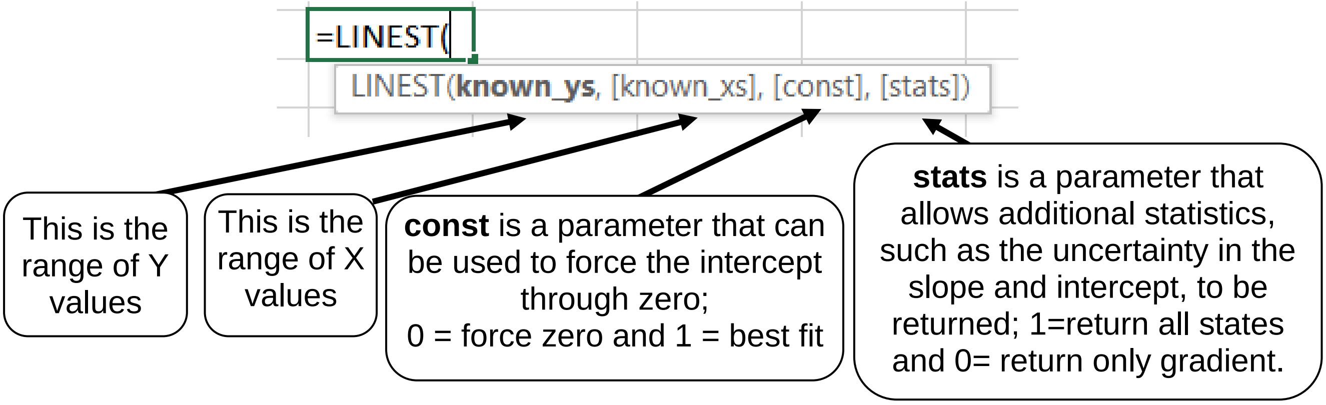
1) Click the graph and then on the **Design Tab** as shown in figure G7.
2) Next select **Add Chart Element**. Click on **Trendline** and then **More Options**. These options can also be found by selecting the green + symbol next to the graph.
3) This with bring up the **Format Trendline** side tab. Use this to select the appropriate trendline to add to you data – the graph may not be linear!
4) The equation of the line and the R^2 value can be displayed on the graph by selecting these option in the Format Trendline side tab.

Part 4c: Using the LINEST Function in Excel

1) Once you have created your graph, you need to select four cells that you want the LINEST array data to be placed. This is shown in figure G9 below.
2) In the formula bar first type = so the software knows you are writing a function, then type LINEST



3) A function with four parameters will then appear, which is explained below:



- The intercept should never be forced to go through (0,0) so **const should always be equal to 1**
- As you want the uncertainty in the gradient and intercept, all statistics are required and **stats should always be equal to 1**

Therefore the function on the formula bar should look like:

=LINEST([range of Y values], [range of X values],1,1)

An example shown in figure G9. Note that each variable is separated by a comma.

4) The range of Y values is entered by highlighting the appropriate data in the spreadsheet. In the example shown in figure G9, the Y data is in column C. After entering the range, add a comma.
5) Next the range of X values is entered by highlighting the appropriate data in the spreadsheet, column B in this example, followed by a comma.
6) Finally type 1,1 to select the const and stats values. If you missed out a parameter or comma (which defines the parameter) it'll come up with an error message.
7) To return the data **press CTRL, SHIFT and ENTER all together**. This should result in values appearing in each of four highlighted cells, as shown in figure G10 below. (It won't work if you just press ENTER on its own).

In this example gradient is equal to 9.9 ± 0.7 (with the uncertainty in the gradient rounded to one significant figure).

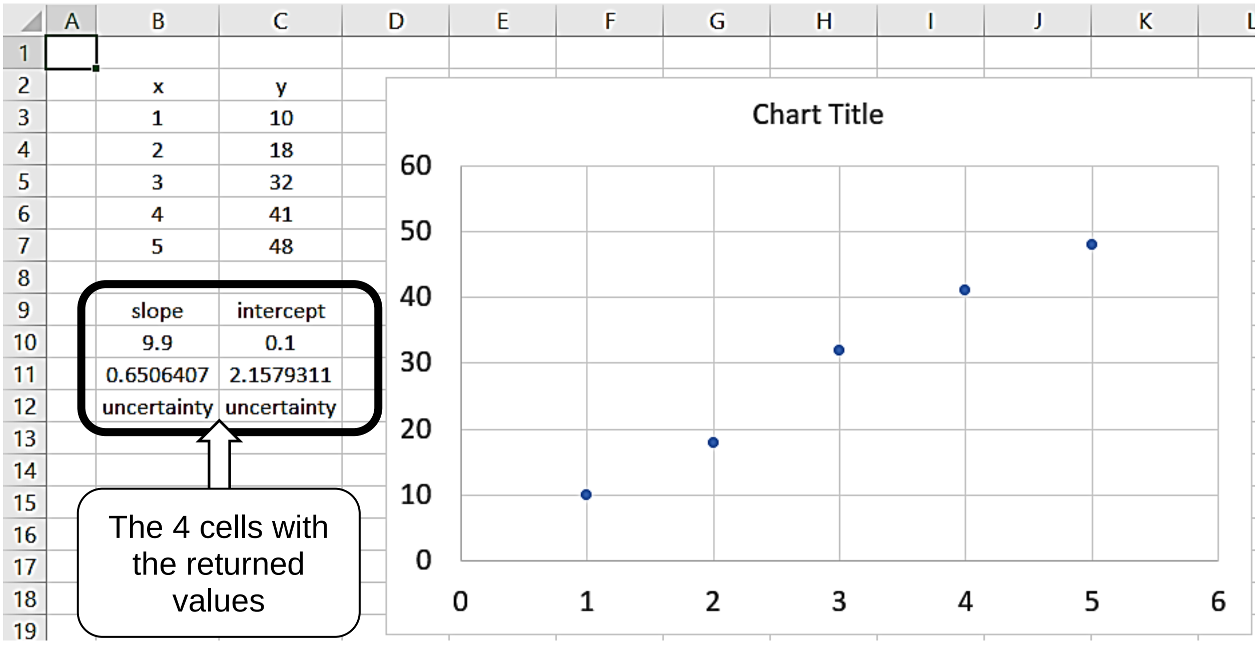


Fig. G10

Experiment 1: Introduction to Laboratory Skills 1

Measurement of Viscosity using Stokes' Law

Experimental Aims:
- To determine the viscosity of Glycerin (at the laboratory temperature) by measuring the terminal velocity of a ball bearing falling through the fluid.
- To determine the 'true' viscosity of Glycerin in the absence of boundary wall effects by measuring the terminal velocity for a range of ball bearing/tube ratios.
- To compare the measured true value of viscosity (and its uncertainty) with a target value taken from the published work of Cheng [1]

Learning Objectives:
- To start developing the skills necessary to become an experimental physicist.
- To understand Stokes' Law and the influence of boundaries on viscosity.
- To learn how to use a graph plotting programme such as MS Excel/LINEST or Origin Pro to determine the intercept of a graph and the uncertainty in this value.

VITALs

E1 a: Safely measure and record experimental data
E1 e: Determine the overall uncertainty in a final value

Preparation:
You are expected to have done these things **before** you turn up to the lab session:
- **Watch the Online Supporting Video** (link is on Minerva) and become familiar with the experimental method and data analysis.
- Read this manuscript and become familiar with the physics behind this experiment.
- Read the section on Viscous Flow in Tipler.
- Filled in the online Health & Safety form as described below.

Risk Assessment and Safety:
Read the Health and Safety information on the next page and fill in the online Health & Safety form. The technician will check online that you have filled this in before you start. It can be reached either via this QR code, via the link on Minerva or this weblink here:
https://forms.office.com/e/JUsKrrd5qD

Things to consider during the experiment:
- What is most appropriate instrument to use for each measurement?
- What is the instrument uncertainty?
- Whether the measurement has a random aspect (e.g. human uncertainty), how can this be reduced?
- If one uncertainty dominates, or if there is a systematic uncertainty, can this be improved for a future experiment?

Appendices at the end of this script:
Appendix 1.1: How to read a Hydrometer. (page 54)

1. Nian-Sheng Cheng , Formula for the Viscosity of a Glycerol-Water Mixture, Ind. Eng. Chem. Res. 2008, 3285-3288 – page 3287 equation 21

School of Physics & Astronomy	RISK ASSESSMENT RECORD
LOCATION:	Bragg Building, Room 4.08, 1st Year Physics Undergraduate Laboratory
DESCRIPTION OF ACTIVITY:	**Experiment 1: Stoke's Law**

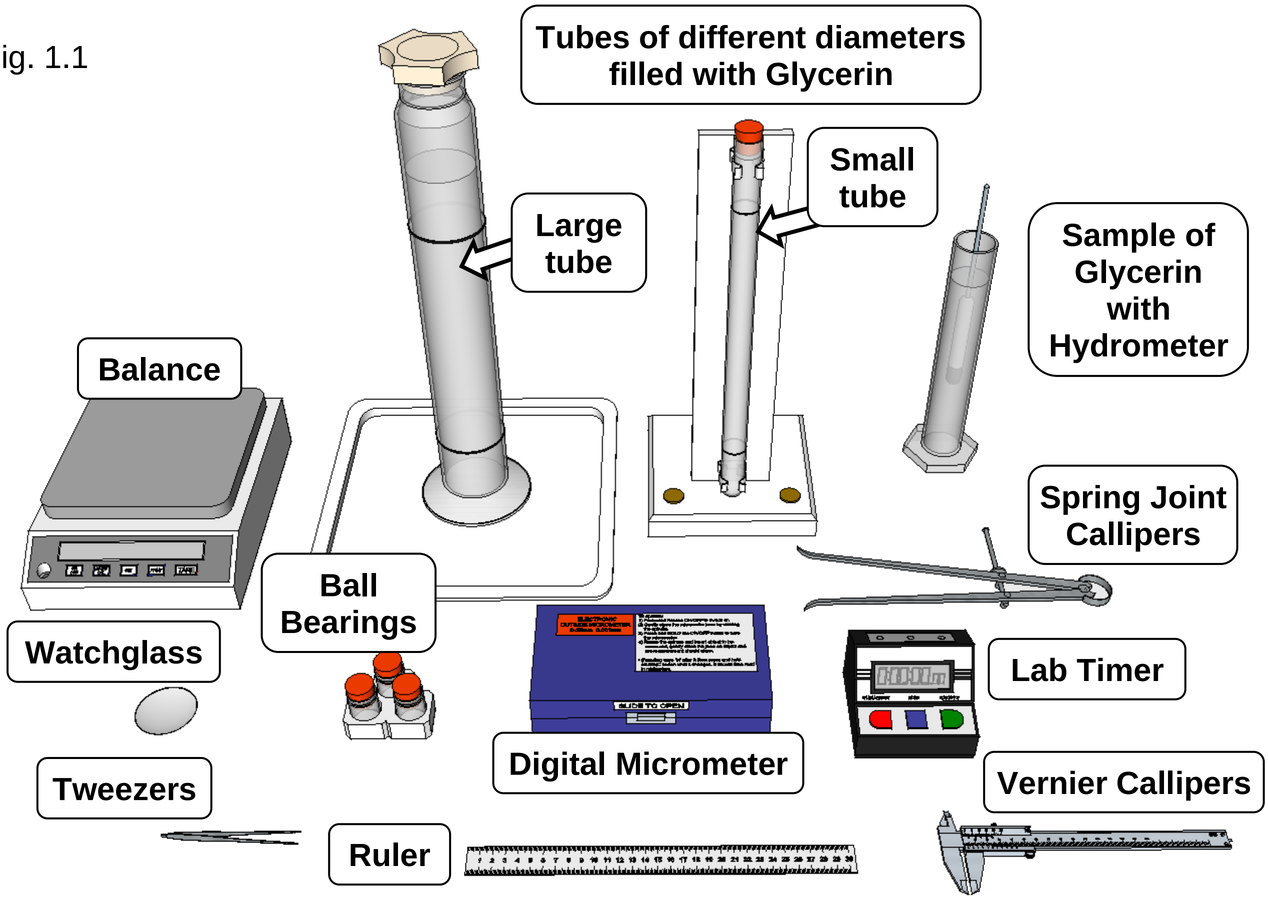
SIGNIFICANT HAZARDS	EXISTING CONTROL MEASURES	SEVERITY (1 = minor, 2 = serious, 3 = major)	LIKELIHOOD (1 = minor, 2 = serious, 3 = major)	RISK RATING
Glycerin (also known as Glycol or Glycerine)	Do not ingest the Glycerin If you get Glycerin on your hands, please wash them before eating or drinking. If any Glycerin drips on the floor please tell the Demonstrator or Technician as this could cause a slip hazard.	1	1	1
Ball Bearings	If you drop small ball bearings on the floor, please tell the Demonstrator or Technician as these could cause a slip hazard.	1	1	1

PEOPLE AT RISK	ADVERSE EFFECTS	ACTIONS TO BE TAKEN & TIMESCALES	REFERENCES
All students, demonstrators and staff members	Ingestion of Glycerin Slip Hazard	Wash hands if you come into contact with Glycerin. Be aware of slip hazards.	Refer COSHH assessments. Refer to Safety Data Sheet

	Name	Signature	Date
ASSESSED BY:	Angela Beddows (Technician)	Angela Beddows	27/07/2024
GROUP HEAD:	Dr Peter Hine (Laboratory Convener)	P. J. Hine	27/07/2024
SAFETY SUPERVISOR:	Stuart Weston (Department Safety Officer)	S Weston	27/07/2024

Experimental Apparatus

Fig. 1.1



Two different sized **tubes** filled with Glycerin are used in conjunction with 3 different sizes of **Ball Bearings** (stored in pots) for the main experiment. For the Large Tube, the diameter is measured using a pair of **Spring Joint Callipers** in conjunction with the **Digital Vernier Callipers**. For the Small Tube, the diameter of the tube is measured using a pair of Digital Vernier Callipers only**.** Once the diameters are measured you can calculate the radii of the tubes. Marks on the tubes allow you to measure the free fall length (x) using a **Ruler** and a **Lab Timer** is used to measure the time it takes for a ball bearing to fall between the two line markers. The diameter of the Ball Bearings is measured using a **Digital Micrometer**. **Tweezers** are used to handle the Ball Bearings as they may be too small to handle with fingers. A sample of Glycerin along with a **hydrometer** in is provided for you to measure the density of the Glycerin, σ. A room temperature sensor is also provided (not shown) The density of the steel balls is given by the manufacturer as 7850 kg/m^3. We will use this value for the pilot calculation at the end of the first week, and then measure this directly in week 3.

Introduction and Background Theory

The aim of this experiment is to use Stokes' Law to determine the true viscosity of Glycerin (that is in an infinite medium with no boundary effects) by measuring its viscosity in a range of tubes (radius r) using balls of different radii (a).

By plotting the measured value of viscosity $\eta_{\text{(measured)}}$ versus (a/r), the results can be extrapolated to a/r = 0, for an infinite tube (i.e. no boundary), to obtain a value for the true viscosity $\eta_{\text{(true)}}$.

A sphere of radius a moving with a velocity v in streamline flow through a viscous fluid with viscosity η experiences a drag force F_{drag} given by Stokes' Law:

$$F_{drag} = 6\pi\eta a v \qquad \text{equation (1.1)}$$

If the sphere is falling under gravity, then it will reach terminal (constant) velocity once the forces acting it are balanced. These forces are shown in figure 1.2 below:

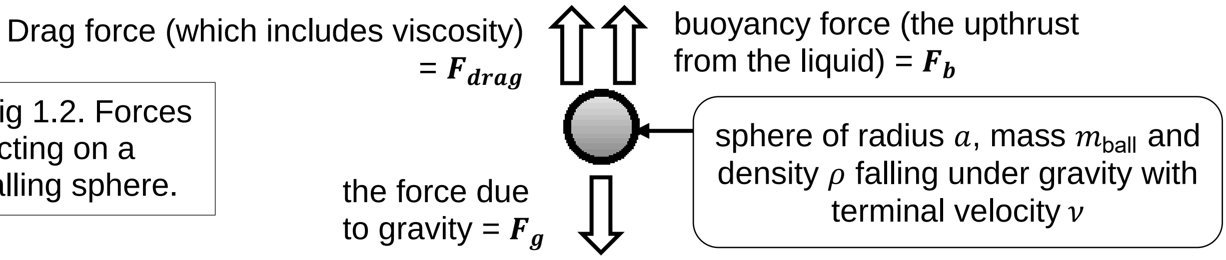


Fig 1.2. Forces acting on a falling sphere.

Where:

$$F_{drag} = 6\pi\eta v a \qquad \text{equation (1.1)}$$

$$F_b = m_{\text{fluid}} g \qquad \text{equation (1.2a)}$$

$$F_g = m_{\text{ball}} g \qquad \text{equation (1.3a)}$$

It is difficult to measure m_{fluid} in equation (1.2a) so we replace it by a volume and a density which are much easier to measure. The buoyancy force can then be written as:

$$F_b = \frac{4}{3}\pi a^3 \sigma g \qquad \text{equation (1.2b)}$$

Where a is the radius of the sphere, σ is the density of the fluid and g is the acceleration due to gravity. Similarly, equation (1.3a) can be written using the density of the sphere, ρ, as:

$$F_g = \frac{4}{3}\pi a^3 \rho g \qquad \text{equation (1.3b)}$$

When moving with terminal velocity v the forces acting on the sphere are balanced so:

$$F_g = F_{drag} + F_b \qquad \text{equation (1.4)}$$

Substituting in for each term gives: $\frac{4}{3}\pi a^3 \rho g = 6\pi\eta a v + \frac{4}{3}\pi a^3 \sigma g$

which yields: $\frac{4}{3}\pi a^3 (\rho - \sigma) g = 6\pi\eta a v$

rearranging for viscosity η yields: $\eta = \frac{2}{9}\frac{a^2(\rho - \sigma)g}{v}$ equation (1.5)

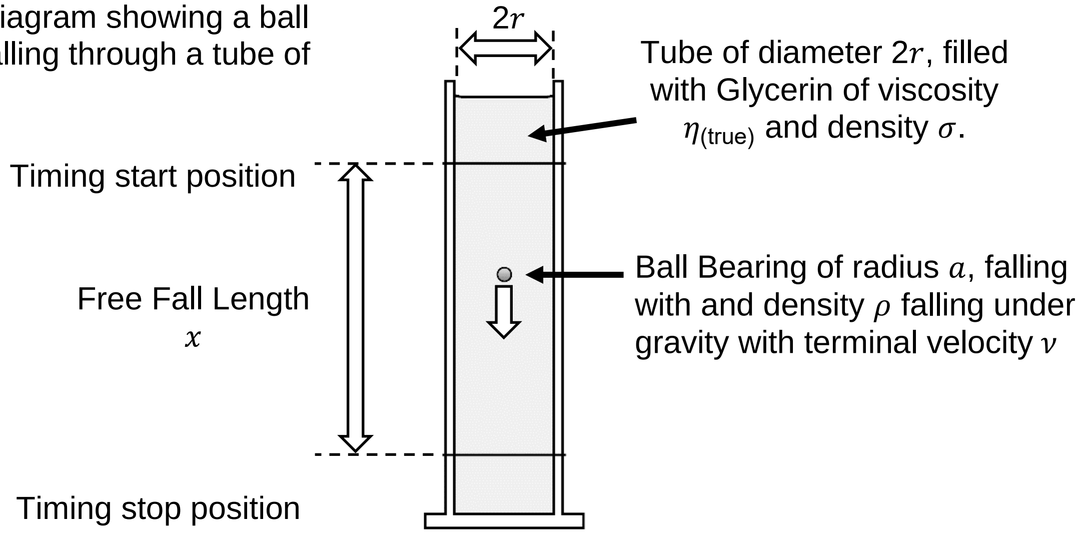
This relationship will be true in an infinite fluid, where the average velocity v in equation (1.6) comes from measuring the time, t, to free fall through a drop length x.

$$v = \frac{x}{t} \qquad \text{equation (1.6)}$$

We can use equation (1.5) to measure the viscosity of a fluid, or alternatively, if we know the viscosity of the fluid, we can determine the radius of the sphere. (This technique was used by Robert Millikan to determine the charge of the electron, as you will discover in rota experiment 3).

In this experiment you will be calculating measured viscosity $\eta_{\text{(measured)}}$ by recording the time taken for a ball bearing to fall through Glycerin as shown in figure 1.3 below:

Fig 1.3. Diagram showing a ball bearing falling through a tube of Glycerin



Here equation (1.5) can be written as: $$\eta_{\text{(measured)}} = \frac{2}{9}\frac{a^2(\rho - \sigma)g}{v} \qquad \text{equation (1.7)}$$

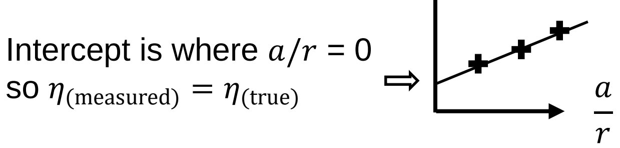
Where: a = the radius of the ball bearing
ρ = the density of the steel ball bearing
σ = the density of the Glycerin
g = the acceleration due to gravity
v = the terminal velocity of the ball bearing determined from the time it taken, t, for the ball to drop through the free fall length, x, using equation (1.6)

As this experiment is carried out in a bounded medium (in a tube), the measured velocity will differ slightly from the expected value due to the additional drag forces at the sides of the tube. Hence the value of viscosity deduced will not be exactly equal to the true value $\eta_{\text{(true)}}$. An expression which attempts to correct for this is as follows:

$$\eta_{\text{(measured)}} = \eta_{\text{(true)}}\left(1 - \frac{ka}{r}\right) \qquad \text{equation (1.8)}$$

Where: $\eta_{\text{(measured)}}$ = the measured value of the viscosity.
$\eta_{\text{(true)}}$ = the true value of the viscosity.
r = the radius of the tube
a = the radius of the ball bearing
k = a constant

Using equation (1.8), if $\eta_{\text{(measured)}}$ is plotted against (a/r), then the intercept on the y axis will be the true viscosity $\eta_{\text{(true)}}$ as a/r = 0 as shown below.



Week 1

Experimental Procedure, Data Recording and calculation of a pilot result.

In the first week of this experiment you will be working in a pair to collect all the necessary data to determine $\eta_{(\mathrm{measured})}$, the measured value of the viscosity of Glycerin.

A key skill to be developed during the 1st year laboratory is how to record accurate experimental details and measurements in your Lab Notebook, as well as describe your data analysis. Before the first session, have a look at the specimen Lab Notebook available on Minerva (there is also a copy posted up in the 1st year laboratory) to see the recommended structure.

The apparatus set up has two different sized Tubes of radii r (one large, one small), and three different Ball sizes of radii a, making a total of six different combinations of a/r.

Task 1: Measurements using the Larger Tube

1.1) Copy Table 1 below into your Lab Notebook. Assess each piece of equipment then add appropriate uncertainties and units to your table.

Table 1	**Large Tube**			**Small Tube**		
Tube diameter, $2r$ (± units)						
Tube radius, r (± units)						
Ball Bearing Size:	**Small**	**Medium**	**Large**	**Small**	**Medium**	**Large**
Ball diameter, $2a$ (± units)						
Ball radius, a (± units)						
Free Fall Length, x (± units)						
Time to fall, t_1 (± units)						
Time to fall, t_2 (± units)						
Time to fall, t_3 (± units)						
Average time to fall, t (units)						
Average Velocity, v (units)						
Uncertainty in the Velocity, Δv (units)						

1.2) Starting with the large tube, carefully take the lid off and use the Spring Joint Callipers, together with the Vernier Callipers, to measure the internal diameter of the tube, as shown in the experiment Video. Record the tube diameter in your table, taking into account the instrument uncertainty to record your values to the correct number of significant figures.

1.3) Use your measurements to calculate the tube radius (r) and the uncertainty in the radius, Δr. Record these values in your table. To calculate the uncertainty in radius, you need to keep the same fractional uncertainty as for the diameter. Therefore, you should divide the uncertainty in the diameter by 2:

$$\frac{\Delta r}{r} = \frac{\Delta D}{D} \qquad \text{equation (1.9)}$$

1.4) Each ball bearing should reach their terminal velocity before passing the top black line drawn on each tube. Therefore, the Free Fall Length is the distance between the two black lines drawn on each tube. Measure the Free Fall Length of the large tube, x, and record this value in your table, using the correct number of significant figures.

1.5) Starting with the smallest ball bearing, use the Digital Micrometer to measure and record its diameter ($2a$) along with its associated uncertainty, as shown in the video. Alternatively, you can use the Digital Vernier Callipers for this measurement. Choose which instrument you think is most accurate. Use your measurements to calculate the radius of the ball (a) and its uncertainty. Record these values in your table.

1.6) Drop the ball bearing into the Glycerin and use the Lab Timer to measure how long it takes to fall between the two black lines.

1.7) Repeat steps 1.4 and 1.5 twice using the **same sized** ball bearing, to give you three measurements of the time (t_1, t_2 and t_3). There will be sufficient ball bearings for you to do the experiment, without needing to fish the ball bearings out of the Glycerin. However if you need more ball bearings, please ask the Lab Staff.

If any measurement looks suspicious, put an asterisk against this measurement and add a comment. Think about what may have caused a problem and how you could prevent this happening again, e.g. did the ball fall close to the side of the tube? You should then repeat the measurement until you have three reliable values.

1.8) Repeat steps 1.3 to 1.5 with the other sizes of ball bearings so you have 3 timings for each size. Calculate average fall time, t, for each size ball bearing.

1.9) Calculate the terminal velocities, v, of each size ball bearing as it moves through the oil in the tube.

You will calculate the uncertainty in the terminal velocity,Δv, next week. However you should consider the possible sources of uncertainty in this measurement and how you might reduce these uncertainties.

Task 2: Measurements using the Smaller Tube

Repeat Task 1 but with the smaller tube.

Task 3: Calculating the Viscosity using a pilot calculation

For this first week we will calculate just **one** value of the viscosity (normally termed a pilot value or calculation). A pilot calculation is excellent practise for any experiment. It allows you to establish if measurements are correct before leaving the laboratory, as the same equipment may not be available if any measurement needs to be repeated.

3.1) Using equation (1.7), also given below, to calculate a single value for $\eta_{\text{(measured)}}$ using the combination of the smallest ball and the largest tube measurements. This will be closest to the true value of the viscosity.

$$\eta_{\text{(measured)}} = \frac{2}{9}\frac{a^2(\rho - \sigma)g}{v}$$

where here:
a = radius of the small ball bearing
ρ = density of the steel ball bearing which is given by the manufacturer as 7850 kg/m^3
σ = density of the Glycerin for the pilot calculation is will take as 1260 kg/m^3. You will measure this more accurately in Week 3.
g = acceleration due to gravity
v = the free fall velocity for the small ball, large tube combination

3.2) Measure and record the room temperature along with its uncertainty using the Digital Thermometer provided. Then look up the appropriate 'true' viscosity from the Table below (or calculate it from the equation given in the reference). If all your measurements and units are correct, and your calculation method is also correct, then you should get a value that is slightly larger than this value due to the boundary effects.

Temperature	Viscosity
^{0}C	Ns/m^2
20.0	1.414
20.5	1.350
21.0	1.290
21.5	1.233
22.0	1.179
22.5	1.127
23.0	1.078
23.5	1.032
24.0	0.988
24.5	0.946
25.0	0.906
25.5	0.868
26.0	0.832
26.5	0.797
27.0	0.764
27.5	0.733
28.0	0.704
28.5	0.675
29.0	0.648
29.5	0.623
30.0	0.598

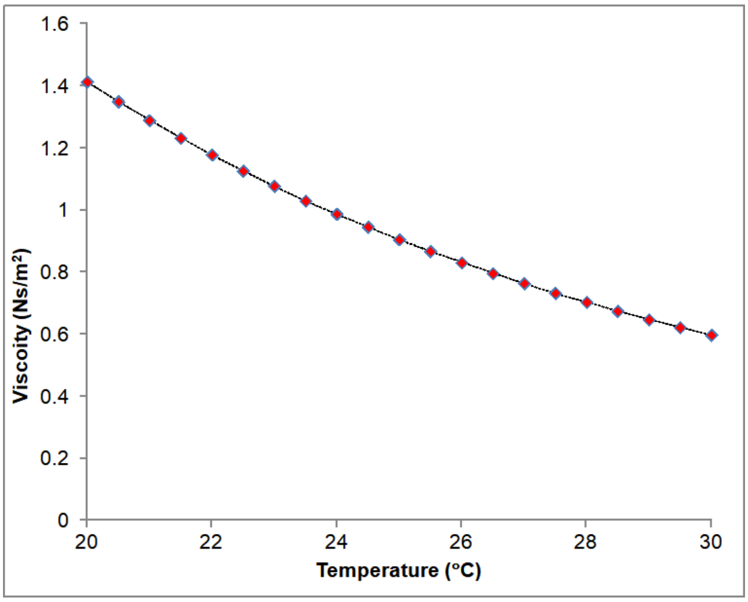


Fig 1.4. Data and graph of viscosity of Glycerin versus temperature (in degrees Centigrade, ℃).

Nian-Sheng Cheng, Formula for the Viscosity of a Glycerol-Water Mixture, Ind. Eng. Chem. Res. 2008, 3285-3288 – page 3287 equation 21.

Week 2

In Week 2 an interactive lecture will take place in your usual lab session. The aim of this lecture is to help you develop the skills needed to analyse your experimental results from Week 1. The first part of the lecture will focus on uncertainty analysis. The second part will look at recording and analysing data using MS Excel. Both of these are important skills which you will use throughout the module.

Task 4: Determining the uncertainty in each measured velocity

In Week 1 you determined the average terminal velocity, v, for each size of ball bearing falling through each tube of Glycerin. The uncertainty in each value, Δv, will come from a combination of the uncertainties in the freefall length Δx (which will be an instrument uncertainty) and the average drop time Δt, which will be a random uncertainty.

The velocity, v of an object moving through a distance x over time t is given by:

$$v = \frac{x}{t} \qquad \text{equation (1.10)}$$

Using the differential method, the fractional uncertainty in the velocity is given by a sum of the fractional uncertainties in t and x, added in quadrature as follows (See pages 27-29)

$$\left(\frac{\Delta v}{v}\right)^2 = \left(\frac{\Delta x}{x}\right)^2 + \left(\frac{\Delta t}{t}\right)^2 \qquad \text{equation (1.11)}$$

Taking square root of both sides and rearranging gives the uncertainty in the terminal velcity:

$$\Delta v = v \times \sqrt{\left(\frac{\Delta x}{x}\right)^2 + \left(\frac{\Delta t}{t}\right)^2} \qquad \text{equation (1.12)}$$

The uncertainty in the Free Fall Length, Δx, comes from the accuracy of the ruler used to measure the distance. Remember that the uncertainty is normally taken as half a division. The uncertainty in the drop time, Δt, comes from the random variations in the three time measurements (which includes human error). This is found by calculating the standard uncertainty, as shown on page 26.

Week 3

In Week 1 a pilot calculation was carried out to determine $\eta_{(\text{measured})}$, the measured value of the viscosity of Glycerin. In the pilot calculation an average value for the density of Glycerin, σ, was used along with a value for the density of steel, ρ, taken from the manufacturer's data sheet. In reality, there are a large number of steel compositions with different densities so it is important to measure the density of the ball bearings directly to get the most accurate result for the true viscosity of Glycerin.

During Week 3 you will:

- Measure the density of the steel balls (and associated uncertainties).
- Measure the density of Glycerin and its associated uncertainty using a hydrometer.
- Use your measured value for the density of steel in equation (1.7), together with the measurements from Week 1, to calculate the measured viscosity of Glycerin, $\eta_{(\text{measured})}$, for the six the different ball/tube combinations.
- Plot a graph of viscosity $\eta_{(\text{measured})}$ versus (a/r) to determine the true viscosity of Glycerin, $\eta_{(\text{true})}$, and the uncertainty in this value.

Task 5: Determination of the Density of Steel

In this task you will determine the mass and volume of a ball bearing, along with the uncertainty in each value. You will then combine these values to determine the density of the steel ball bearing, ρ, and use the differential method to calculate the uncertainty in this value.

The density, ρ, of an object is given by

$$\rho = \frac{m}{V} \qquad \text{equation (1.13)}$$

where m is the mass of the object and V is it's volume.

The volume, V, of a sphere of radius a is given by:

$$V = \frac{4}{3}\pi a^3 \qquad \text{equation (1.14)}$$

Substituting equation (1.13) into equation (1.12) gives:

$$\rho = \frac{m}{\left(\frac{4}{3}\pi a^3\right)} \qquad \text{equation (1.15)}$$

This shows that the density, hence uncertainty is dependent on the mass and radius of the object.

The uncertainty in the density can be to be determined by comparing equation (1.15) with the general uncertainty equations given in the table on page 29. This leads to:

$$\frac{\Delta\rho}{\rho} = \sqrt{\left(\frac{3\Delta a}{a}\right)^2 + \left(\frac{\Delta m}{m}\right)^2} \qquad \text{equation (1.16)}$$

Equation (1.15) can be proved using the differential method described on page 27 where:

$$(\Delta\rho)^2 = \left[\left(\frac{\partial\rho}{\partial a}\right)_m \ \Delta a\right]^2 + \left[\left(\frac{\partial\rho}{\partial m}\right)_a \ \Delta m\right]^2$$

Partially differentiate equation (1.14) with respect to a and m and then use the examples shown on page 28 to prove that equation (1.15) is correct.

Minimising uncertainties

Equation (1.15) shows that in order to reduce the uncertainty in the density, the uncertainty in the mass and radius should both be minimised.

- To improve the accuracy of the measured mass, the **total mass** of at least 6 ball bearings should be measured.

When the total mass of n ball bearings is measured, the uncertainty in the mass of a single ball bearing, Δm, is given by:

$$\Delta m = \frac{\Delta m_n}{n} \qquad \text{equation (1.17)}$$

where Δm_n is the uncertainty in the total mass of the balls bearings, which is **equal to the instrument uncertainty**. Therefore the instrument uncertainty is effectively reduced by measuring the total mass of several ball bearings.

- To improve the accuracy of the measured diameter **think about which size ball bearing will give the lowest percentage uncertainty when measured with the same device** (assume all ball bearings are made of the same material).

5.1) Copy the table below into your Lab Notebook. Measure the **total mass** of at least 6 steel ball bearings, then calculate the mass of a single ball bearing and the uncertainty in this value:

	Mass in (g)
Number of ball bearings, n,	
Mass of n ball bearings	
Instrument uncertainty	
Mass of a single ball bearing, m	
Uncertainty in the mass of a single ball bearing, Δm	

5.2) Record the **mass of one ball bearing** and the uncertainty in this value: $\boldsymbol{m} \pm \Delta \boldsymbol{m}$

5.3) Copy the table below into your Lab Notebook. Measure the diameters of the 'n' ball bearings you used for the mass measurements.

		Diameter in (mm)
Diameters of n Ball Bearings:	n_1	
	n_2	
	n_3	
	n_4	
	n_5	
	n_6	
Instrument uncertainty		
Average diameter of n steel Ball Bearings		
Standard uncertainty		

5.4) Calculate the average (mean) of the diameter and standard uncertainty in this value.

- **Is the standard uncertainty smaller or larger than the instrument uncertainty?**

Record the **average diameter** of the ball bearing along with the appropriate uncertainty in this value: $\boldsymbol{D} \pm \Delta \boldsymbol{D}$

5.5) Calculate the mean **mean radius** and the uncertainty in the radius, Δa, using equation (1.9). Record these values in your notebook**:** $\boldsymbol{a} \pm \Delta \boldsymbol{a}$

5.6) Calculate the density of the steel along with its with uncertainty using equations (1.15) and (1.16) .Record these values in your Lab Notebook, $\boldsymbol{\rho} \pm \Delta\boldsymbol{\rho}$

Task 6: Determining the density of the Glycerin using a hydrometer

Use the hydrometer to measure the density of the Glycerin sample available in the laboratory. A guide to reading the hydrometer is given in Appendix 1.1 on page 54. Please ask your demonstrator If you need any additional help. The uncertainty in the density of the Glycerin, $\Delta\sigma$, will be the instrument uncertainty (usually half a division).

Record the **Density of the Glycerin** and its uncertainty, $\boldsymbol{\sigma} \pm \Delta\boldsymbol{\sigma}$ in your Lab Notebook**.**

Task 6: Determining the true viscosity of Glycerin.

7.1 Copy the table below into your Lab Notebook, adding the tube and ball bearing radii with appropriate units.

Tube radii ▶ / **Ball radii** ▼	**Large Tube** (r = "**??**")	**Small Tube** (r = "**??**")
Small (a = "**??**")	$\eta_{\text{(measured)}}$ (a/r) value	$\eta_{\text{(measured)}}$ (a/r) value
Medium (a = "**??**")	$\eta_{\text{(measured)}}$ (a/r) value	$\eta_{\text{(measured)}}$ (a/r) value
Large (a = "**??**")	$\eta_{\text{(measured)}}$ (a/r) value	$\eta_{\text{(measured)}}$ (a/r) value

7.2 Use equation (1.7), also given below, to calculate six values of $\eta_{\text{(measured)}}$, one for each combination of ball bearing and tube. Record these values in your table.

$$\eta_{\text{(measured)}} = \frac{2}{9}\frac{a^2(\rho - \sigma)g}{v}$$

Where:
a = radius of the ball bearing
ρ = density of the steel ball bearing as determined from Task 5
σ = density of the Glycerin as determined from Task 6
g = acceleration due to gravity
v = the free fall velocity you calculated in Task 1 and its uncertainty from Task 4.

7.3 The uncertainty in each value of $\eta_{\text{(measured)}}$ can be found by comparing equation (1.7) with the general uncertainty equations given in the table on page 29. This leads to:

$$\left(\frac{\Delta\eta}{\eta}\right)^2 = \left(\frac{\Delta v}{v}\right)^2 + \left(2\frac{\Delta a}{a}\right)^2 + \left(\frac{\Delta(\rho - \sigma)}{\rho - \sigma}\right)^2 \qquad \text{equation (1.18)}$$

Here the uncertainty in the difference between the density of the ball bearing and the density of Glycerin can also be determined using the general uncertainty equations:

$$\Delta(\rho - \sigma) = \sqrt{(\Delta\rho)^2 + (\Delta\sigma)^2}$$

which leads to:

$$\left(\frac{\Delta\eta}{\eta}\right)^2 = \left(\frac{\Delta v}{v}\right)^2 + \left(2\frac{\Delta a}{a}\right)^2 + \left(\frac{(\Delta\rho)^2 + (\Delta\sigma)^2}{(\rho - \sigma)^2}\right) \qquad \text{equation (1.19)}$$

Calculate the uncertainty in each value of $\boldsymbol{\eta}_{\textbf{(measured)}}$

7.4 Create a graph of your $\eta_{(\text{measured})}$ against a/r using either MS Excel or Origin Pro. Note that each value of a/r will be unitless.

7.5 Use the intercept on the y axis, where (a/r) = 0, to determine a value of $\eta_{(\text{true})}$ along with its uncertainty, as described on page 45. It is recommended that you use either the LINEST function in MS Excel or Origin Pro to find the intercept and the uncertainty in the intercept. See page 39 for instructions on how to use the LINEST function in MS Excel.

7.6 Use the table on page 48 to find the expected true viscosity of Glycerin at the laboratory temperature measured in Week 1. Compare this true viscosity with the value determined from the intercept of your graph, within uncertainties.

Hints and Tips for your Lab Notebook write up: You should include:

1) **Experimental Notes**: A short introduction describing the Experimental Aims including the Target value(s) and references. Brief description of the experimental method with any necessary schematic diagrams and key equations. Notes recording problems encountered during the experiment or techniques used to improve the data.

2) **Data**: All data recorded (in tables where appropriate). Filenames clearly recorded for any data taken or stored electronically. Measurement uncertainties recorded for all data. Record all your data in your Lab Notebook using the Tables suggested above. Add any relevant comments as a reminder when you come back to your Lab Notebook in the future.

3) **Graphs**:
- Graphs to be plotted using either MS Excel or Origin
- Must have with clear titles and axis labels
- Uncertainty bars and lines/curves of best fit added to graph where appropriate.
- The LINEST function in MS Excel is a good way to determine the intercept and its uncertainty ($\eta_{(\text{true})}$+ $\Delta\eta_{(\text{true})}$) for straight line graphs. If you think the data is non-linear then the ORIGIN programme is a good option (and good thing to learn) for finding the intercept and its uncertainty on graphs.
- Graphs must be printed out and stuck in your Lab Notebook and added to the electronic version of your Lab Notebook before you upload your work.

4) **Analysis**: Calculations performed using appropriate equations to determine the final values and the uncertainty in these values. Final values and their uncertainties given to the correct number of sig figs and with appropriate units.

5) **Conclusions**: A summary of the final results with a comparison to any expected values. A discussion on the quality of the data obtained and possible sources of uncertainties. Suggestions for improving the experimental method or apparatus.
To help write your conclusion for every experiment, consider the following questions:
a) How did your value compare with the expected/reference value?
b) Was the expected value within your calculated uncertainty or not?
c) Were there any random uncertainties to be considered?
d) Was your value precise and accurate?
e) What were possible sources of a systematic error?
f) Can you think of ways in which the apparatus or experimental method can be improved?

Appendix 1.1: How to read a Hydrometer

A hydrometer is an instrument used to measure the **specific gravity** (or relative density) of liquids; that is, the ratio of the density of the liquid to the density of water.

The diagram on the right depicts the most commonly found hydrometer in the First Year Lab. The scales on hydrometers usually cover 0.1 and read **downwards**. Each individual marking is equivalent to 1/10th of 0.02 so is equivalent to 0.002.

In the example shown in figure 1.5, the whole scale is between 1.2 and 1.3. There are further markings at 20, 40, 60 and 80. These are equivalent to 1.220, 1.240, 1.260 and 1.280 respectively.

Therefore, the reading illustrated on the hydrometer is 1.275. As the density of water is equal to 1g/ml (1000 kg/m^3) this gives the density of the liquid as:

1.275 g/ml (1275 kg/m^3)

Please ask a Demonstrator if you have any problems reading the hydrometer.

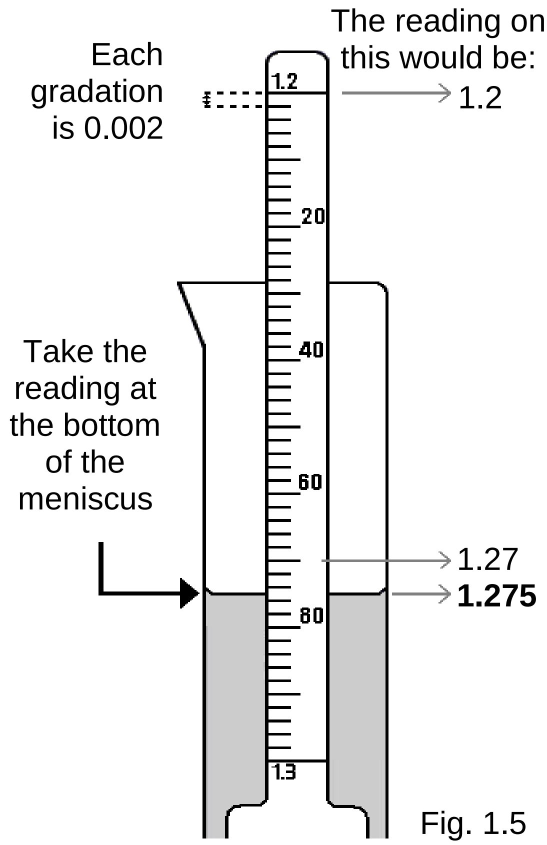


Fig. 1.5

Experiment 2: Introduction to Laboratory Skills 2

Electrical Circuits

This Experiment is in 2 Parts done over two weeks.

Parts 1 will take you two hours and you will either be assigned a session from 9am until 11am or 11am until 1pm.

Part 2 is undertaken in the same allocated time slot but in the following week.

Learning Objectives

Part 1:
- To learn how to use Locktronics components to build different electrical circuits.
- To learn how to use a Digital Multimeters to measure the current, potential difference and resistance at different points in an electric circuit.
- To validate Kirchhoff's Laws and the equations for the total resistance of resistors connected in series and parallel.
- To learn how to use the differentiation and substitution methods to evaluate the overall uncertainties in experimental measurements.

Part 2:
To learn how to use a Digital Oscilloscope to
- investigate time dependent voltage signals.
- display and analyse the phase between two input signals.
- to measure the potential difference across a capacitor and determine the time constant of an RC circuit.

VITALs

E1 a: Safely measure and record experimental data
E1 e: Determine the overall uncertainty in a final value

Preparation:
You are expected to have done these things before you turn up to the lab session:
- **Watch the 3 Online Supporting Videos** (links are on Minerva) and become familiar with the experimental method and data analysis.
- Read this manuscript to become familiar with the physics behind these tasks:
  Part 1: DC circuits. Page 57
  Part 2: RC circuits and Phase differences. Page 63.
- Read the "How to Use Digital Multimeters" document on Minerva
- Fill in the online Health & Safety form as described below.

Risk Assessment and Safety:
Read the Health and Safety information on the next page and fill in the online H&S form. The technician will check online that you have filled this in before you start. It can be reached either via this QR code, via the link on MINERVA or this weblink here: https://forms.office.com/e/G7pkq2Pent

Appendices at the end of this script:
Appendix 2.1: Derivations for an RC circuit (page 68)

School of Physics & Astronomy	**RISK ASSESSMENT RECORD**
LOCATION:	Bragg Building, Room 4.08, 1st Year Physics Undergraduate Laboratory
DESCRIPTION OF ACTIVITY:	**Experiment 2: Electrical Circuits**

SIGNIFICANT HAZARDS	**EXISTING CONTROL MEASURES**	**SEVERITY**	**LIKELIHOOD**	**RISK RATING**
		1 = minor, 2 = serious, 3 = major		
Electrical equipment	All equipment to have an up-to-date PAT test sticker. No such instrument should have its fuse or plug tampered with. If an item appears to be faulty, consult the Laboratory Technician.	2	1	2

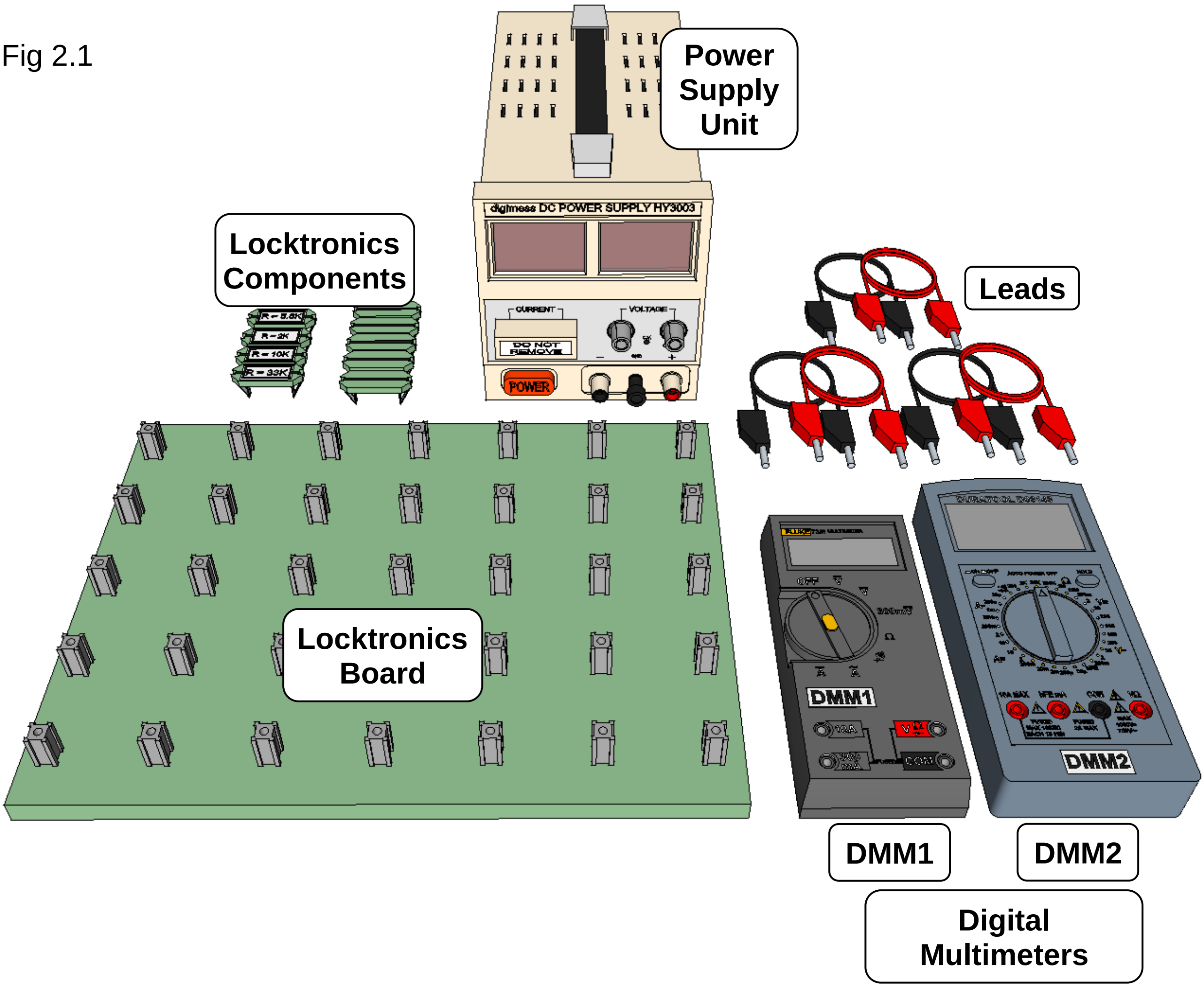
PEOPLE AT RISK	**ADVERSE EFFECTS**	**ACTIONS TO BE TAKEN & TIMESCALES**
All students, demonstrators and staff members	Electrical shock	If an electrical item appears to be faulty, consult the laboratory technician.

	Name	**Signature**	**Date**
ASSESSED BY:	Angela Beddows (Technician)	Angela Beddows	27/07/2022
GROUP HEAD:	Dr Peter Hine (Laboratory Convener)	P.J. Hine	27/07/2022
SAFETY SUPERVISOR:	Stuart Weston (Department Safety Officer)	S Weston	27/07/2022

Parts 1: DC Circuits

Experimental Apparatus

Fig 2.1



A **30V Power Supply Unit** (hereafter referred to as a “PSU”) is used in conjunction with **Locktronics components** to make circuits on a **Locktronics Board**. The **Locktronics components** consist of 4 Resistors (of known resistance) and 6 connecting links. There are two **Digital Multimeters** (hereafter referred to as a “DMM”). **DMM1** will be used to measure voltage and resistance. **DMM2** will be used to measure current. **Leads** are used to attach the equipment to the circuit under investigation.

If you are unsure how to use Multimeters, Power Supplies, and Locktronics then please see the companion document **“How to Use Electrical Circuits Apparatus”** that goes along with this script. This is available on Minerva and will form part of the instruction booklet.

Introduction and Background Theory

The aim of these experiment tasks is to investigate the properties of DC circuits and to verify Kirchhoff's Laws as well as the equations defining the equivalent resistance of combinations or resistors.

Kirchhoff's 1st Law – the Junction Rule

Kirchhoff's 1st Law states that:

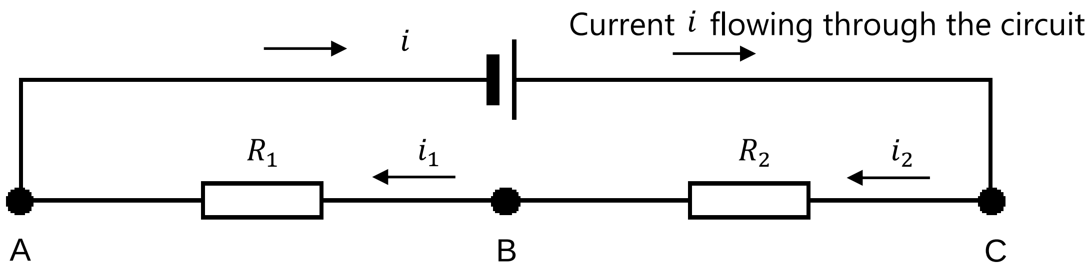
> 'The sum of all currents entering a junction must equal the sum of all currents leaving the junction.'

Kirchhoff's first law results from the conservation of charge, which means that current cannot disappear around the circuit.

Kirchhoff's 1st Law means that:

- In a **series circuit** the current must be the same at all points in the circuit:

Fig 2.2

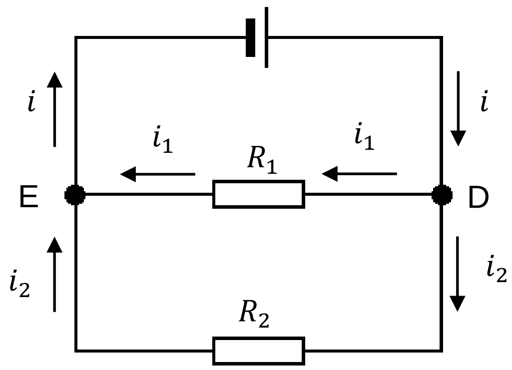


The current is the same everywhere in the circuit so that:

$$i = i_1 = i_2 \qquad \text{equation (2.1)}$$

- In a **parallel circuit** the current splits/joins at a junction.

Fig 2.3



Here the total current i branches off at junction D and recombines at junction E such that:

$$i = i_1 + i_2 \qquad \text{equation (2.2)}$$

Kirchhoff's 2nd Law

Kirchhoff's 2nd Law states that:

> 'Around any **closed** loop in a circuit the sum of the e.m.f.s is equal to the sum of the potential drops.'

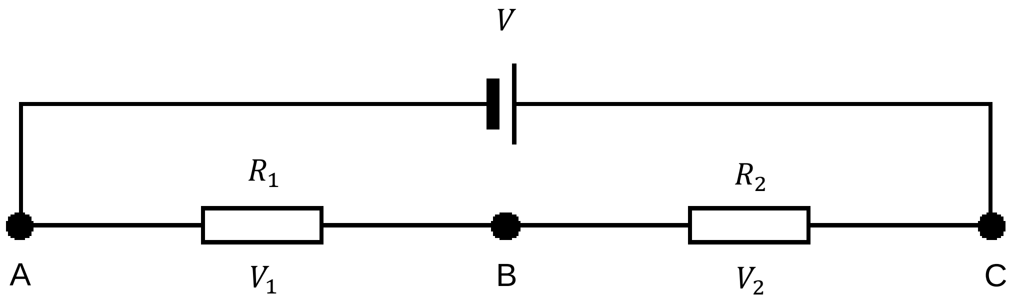
Kirchhoff's second law is a statement of conservation of energy around each loop of a circuit:

Total electrical energy supplied to the charge carriers from the power source(s) in the loop	=	Total electrical energy lost by the charge carriers due to the resistance in the loop

Kirchhoff's 2nd Law means that:

- In a **series** circuit the potential difference across the power supply is shared between the components.

Fig 2.4

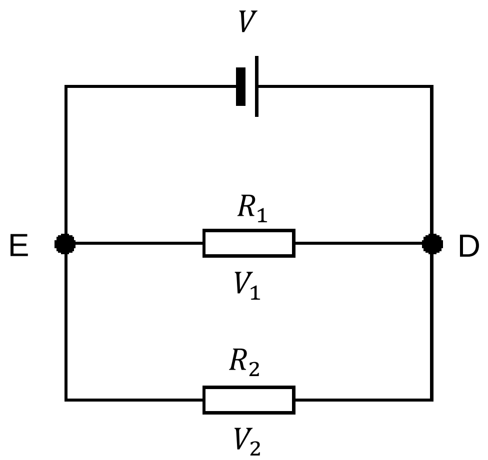


Here the potential difference across the cell, V, is shared between the two resistors:

$$V = V_1 + V_2 \qquad \text{equation (2.3)}$$

- In a **parallel** circuit the potential difference across the power supply is equal to the potential drop across each closed loop.

Fig 2.5



Therefore here:

$$V = V_1 = V_2 \qquad \text{equation (2.4)}$$

Total Resistance in a Circuit

Ohm's law states that the current through a conductor, R, between two points is directly proportional to the voltage, V, (potential difference, p.d.) across the two points.

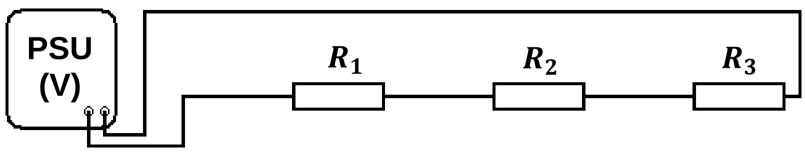
$$V = iR \qquad \text{equation (2.5)}$$

For any circuit, the combination of resistors can be replaced by a single resistor to give an equivalent circuit. Ohm's law can be combined with Kirchhoff's Laws to find the value of the equivalent resistance in any circuit.

Total Resistance in Series

Consider the circuit shown in figure 2.6 below where three resistors are connected in series to a Power Supply Unit (PSU). These three resistors can be replaced by a single equivalent resistor, R_S, which would give the same output.

Fig 2.6



Using Ohm's Law, the potential different across each resistor, R_1, R_2, and R_3 is given by:

$$V_1 = i_1R_1, \quad V_2 = i_2R_2 \quad \text{and} \quad V_3 = i_3R_3$$

According to Kirchhoff's 1st Law, the current is the same everywhere in a series circuit. Therefore:

$$i = i_1 = i_2 = i_3$$

And according to Kirchhoff's 2nd Law, in a series circuit the total p.d. across the power supply, V, is shared between the resistors such that:

$$V = V_1 + V_2 + V_3$$

Therefore:

$$V = i_1R_1 + i_2R_2 + i_3R_3 = i\,(R_1 + R_2 + R_3) \qquad \text{equation (2.6)}$$

Ohm's law is also true for the equivalent circuit such that:

$$V = iR_S \qquad \text{equation (2.7)}$$

where R_S is the equivalent resistance of the series combination.

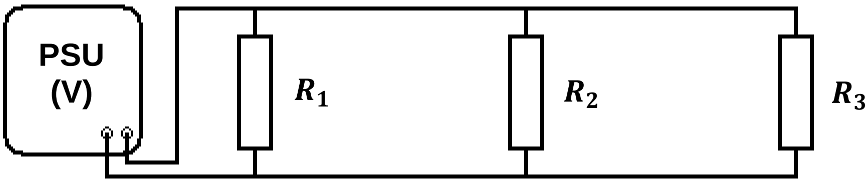
By comparing equations (2.6) and (2.7) it can be shown that the equivalent resistance of resistors connected in series is given by:

$$R_S = R_1 + R_2 + R_3 \qquad \text{equation (2.8)}$$

Total Resistance in Parallel

Consider the circuit shown in figure 2.7 below, where three resistors are connected in parallel to a Power Supply Unit (PSU). These three resistors can be replaced by a single equivalent resistor, R_P, which would give the same output.

Fig 2.7



By considering Ohm's Law, the current through each resistor, R_1, R_2, and R_3 is given by:

$$i_1 = \frac{V_1}{R_1}\ , \quad i_2 = \frac{V_2}{R_2} \quad \text{and} \quad i_3 = \frac{V_3}{R_3}$$

According to Kirchhoff's 1st Law, the current leaving the power supply in a parallel circuit is equal to the sum of the currents through each resistor:

$$i = i_1 + i_2 + i_3$$

Therefore:

$$i = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}$$

According to Kirchhoff's 2nd Law, in a parallel circuit the total p.d. across the power supply, V, is equal to the p.d. across each resistor:

$$V = V_1 = V_2 = V_3$$

Hence:

$$i = V\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right) \qquad \text{equation (2.9)}$$

Using Ohm's law for the equivalent circuit, the total current leaving the power supply is given by:

$$i = \frac{V}{R_P} \qquad \text{equation (2.10)}$$

where R_P is the equivalent resistance of the parallel combination.

By comparing equations (2.9) and (2.10), it can be shown that the equivalent resistance of resistors connected in series is given by:

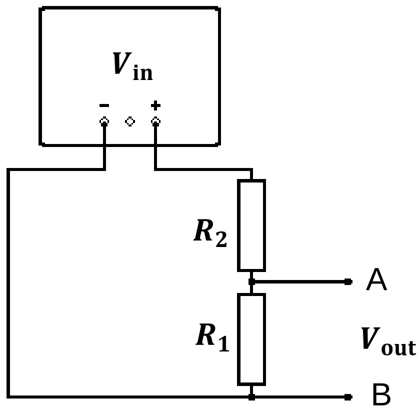
$$\frac{1}{R_P} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \qquad \text{equation (2.11)}$$

The Potential Divider Circuit

Potential divider circuits allow the potential difference from a power source to be split between two or more components, resulting in an output voltage which is smaller than the input voltage. This output voltage can then be used as safe working voltage for an external component. Where variable resistors (rheostats) are used, a variable output voltage can be produced.

An example of a potential divider circuit is shown in figure 2.8 below, where two resistors are connected in series. Here the external component is connected between A and B.

Fig 2.8



According to Kirchhoff's 1st Law, the current through both resistors is the same, i.

Using Ohm's Law for resistor 1:

$$V_{\text{out}} = iR_1 \qquad \text{equation (2.12)}$$

Considering Ohm's law for the equivalent circuit, along with equation 2.6, gives:

$$V_{\text{in}} = iR_S = i(R_1 + R_2) \qquad \text{equation (2.13)}$$

Dividing equation (2.12) by equation (2.13) leads to the potential divider equation:

$$V_{\text{out}} = V_{\text{in}}\left(\frac{R_1}{R_1 + R_2}\right) \qquad \text{equation (2.14)}$$

In potential divider circuits, the resistor with the largest resistance will have the greatest share of the potential difference. This can be proved by considering Ohm's Law.

If the resistance of one of the resistors is increased, it will gain a greater share of the input voltage while the second resistor will get a smaller share.

Note: equation (2.14) is valid for an **unloaded** potential divider circuit. When an external component is connected between A and B, the resistance of this component needs to be taken into account and an equivalent resistance calculated for R_1.

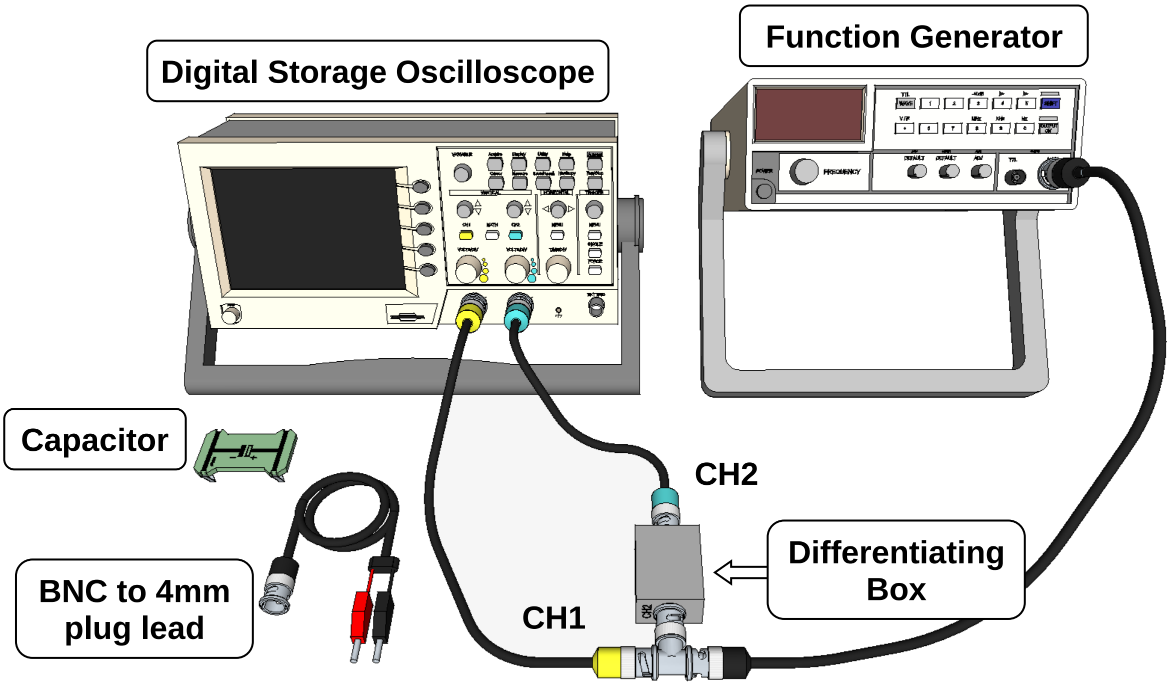
Experimental Procedure:

The equipment shown on page 57 will be used to build and test different electrical circuits. Instructions will be provided during the lab session and results will be recorded in a booklet, which will also be provided.

Part 2: Oscilloscope Skills

Experimental Apparatus:

Fig 2.9



The **Oscilloscope** is supplied with a signal from the **Function Generator**. During the first two tasks, you will learn how to use both pieces of apparatus.

The leads connected to the Oscilloscope have coloured sleeving to assist in identifying Channel 1 (Yellow) and Channel 2 (Blue). These colours correspond to the Channel colours on the LCD display.

The output of the Function Generator is connected to a **Differentiating Box** which allows two signals to be input to the Oscilloscope; one signal bypasses the box and the second passes through it and is delayed, as described on the following page. The delayed signal can then be displayed on Oscilloscope alongside the original signal.

During the last two experimental tasks, the Oscilloscope is used along with the a **Power Supply Unit** (**PSU**) and Locktronics components to study the charging and discharging of a **Capacitor**.

Introduction and Background Theory

The **Digital Storage Oscilloscope** (Oscilloscope) is a versatile scientific instrument used to examine electrical signals. Oscilloscopes allow time dependent potential differences (voltages) to be displayed in real time enabling information such as the frequency and amplitude of a signal to be determined. This cannot be done using a multimeter, making an oscilloscope a more powerful instrument to analyse electrical signals which vary with time.

The signal or 'trace' displayed on oscilloscopes are typically graphs of potential difference (voltage) against time, with **time on the x-axis** and **potential difference on the y-axis**,. The scale (or resolution) of both axes is set automatically by the oscilloscope, but can be changed using the **Vertical Sensitivity** (**VOLTS/DIV** knob) for the vertical axis and the **Time Base** (**TIME/DIV** knob) for the horizontal axis. Changing the resolution allows users to zoom in an out of the signal, increasing the precision of measurements.

Oscilloscopes have a wide range of applications including the ability to:

- Measure the **frequency and amplitude** of a signal. This can be used to record accurate experimental measurements, or 'debug' a circuit by identifying components that have malfunctioned.
- Identify the **noise** is a measured signal or electrical circuit.
- Identify the **shape** of a wave, such as sinusoidal wave, a square or triangular wave, a sawtooth or more complex waves.
- Identify different **components** in a signal, which can be used to identify different sources or change the configuration of the signal.
- Quantify **phase differences** between two different signals.

Oscilloscopes are used extensively during physics and engineering degree courses, as well as in many industrial and commercial settings. Therefore, the use of an oscilloscope is an essential skill to learn and this forms part of the government requirements for all A level Physics courses.

The Two Channel Oscilloscope

Many oscilloscopes also have the ability to display more than one signal, which allows comparisons to be made between sources.

For Task 2b an Oscilloscope will be used to compare two input signals. For this task the two input signals are obtained by using the **Differentiating Box**. The differentiating box is a device which contains an RC circuit where a resistor and a capacitor are connected in series. Here $R = 1 \times 10^4\ \Omega$ and $C = 1 \times 10^{-7}$ F.

As shown in figure 2.9, the signal from the Function Generator is split between one input to the Oscilloscope (CH1) and the differentiating box. The signal from the differentiating box then goes to the second Oscilloscope input (CH2).

- The signal going directly to the Oscilloscope (CH1) has same phase and amplitude, V, as the signal from the function generator.
- The signal from the function generator which goes into the differentiating box results in a potential difference across the resistor component of the RC circuit, V_R. This potential difference is the second Oscilloscope input signal (CH2).

The potential difference across the resistor, V_R, is delayed with respect to the original signal, V. This leads a phase difference between the two Oscilloscope input signal, α, which is given by:

$$\alpha = \tan^{-1}\left(\frac{1}{\omega CR}\right) \qquad \text{equation (2.15)}$$

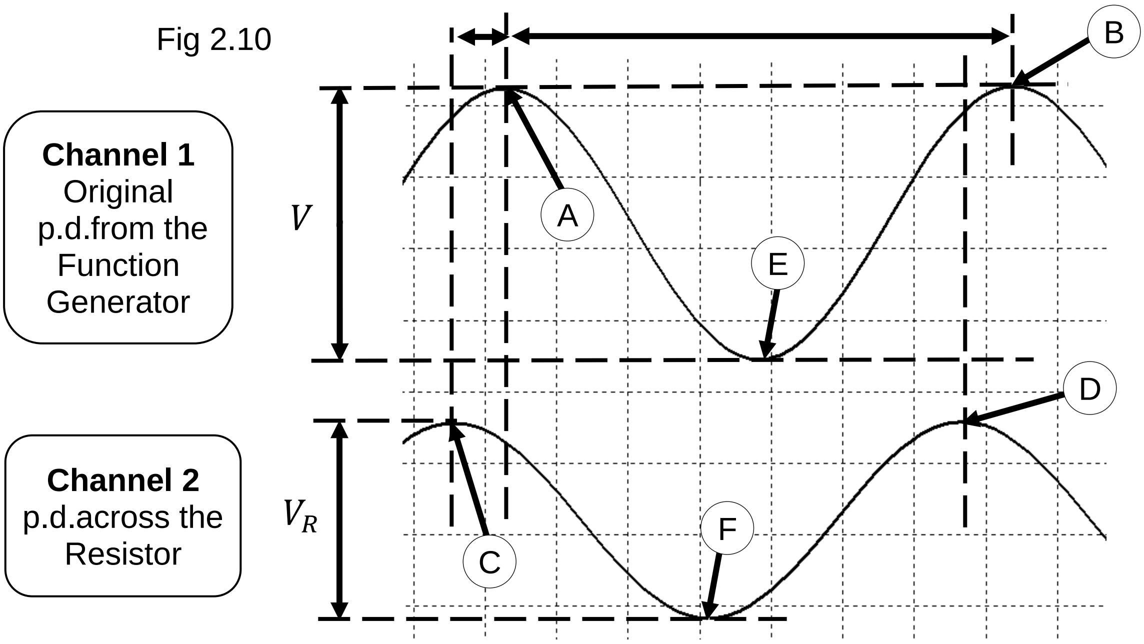
Here C is the capacitance and R is the resistance of the RC circuit respectively, and ω is the angular frequency of the signals given by:

$$\omega = 2\pi \times f \qquad \text{equation (2.16)}$$

In equation (2.16) f is the frequency of the signal from the Function Generator.
The derivation of equation (2.15) can be found in Appendix 2.1 on page: 68

If this original function from the frequency generator is a sine wave, this results in two sine waves which are out of phase, as shown in figure 2.10 below:

Fig 2.10



Considering the traces illustrated above, the period of the waves, T, is shown as:

AB = CD = T

and the time difference, t, between the two signals is shown as:

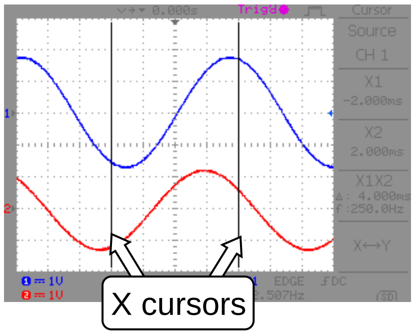
CA = DB = t

The phase difference, α, between the waves is then given by:

$$\alpha = \frac{t}{T} \times 360° \qquad \text{equation (2.17)}$$

The time difference between the two signals can be accurately measured using the **Cursors** on the Oscilloscope. The X cursors are two vertical lines as indicated in figure 2.11.

Fig 2.11



Phase Diagrams

In an RC circuit, the potential differences across the capacitor, V_C, and the resistor, V_R, can be treated as mutually perpendicular vectors, as shown in figure 2.12 below. Here the resultant vector is equal to the potential difference from the function generator, V, and α is the phase difference between the original signal and the potential difference across the resistor:

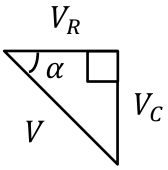


Fig 2.12

By using trigonometric identities and combining with equation (2.15), it can be shown that the ratio of V_R to V is equal to:

$$\frac{V_R}{V} = \left[1 + \left(\frac{1}{\omega^2 C^2 R^2}\right)\right]^{-\frac{1}{2}}$$ equation (2.18)

This equation provides another way of determining the phase. An alternative derivation of this equation 2.18 can be found in Appendix 2.1 on page 68.

Charging a Capacitor

A simple charging circuit for a capacitor is shown in figure 2.13 below:

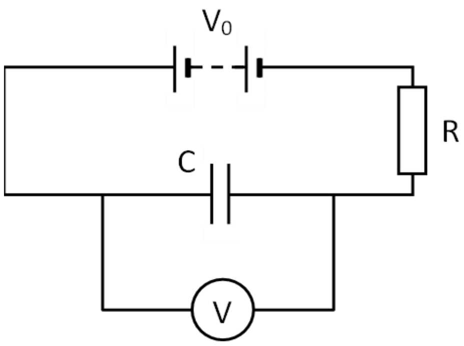


Fig 2.13

The potential difference, V, across the Capacitor of capacitance, C, at a time t after the capacitor starts to charge is given by:

$$V = V_0\left(1 - e^{-\frac{t}{RC}}\right)$$ equation (2.19)

where V_0 is the potential difference across the power supply and R is the resistance of the resistor. The time constant, τ, of the charging circuit is defined as:

$$\tau = RC$$ equation (2.20)

The time constant of the charging circuit is equal to the time taken for the potential difference across the capacitor to rise to 63.2% of the voltage set on the PSU (V_0). This can be proved algebraically by substituting τ into equation (2.19). The time constant is illustrated in figure 2.14 below, which shows the potential difference across a capacitor charging to 10 V.

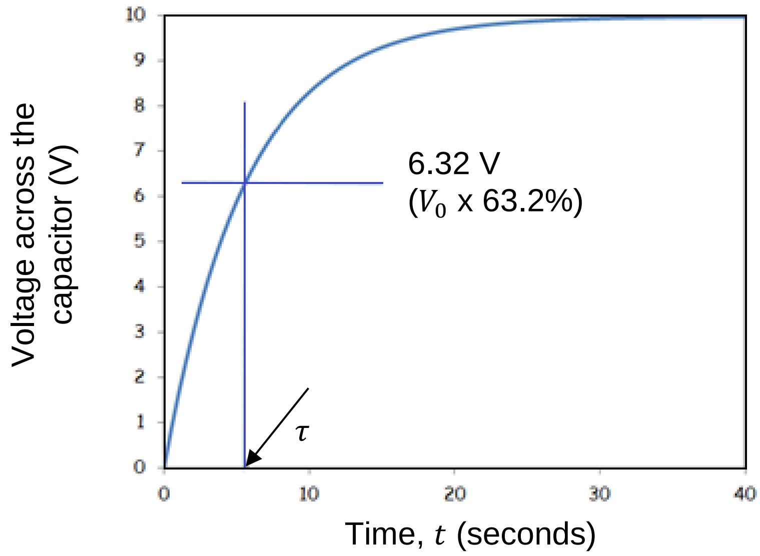


Fig 2.14

Capacitor voltage versus time for a charging capacitor when the PSU is set at 10V.

Discharging a Capacitor

Once a capacitor is charged, it is usually discharged through a resistor as shown in figure 2.15 below. Here the resistor slows the flow of charge from the capacitor.

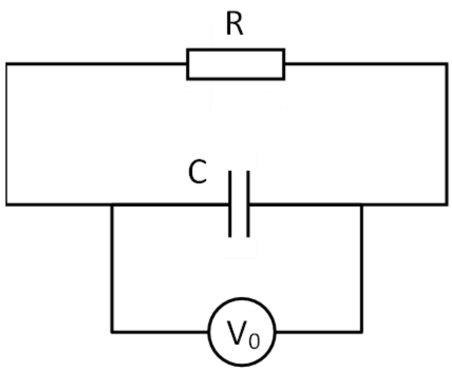


Fig 2.15

The potential , V, across a Capacitor of capacitance, C, at a time t after the capacitor starts to discharge is given by:

$$V = V_0\left(e^{-\frac{t}{RC}}\right) \qquad \text{equation (2.21)}$$

where V_0 is the charging potential difference and R is the resistance of the charging circuit.

Here the time constant, $\tau = RC$, is the time taken for the voltage to fall by 63.2% of the original charging potential, V_0. This is illustrated in figure 2.16 given in the next page.

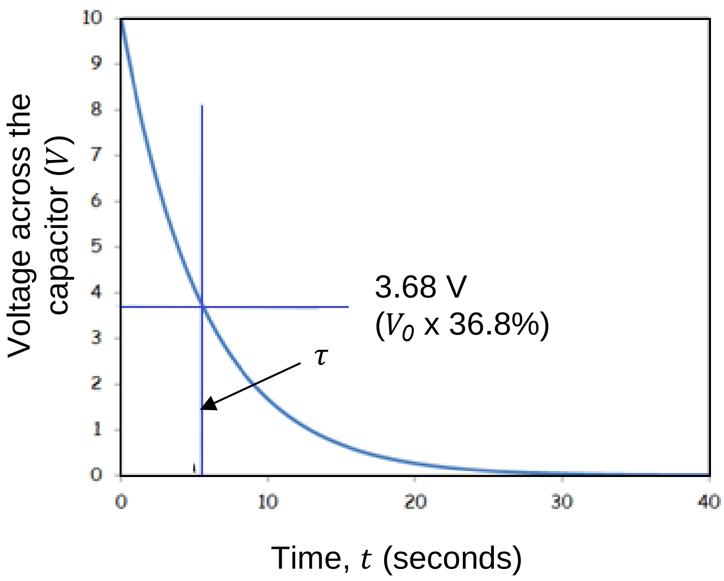


Fig 2.16

Capacitor voltage versus time for discharging capacitor when the PSU is set at 10 V.

Experimental Procedure:

The equipment shown on page 63 will be used to analyse time dependent electrical signals and determine the time constant of an RC circuit. Instructions will be provided during the lab session and results will be recorded in a booklet, which will also be provided.

Appendix 2.1: Derivations for an RC circuit

A sinusoidal potential difference, V, from a function generator will lead to a sinusoidal current given by:

$$i = i_0 \sin \omega\, t$$

If the signal from the function generator is put through an RC circuit, the potential difference across the resistor, V_R, at a time t is given by Ohm's Law such that:

$$V_R = iR = i_0 R \sin \omega t \qquad \text{equation (2.22)}$$

In general the potential difference across a capacitor, V_C, at a time t given by:

$$V_C = \frac{Q_t}{C}$$

where Q_t is the instantaneous charge stored by the capacitor and C is the value of its capacitance. This relationship applies to both static (DC) conditions and to time varying (AC) potentials.

The total charge on the capacitor at time t is the integral i with respect to time:

$$Q_t = \int_0^t i.\,dt$$

Therefore, for a sinusoidal current:

$$Q_t = \int_0^t i_0 \sin \omega\, t.\,dt = \frac{-i_0}{\omega} \cos \omega t$$

By considering the trigonometric relationship:

$$-\cos\theta = \sin\left(\theta - \frac{\pi}{2}\right)$$

the total charge on a capacitor at a time t can be written as:

$$Q_t = \frac{i_0}{\omega}\sin\left(\omega t - \frac{\pi}{2}\right)$$

Hence:

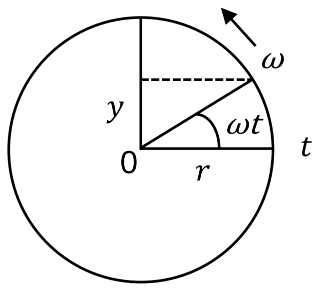
$$V_C = \frac{i_0}{\omega C}\sin\left(\omega t - \frac{\pi}{2}\right) \qquad \text{equation (2.23)}$$

Comparing equations (2.22) and (2.23) shows that the potential difference across the capacitor lags behind the potential difference across the resistor by $\frac{\pi}{2}$.

This can be illustrated by considering the vector representation of a sinusoidal function, which can lead to an expression for the phase angle. Here the function is represented by a vector of amplitude r which rotates with a uniform angular velocity ω, as shown in figure 2.17

$$y = r\sin\omega t$$

Fig 2.17



where $\alpha = \omega t$ is the phase angle.

For an RC circuit, the potential difference across the resistor, V_R, can be represented as a vector of amplitude i_0, which maps into 'y', whereas the potential difference across the capacitor, V_C, has an amplitude $i_0/\omega C$ which, at any instant, is in a direction $\pi/2$ (or 90°) behind V_R. This is illustrated in figure 2.18a

Fig 2.18a

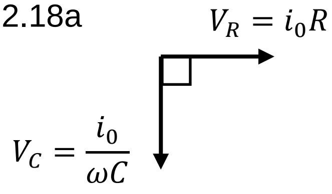
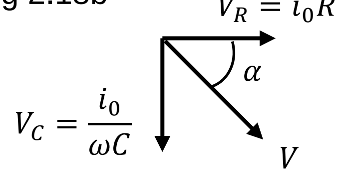


Fig 2.18b



At any instant, the potential difference across both R and C, equal to the potential difference from the function generator, V, must be the vector sum of V_R and V_C, such that:

$$V = V_R + V_C$$

which is illustrated in figure 2.18b. This shows that V_R leads the potential difference from the input signal, V, by the 'phase angle' α where:

$$\tan\alpha = \frac{1}{\omega CR}$$

By considering the definition of the tangent along with Pythagoras' Theorem:

$$V^2 = V_R^2 + V_C^2$$

it can be shown that the ratio of the potential difference across the resistor,V_R, to the potential difference from the function generator, V, is given by:

$$\frac{V_R}{V} = \frac{i_0 R}{\left[i_0^2 R^2 + \frac{i_0^2}{\omega^2 C^2}\right]^{\frac{1}{2}}}$$

This leads to equation (2.18):

$$\frac{V_R}{V} = \left[1 + \frac{1}{\omega^2 C^2 R^2}\right]^{-\frac{1}{2}}$$

The 'phase diagram' shown in figures 2.18a and 2.18b show an instantaneous snapshot of the potential differences. However, as all voltages are rotating with the same angular velocity ω, the components retain the same phase difference at all times.

Experiment 3

Millikan's Oil Drop Experiment

Experimental Aims:

- To measure an accurate value for the charge on an electron, e, using the Millikan oil drop apparatus.
- To demonstrate that the volume of an oil drop can be determined from its terminal velocity.

Learning Objectives:

- To observe and understand the action of electrical and gravitational fields on charged particles and demonstrate the validity of the expressions describing these effects.
- To develop skills in making careful observations and taking accurate measurements.
- To practice complex data analysis skills to determine the final value and the uncertainty in this value.
- To be able to critically evaluate the results of an experiment; to compare measured results with expected values and comment on the agreement within uncertainties.

VITALs

E1 a: Safely measure and record experimental data
E1 b: Keep a detailed laboratory notebook

Preparation:

You are expected to have done these things before you turn up to the lab session:

- **Watch the Online Supporting Video** (link is on Minerva) and become familiar with the experimental method and data analysis.
- Read this manuscript and become familiar with the physics behind this experiment.
- Make a note of the accepted value for, e, along with its reference
- Set up an MS Excel spreadsheet to calculate the oil drop radius, the corrected charge and the charge ratio using equations (3.9), (3.10) and (3.11). A pilot set of measurements are given below so you can check your spreadsheet formulas.
- Fill in the online Health & Safety form as described below.

Risk Assessment and Safety:

Read the Health and Safety information on the next page and fill in the online Health & Safety form. The technician will check online that you have filled this in before you start. It can be reached either via this QR code, via the link on MINERVA or this weblink here: https://forms.office.com/e/86mRAncUTV

School of Physics & Astronomy	**RISK ASSESSMENT RECORD**
BUILDING:	Bragg Building, Room 4.08, 1st Year Physics Undergraduate Laboratory
DESCRIPTION OF ACTIVITY:	**EXPERIMENT 3:** THE MILLIKAN OIL DROP

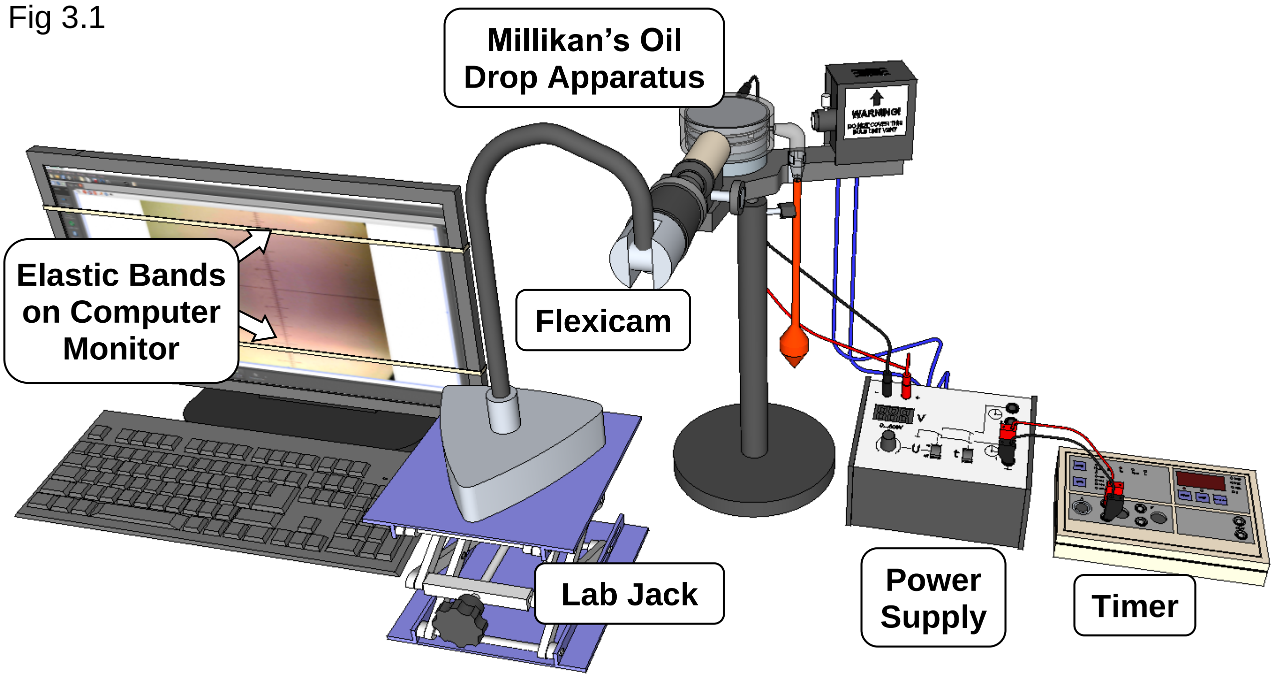
SIGNIFICANT HAZARDS	**EXISTING CONTROL MEASURES**	SEVERITY 1=minor/2=serious/ 3=major	LIKELIHOOD 1=low/2=medium/ 3=high	RISK RATING
High Voltage	The voltages applied to the parallel plate capacitor are large (up to 600V) so do **not** interfere with or disconnect the wiring whilst the power supply is switched on.	2	2	4
Electrical equipment	All equipment to have an up to date PAT test sticker. Some of the instruments used are powered by mains electricity. No such instrument should be tampered with or have its plug or fuse replaced. If an electrical item appears to be faulty, consult the Laboratory Technician.	2	1	2

PEOPLE AT RISK	**ADVERSE EFFECTS**	REFERENCES	ACTIONS TO BE TAKEN & TIMESCALES
All students, demonstrators and staff members	Electrical shock High voltage		If an electrical item appears to be faulty, consult the laboratory technician. Ensure power supply to Capacitor is switched off before removing leads. Spring loaded covers for lead plugs leads to be used as additional safety feature

	Name	**Signature**	**Date**
ASSESSED BY:	Angela Beddows (Technician)	Angela Beddows	27/07/2023
GROUP HEAD:	Dr Peter Hine (Laboratory Convener)	P.J. Hine	27/07/2023
SAFETY SUPERVISOR:	Stuart Weston (Department Safety Officer)	S Weston	27/07/2023

Experimental Apparatus

Fig 3.1



The experimental apparatus consists of **Millikan's Oil Drop Apparatus** connected to its **Power Supply** which supplies both the power to the Lamp and the Capacitor. The **Timer** is also connected to the Power Supply and is used to time the drops as they fall in order for the User to determine their velocity. A **Flexicam** is used along with the **Computer** to display the view through the Microscope so the drops can be seen. Two **Elastic Bands** on the Computer Monitor are used to measure the distance the oil droplet falls.

Further Details of the Apparatus

The **Millikan's Oil Drop Apparatus** consists of two metal plates forming the **Capacitor** with a cover, a viewing **Microscope**, an **illuminating Lamp** and a small reservoir of oil with an **Atomiser** attached.

The Atomiser is used to inject a fine spray of oil droplets into the capacitor, which can be observed through the microscope eyepiece using the Flexicam connected to the PC.

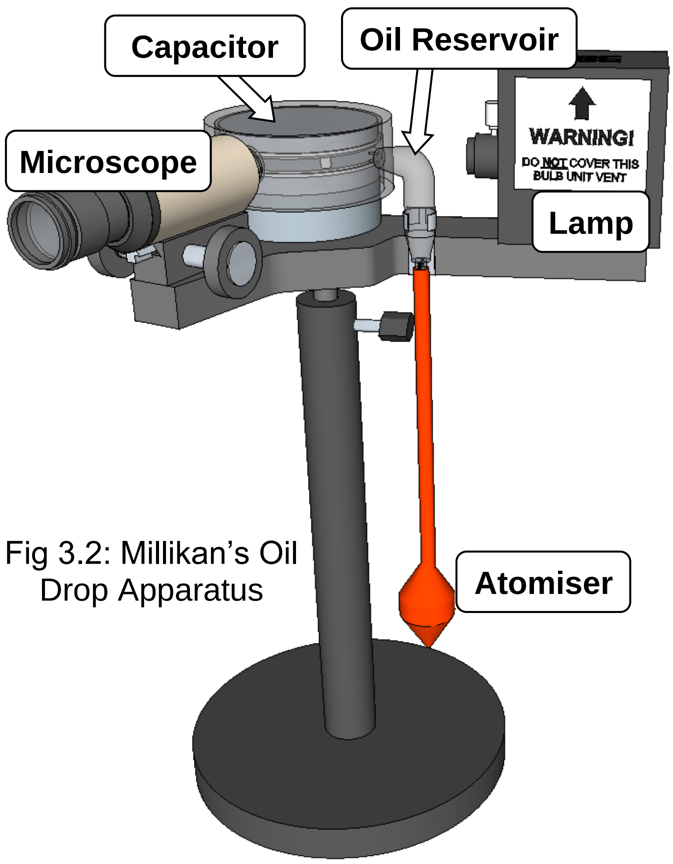
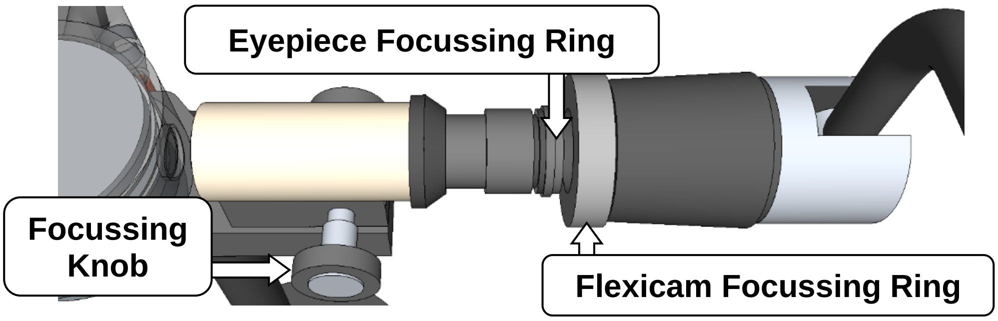
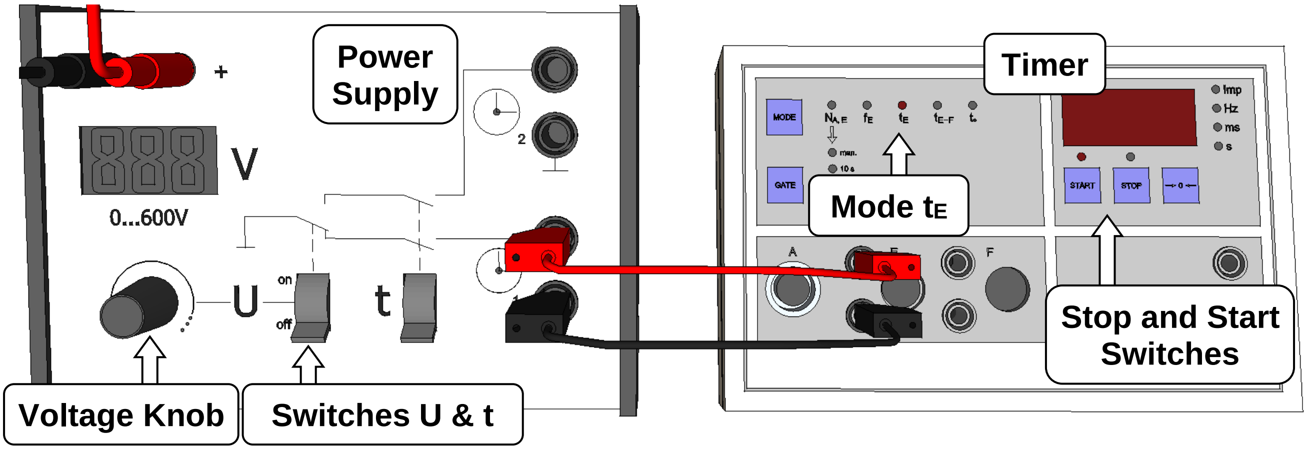


Fig 3.2: Millikan's Oil Drop Apparatus



The whole microscope eyepiece moves back and forth to define the focal plane inside the capacitor using the Focussing Knob, whilst the microscope eyepiece has a rotatable Focussing Ring to allow focussing of the graduated scale. The Flexicam also has its own Focus Ring to sharpen images of the droplets on the PC monitor.



Introduction and Background Theory

The Millikan Oil Drop experiment is of historical importance as it was the first experimental demonstration that showed that electrical charge is quantised, and moreover the size of the charge quantum e was measured for the first time. Quantization is the concept that a physical quantity can have only certain discrete values. In this experiment this applies to the charge on an electron which is a fundamental constant of the universe. Every amount of observable electric charge is always an integer multiple of this basic unit.

The experiment is performed by creating a fine mist of micron scale oil droplets between two metal electrode plates. Each oil drop gains or loses a few electrons during the atomisation process. These droplets will then either rise or fall depending on the balance between the gravitational force F_g and the electric force F_e between the plates. There is an additional small buoyancy force.

The **electric force**, F_e, is given by: $F_e = qE$ equation (3.1)

where E is the uniform electric field between the two metal plates and q is the charge on the oil droplet. By considering the definition of a electric field, this can be written as

$$F_e = q\frac{V}{d} \qquad \text{equation (3.2)}$$

where: V is the applied Voltage in and d is the distance between the electrode capacitor plates.

The **gravitational force**, F_g, is given by

$$F_g = m_{oil}g \qquad \text{equation (3.3)}$$

where m_{oil} is the mass of the oil droplet and g is the acceleration due to gravity.

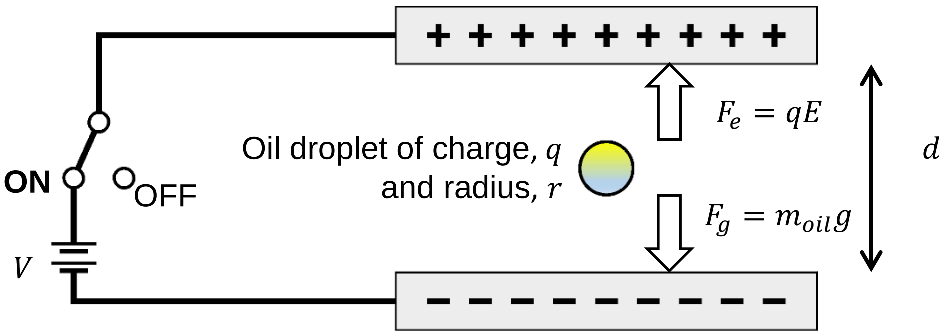
As the mass is too small to be measured we can use the density of the oil droplet instead, which is assumed to be spherical (we used the same strategy for the measurement of viscosity for the experiment you carried out earlier in the module):

$$F_g = \frac{4}{3}\pi r^3 \rho_{oil} g \qquad \text{equation (3.4)}$$

where r is the radius of the oil droplet and $\rho_{oil}$is the density of the oil drop. Here the density of the oil temperature of 22°C.is given by the manufacturer as 873 kgm^{-3}.

If the applied Voltage, V, is varied to keep the oil drop stationary between the metal electrode capacitor plates of separation d then the two forces are balanced as indicated in figure 3.3 below

Fig 3.3



Here

$$F_g = F_e \qquad \text{equation (3.5)}$$

hence

$$\frac{4}{3}\pi r^3 \rho_{oil} g = q\frac{V}{d} \qquad \text{equation (3.6)}$$

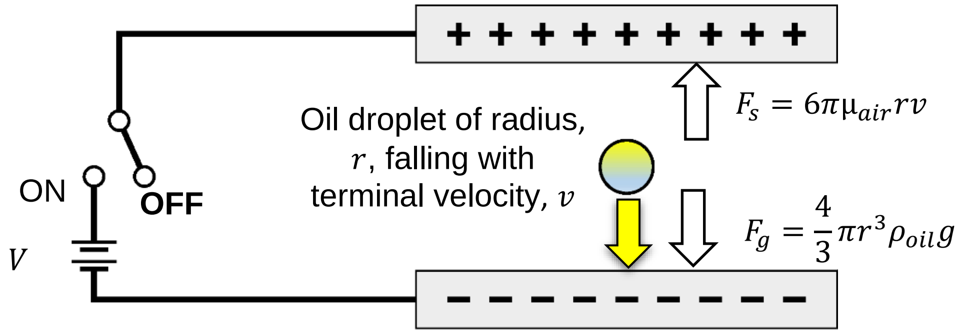
There is also a small upwards buoyancy force, but this is very small due the difference in density between the oil and air, and so is not included in this analysis.

The only unknown in the equation, apart from the required calculation of charge, q, is the oil drop radius r. Nobel Prize winning Physicist Robert Millikan suggested an elegant experiment to measure the oil drop radius. If the Voltage is switched off, the oil drop will then fall due to gravity and at its terminal velocity it is resisted by the drag force F_s as illustrated in figure 3.4 below, where the drag force is given by Stokes Law:

$$F_s = 6\pi\eta_{air} r v \qquad \text{equation (3.7)}$$

where η_{air} is the viscosity of air in pascal seconds, r is the radius of the oil droplet in metres and v is the terminal velocity as it falls through the air in metres per second.

Fig 3.4: Oil drop acting under freefall once the Voltage, V, is switched off.



Equating equations (3.4) and (3.7) leads to

$$\frac{4}{3}\pi r^3\rho_{oil}g = 6\pi\eta_{air}rv \qquad \text{equation (3.8)}$$

which rearranging for r gives:

$$r = \sqrt{\frac{9}{2}\frac{\eta_{air}v}{\rho_{oil}g}} \qquad \text{equation (3.9)}$$

Therefore by measuring the terminal velocity, v, of a freely falling droplet of known density it is possible to determine its radius, r. The uncertainty in r can be found by comparing equation (3.9) with the general uncertainty equation given on page 29, leading to:

$$\frac{\Delta r}{r} = \sqrt{\left(\frac{\frac{1}{2}\Delta\eta_{air}}{\eta_{air}}\right)^2 + \frac{\frac{1}{2}\Delta v}{v}} \qquad \text{where} \qquad \frac{\Delta v}{v} = \sqrt{\left(\frac{\Delta x}{x}\right)^2 + \left(\frac{\Delta t}{t}\right)^2}$$

where x is the distance the droplet falls over time t.

The value of r calculated can then be substituted into equation (3.6) which can be rearranged to make q the subject:

$$q = \frac{4d}{3V}\pi r^3\rho_{oil}g \qquad \text{equation (3.10)}$$

The uncertainty in q can then be found using equation (3.11)

$$\frac{\Delta q}{q} = \sqrt{\left(\frac{\Delta d}{d}\right)^2 + \left(\frac{\Delta v}{v}\right)^2 + \left(\frac{3\Delta r}{r}\right)^2} \qquad \text{equation (3.11)}$$

The experimentally measured variables for each oil drop are the Voltage, V, needed to keep the oil drop stationary under an electric field; and the free fall terminal velocity, v, measured with the field turned off, which allows r to be determined.

For these small oil droplets there is a 'non-slip' **correction** to Stokes law that gives the correct charge value q_c through the Cunningham formula

$$q_c = \frac{q}{\sqrt{\left(1 + \frac{A}{r}\right)^3}} \qquad \text{equation (3.12)}$$

where A = 0.07776 μm at standard pressure at 25 ºC. (It is this correction that means the simple pilot experiment must be done with a large enough droplet).

The uncertainty in q_c can be found by:

$$\frac{\Delta q_c}{q_c} = \sqrt{\left(\frac{\Delta q}{q}\right)^2 + \left(\frac{-\frac{3}{2}\Delta B}{B}\right)^2}$$

$$\boxed{\Delta B = -\frac{\Delta r}{r}}$$

$$\boxed{q_c = q_c\, B^{-\frac{3}{2}}}$$

$$\boxed{B = 1 + \frac{A}{R}}$$

After carrying out the experiments, r can be calculated using equation (3.9).
The charge, q, can then be calculated using equation (3.10) before the corrected charge, q_c, is determined using equation (3.12).

Experimental Procedure

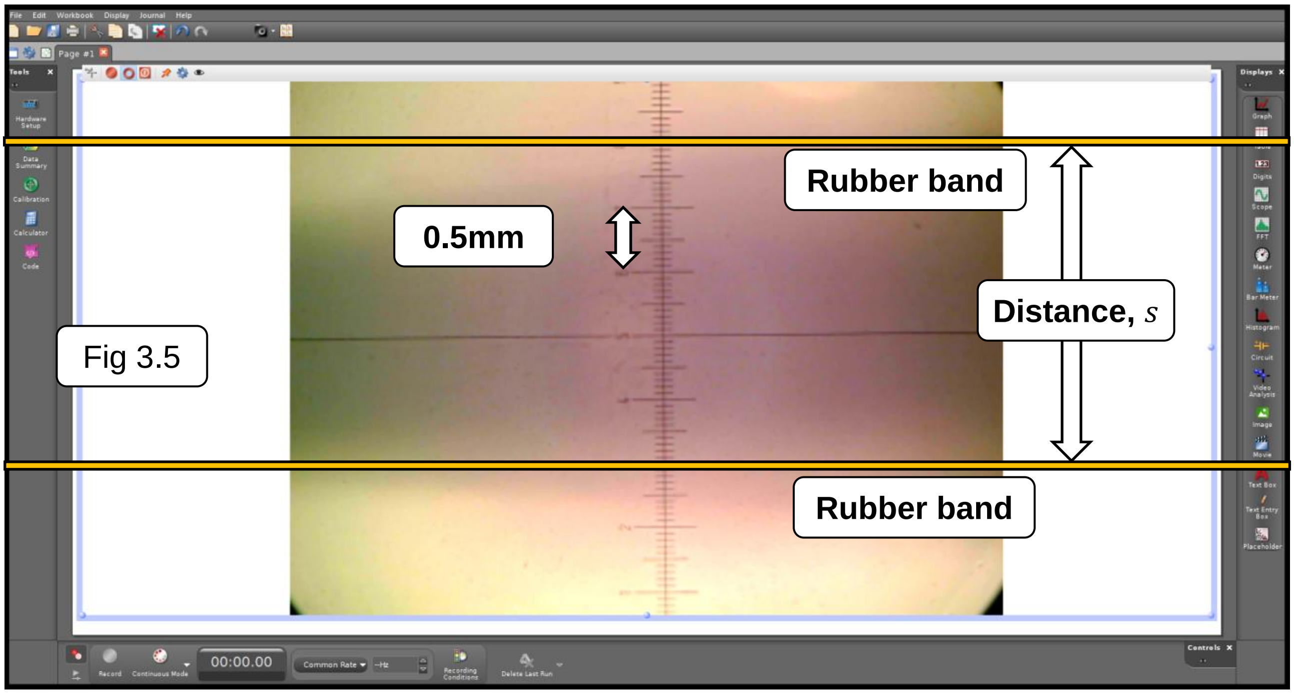
Task 1: Setting up the PC and Software

There are a few quantities that you will need to source for your calculations before you start. Record these in your Lab Notebook and look up the values in the lab as necessary.

Constant	Value	Reference Source
Temperature in Lab		can be found on the digital thermometer near the experiment.
Air Pressure in Lab	1011 mbar (101.4 KPa)	
Plate separation, d	5.80 ± 0.05 mm	
Acceleration due to gravity, g	9.81 m/s^2	
air viscosity, η_{air}		The Lab copy of the Kaye and Laby book for the appropriate room temperature
density of oil, ρ_{oil}	873 kg/m^3	Manufacturer’s data sheet at 22°C
Magnification scale	x2	The magnification scale of the microscope is x 2, so 5mm on the graduated scale in the telescope is equal to 2.5mm actual distance

1.1) Log in to the PC and load the **PASCO Capstone** software. Click on the **Movie** icon on the **Displays** bar on the right and drag it to the centre of the screen. Then click on **Capture Video Only**. It make take a few seconds for the live image to be initially displayed. Once the live image is displayed, maximise the captured image to fill the available screen. Switch on the Millikan Power Supply to turn the bulb which illuminates the area between the capacitor plates (which you see on camera) as well as supply the Voltage V to the plates.

1.2) The Flexicam should be in front of the microscope eyepiece to give a good image, but feel free to adjust it to get the best image of the micrometre scale through the eyepiece. (It will have been set at the roughly the correct height by the Technician so you won’t need to wrestle it into place). Use the Flexicam camera Focus Ring (as shown in figure 3.2 to focus on the scale which can be seen through the Microscope. The scale is shown in figure 3.5. which is a typical video image. Each large division of the scale is equivalent to 0.5mm, so 5 is equivalent to 2.5 actual drop distance.



1.3) Set the rubber bands attached to the PC screen to a separation of either 2.5mm (a distance of 5 larger divisions on the scale) or 2mm (4 divisions on the scale) on the field of view, depending on how even the illumination is. Figure 3.5 shows the bands set at a real distance of 2.5mm. Once set do **not** move the Rubber Bands.

Task 2: Measuring the Droplets

To perform this experiment you will use what is known as the float method. A voltage is applied to the droplet that holds it stationary, exactly opposing the force due to gravity. The voltage is then switched off and the terminal velocity of the droplet is measured. With this data the radius r and charge q of the droplet can be calculated using equations (3.9), (3.10) and (3.12).

To measure each droplet it is first of all necessary to find one that is moving in the focal plane of the eyepiece. Any forward or backward motion will cause the droplet to disappear from view over time. And as described above, concentrate on oil drops that have a fall time of around 50-100s and do not rise too rapidly under a high Voltage. Once you have chosen a particular oil drop you can experiment with moving it up and down (Voltage on and off).

2.1) Turn **Switch U** to the **ON** position to apply a voltage to the Capacitor plates. Turn the Voltage Adjustment Knob so the voltage is around ~500V and inject some droplets into the Capacitor by squeezing the Atomiser (as shown in figure 3.2) three or four times. Check that the Atomiser is pointing at the two little holes in the side of the plastic cover of the capacitor first.

Most droplets are uncharged so it is useful to first of all apply a large voltage and see which ones can be made to rise at all. If there's no useful droplets, squeeze the Atomizer again. On the live video, the droplets will appear as bright points of light. Charged particles (of the correct polarity) **will rise under a voltage**, and then fall when the voltage is switched off. You may need to refocus the video camera for a particular particle (or over time if the particle drifts out of the focal range).

2.2) Once you have a droplet, vary the voltage until you can keep your chosen droplet stationary in the centre of the field of view. You may need to adjust the Flexicam focus to keep it in view, there is an outer focus ring on the Flexicam camera for you to do this. The millimetre scale may go out of view, which is why you need the 2 elastic bands, as you are using those as your markers. Experiment with controlling the particles by switching the voltage on and off. The mouse pointer on the screen is a convenient reference point to study the particle movement. Record the Voltage required to keep the oil drop stationary. There may be a range so you can record this as your uncertainty. A range of ± 5V is a normal confidence range for the hovering Voltage. For this reason it is good to find oil drops with a hovering Voltage in the range of ~100V to 400V as the large the hovering Voltage the lower in this fractional uncertainty. This is something you can experiment with yourself with each oil drop you choose.

2.3) Turn **Switch t** on the Power Supply to **ON** position. Also switch on the **Timer** at the plug. It will have already been connected to the Millikan Power Supply by the Technician but you need to put it into mode $\boldsymbol{t_E}$. by pressing the **MODE** button until the LED above it is lit. Press the blue **START** button before each timing measurement to have the clock trigger on the signal provided from the Power Supply, **so when the voltage is turned off, the Timer starts.**

2.4) Now increase the voltage until the droplet reaches your upper rubber band, then switch off the voltage using **Switch U**, which will start the clock on the Timer. Once the droplet has fallen your predetermined distance s (as indicated in figure 3.5) switch the voltage back on again as this stops the clock with a time measurement, t. Record the Time, t, along with its uncertainty taken for the droplet to fall the required distance.

The **velocity, $\boldsymbol{v}$,** of the freefalling drop can be calculated from these values of distance, s, and time, t. This can then be used to calculate r and q.

2.5) Before proceeding further set up a spreadsheet in MS Excel and perform a pilot calculation (even better do this before coming to the Lab session using the test data in the Table below to check your MS Excel equations).

The spreadsheet below shows a suggested layout and includes a set of specimen data that you can use to check your spreadsheet. All uncertainties should be rounded to 1 sig fig and then put the associated value to the same precision. Once this is setup then you can add new measurements on succeeding lines, of the hovering Voltage and the drop time, and copy the formulas down with confidence.

Voltage	Distance	Fall Time	Velocity	uncertainty in V	r	uncertainty in r	q	uncertainty in q	% uncertainty	corrected q_c	uncertainty in corrected q_c	% uncertainty	Integer $\frac{q_c}{e}$	uncertainty
(v)	(m)	(s)	(ms^{-1})	(ms^{-1})	(m)	(m)	(c)	(c)		(c)	(c)			
± 5V	± 0.03E-03	± 0.1s												
204	2.50E-03	68.5	3.65E-05	4.E-07	5.90E-07	4.E-09	2.2E-19	7.E-21	3	1.79E-19	5.E-21	3	1.12	0.06

In your spreadsheet record all the quantities you need to measure to determine r and q for an individual droplet, you can then refer to the cells containing these values when you are typing in the required formulas. (You will have been shown how to use formulas in Excel in week 2 of the module but if you need a reminder then please refer to the screencast videos available on Minerva or ask the Demonstrator).

2.6) Estimate the fractional uncertainty in each value. Which uncertainty is the largest and smallest? Does the uncertainty in one value dominate? When q_c is divided by the known value of e this should be close to an integer number, within the uncertainty of the experiment. This number indicates how many electrons the droplet is away from charge neutrality.

2.7) Spend the remainder of the lab session measuring as many droplets as time allows (around 20 if possible).

What to include in your Lab Notebook

1) A short Introduction describing the Experimental Aims and including the expected target value with a reference.
2) A short method section explaining what you did, also include labelled schematic diagrams of the apparatus.
3) You may also want to develop the key physics equations as a reminder of what you will measure and how you will do the analysis including the uncertainty analysis.
4) A table of the measurements and calculations for the various parameters and their uncertainties.
5) In your Conclusion answer the following questions:
   - Is there any correlation between the oil drop radius r and the ratio $\frac{q_c}{e}$ against r?

     You should plot a graph of ratio $\frac{q_c}{e}$ against r to investigate.
   - Is there any correlation between the hovering Voltage (suggested between 100V and 400V) and the ratio $\frac{q_c}{e}$? Again plot a graph to investigate

     Any recommendation for future experiments?
   - Is there any evidence that the charge on the droplets is quantised (clustered around 1e, 2e, 3e etc). If possible use MS Excel to form a histogram to assess whether these predicted values of 'e' are clustered closely around quantised units of charge. Instructions for how to create and use Histograms in MS Excel this can be found in the information for Data Analysis Task 2 which will be provided in week 5.
   - Were any of your measured any charges less than 0.9e? Comment on whether this is good evidence for a lower threshold for the electron charge.

Please also send a spreadsheet of your results to p.j.hine@leeds.ac.uk as later in semester 2, once everyone has completed the experiment, we will post a summary of everyone's combined results to produce a single large combined data set which you can analyse if you are interested. This will then be available for further analysis if you decide to do this experiment as a Formal Report.

When you have completed the experiment, switch off the equipment. **Remember to log off the computer before you leave the lab.**

Experiment 4

Diffraction and Interference

Experimental Aims:

- To become familiar with interference and diffraction effects for single, double and multiple slits.
- To measure the slit width and separation of a number of different slits and compare these to the expected values.
- To find the relationship between the number of slits and the number of subsidiary maxima observed.

Learning Objectives:

- To learn how to accurately align a set of optical components.
- To learn how to use computer data collection and analysis software.
- To learn how to analyse spectra to obtain accurate values for peak maxima and minima.
- To be able to critically evaluate the results of an experiment; to compare measured results with expected values and comment on the agreement within uncertainties.

VITALs

E1 b: Keep a detailed laboratory notebook
E1 c: Perform appropriate calculations

Preparation:

You are expected to have done these things before you turn up to the lab session:

- **Watch the Online Supporting Video** (link is on Minerva) and become familiar with the experimental method and data analysis.
- Read this manuscript and become familiar with the physics behind this experiment.
- Refer to Tipler (Sixth Edition) Chapter 33 for help in understanding the physics of interference and diffraction.
- Fill in the online Health & Safety form as described below.

Risk Assessment and Safety:

Read the Health and Safety information on the next page and fill in the online H&S form. The technician will check online that you have filled this in before you start. It can be reached either via this QR code, via the link on MINERVA or this weblink here: https://forms.office.com/e/gXLy9cDts9

School of Physics & Astronomy	RISK ASSESSMENT RECORD
LOCATION:	Bragg Building, Room 4.08, 1st Year Physics Undergraduate Laboratory
DESCRIPTION OF ACTIVITY:	**Experiment 4: Diffraction and Interference**

SIGNIFICANT HAZARDS	**EXISTING CONTROL MEASURES**	**SEVERITY**	**LIKELIHOOD**	**RISK RATING**
		1 = minor, 2 = serious, 3 = major		
1mW LASER – Class 2. Safe to use in an open laboratory.	Never look directly down the beam of the Laser. Do not stare at the Laser spot for any prolonged length of time. Remove all watches and rings to restrict stray reflections. Do not put anything in the path of the beam which could reflect the Laser. Users should not attempt any adjustments to the Laser. Always switch off Laser when not in use.	2	1	2
Electrical equipment	All equipment to have an up-to-date PAT test sticker. No such instrument should have its fuse or plug tampered with. If an item appears to be faulty, consult the Laboratory Technician.	1	1	1

PEOPLE AT RISK	**ADVERSE EFFECTS**	**ACTIONS TO BE TAKEN & TIMESCALES**
All students, demonstrators and staff members	Laser light Electrical shock	Laser power to be checked every three months. Must be less than 1mW. If an electrical item appears to be faulty, consult the laboratory Technician

	Name	**Signature**	**Date**
ASSESSED BY:	Angela Beddows (Technician)	Angela Beddows	27/07/2023
GROUP HEAD:	Dr Peter Hine (Laboratory Convener)	P.J. Hine	27/07/2023
SAFETY SUPERVISOR:	Stuart Weston (Department Safety Officer)	S Weston	27/07/2023

Experimental Apparatus

This experiment is about the diffraction of light at a slit and the interference which occurs between the diffracted light from a number of adjacent slits forming a diffraction pattern on a screen.

Fig 4.1a

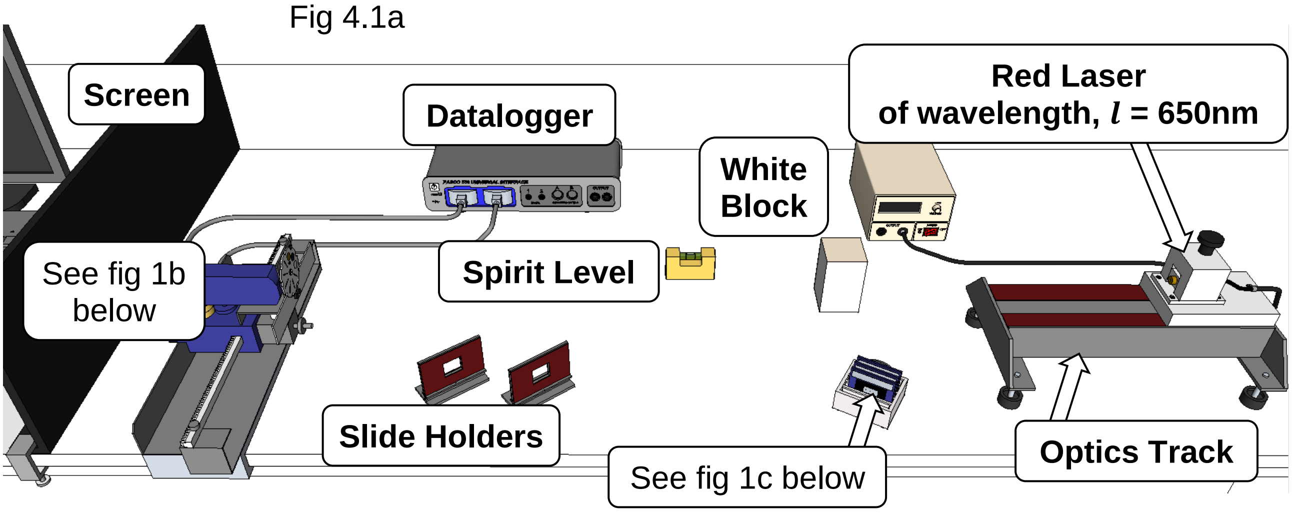


Figure 4.1a above shows the experimental apparatus used in this experiment. On one side mounted onto an **Optics Track** is a Red **Laser*** diode (emitting light of wavelength, λ, 650nm) connected to a power supply. On the other side is a **Linear Translator Rack** which has a **High Sensitivity Light Sensor** on top of a **Rotational Sensor** (shown in figure 4.1b) mounted onto the Rack. The Rack allows light sensor to be scanned across any diffraction pattern. These sensors are connected to a **Datalogger**, and then to a computer allowing the diffraction patterns to be recorded and analysed by datalogging software. An **Aperture Bracket Wheel** contains slits which allow the light entering the Light Sensor to be controlled. **Slide Holders** are used along with the Optics Track and **Diffraction Gratings** and **Polarizer** (shown in figure 4.1c) to create diffraction patterns. The Polarizer can be rotated to reduce the intensity of the beam if required. A **Spirit Level** is used to check the Optics Track is level before readings are taken. A **White Block** is used to align the Slide under investigation with the Laser beam. A **Screen** is also in place as a safety precaution to protect other users on the bench from the Laser beam.

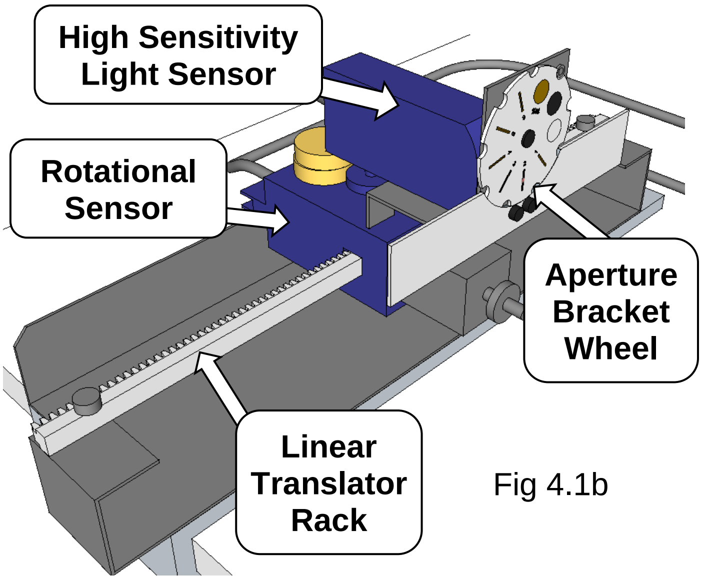
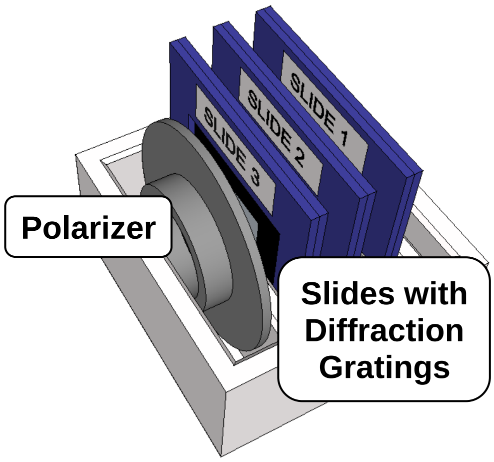


Fig 4.1b

Fig 4.1c



*LASER is an acronym, meaning **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation.

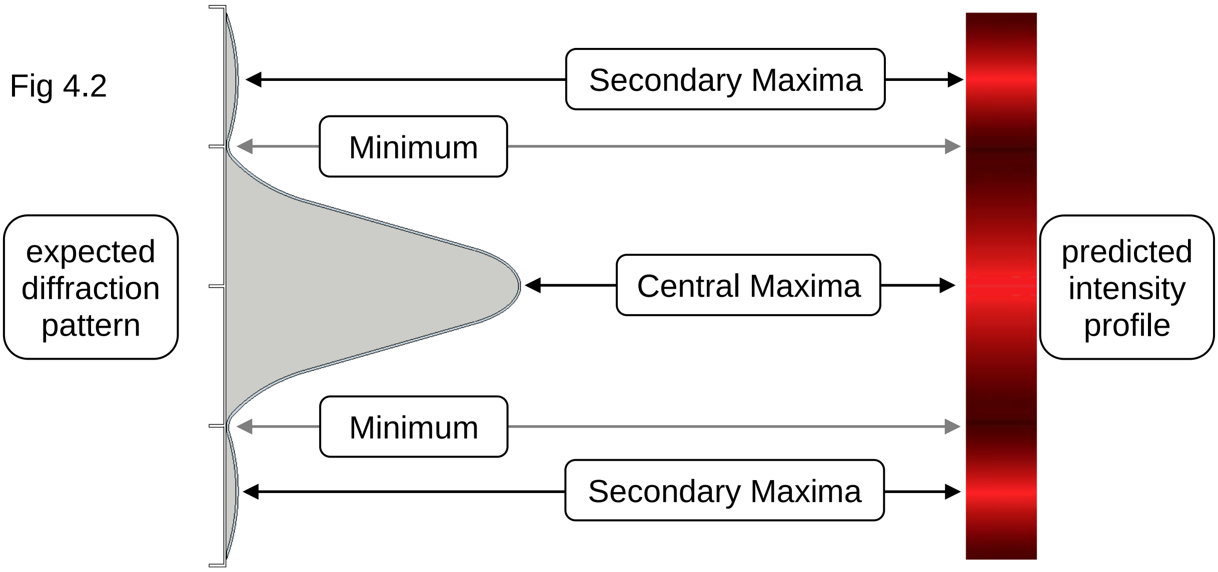
Introduction and Background Theory

In this experiment we will be viewing and then taking measurements of the far field diffraction patterns (Fraunhofer patterns) from a range of single slits, double slits and multiple slits. The aim of the experiment is to understand the links between the observed diffraction patterns and such parameters as the slit width, a, the slit separation between multiple slits, d, and the number of multiple slits (2, 3 and 5 slits in this experiment).
You will use a low power red diode Laser as our coherent light source, which has a wavelength of 650nm. This is class 2 Laser source (power <1mW) as so is safe to use in an open lab. However, it is still good practise to follow Laser safety procedures, so do not wear rings etc when adjusting the Laser (to stop stray reflections) and do not look directly into the beam.

Single Slit Diffraction Pattern (Tipler 33-4)

Figure 4.2 below shows the expected diffraction pattern for a single slit of width a, along with associated predicted intensity profile. Most of the light is concentrated into the central maximum, but there are also subsequent maxima outside this.

Fig 4.2



The angular position of each minimum (zero intensity) in the diffraction pattern, with respect to the central maximum, is given by the familiar expression.

$$a\sin(\theta) = n\lambda \qquad \text{equation (4.1)}$$

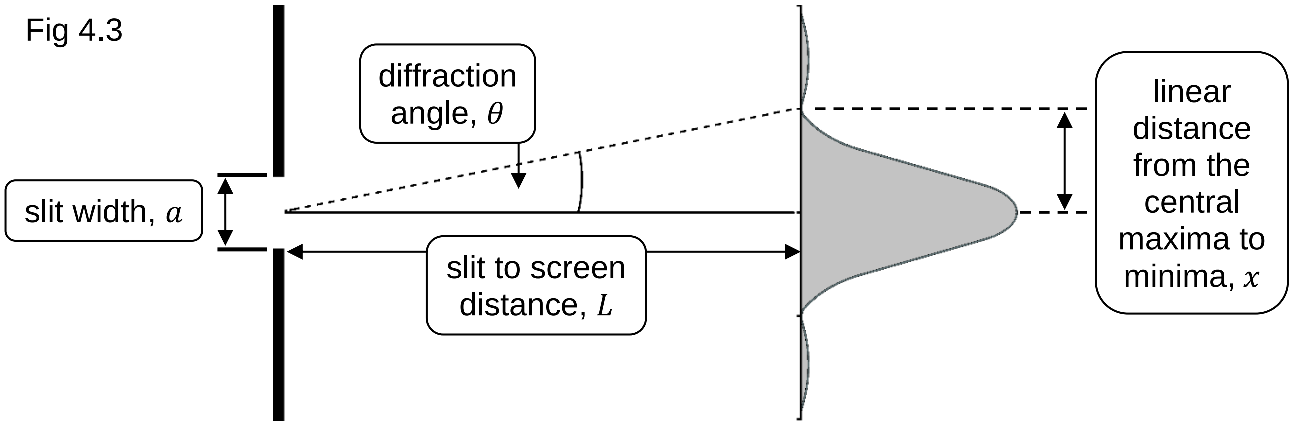
Where: a = the slit width
θ = diffraction angle
n = diffraction order and
λ = wavelength of the Laser light = 650nm

In single slit diffraction the linear distance (which is what you will measure) from the central maxima to each minima, x, is then given by

$$x = \frac{n\lambda L}{a} \qquad \text{equation (4.2)}$$

Where L = the slit to screen distance as shown in in figure 4.3 on the next page

Fig 4.3



Assuming for small angles that sinθ ~ tanθ and where in this experiment the distance between the slit and the screen, L, equation (4.2) shows that if the slit width, a, is increased, then the distance to the first minima, x, is decreased (and vice versa).

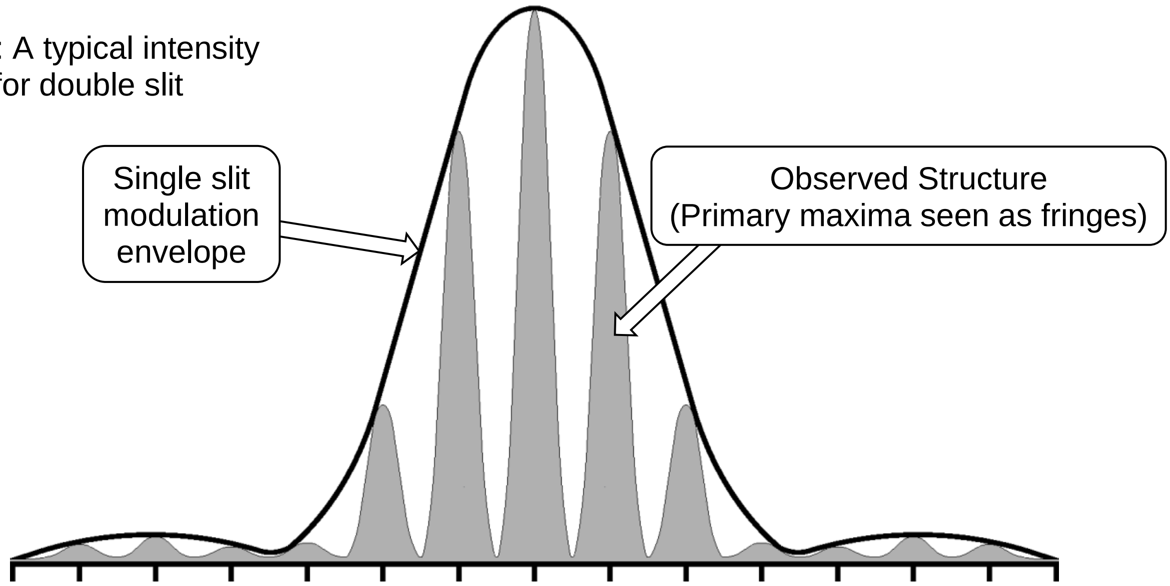
It can also be seen that if we measure the distance between the first minima on either side of the central maxima, $2x$, (which is an easier measurement to make compared to finding the peak intensity), then the slit width, a, will be given by:

$$a = \frac{\lambda L}{(\frac{2x}{2})} \qquad \text{equation (4.3)}$$

Double Slit Diffraction Pattern (Tipler 33-4)

When there are two slits of the same width, a, then the intensity pattern on a screen far away from the slits will be combination of the single slit diffraction pattern and that for multiple slits as shown below.

Fig 4.4: A typical intensity profile for double slit



The single slit modulation envelope (solid black line in figure 4.4) is due to the intensity profile from each individual slit of width a, while the finer structure of the observed pattern structure (the grey pattern in figure 4.4) is due to the separation between the slits, d. As shown above, as the slit separation d is greater than the slit width a then this structure is closer spaced in the diffraction pattern.

The distance between the primary maxima, w, in the pattern is given as follows.

$$w = \frac{\lambda L}{d} \qquad \text{equation (4.4)}$$

For finer structures, it is often more accurate to measure the distance between multiple primary maxima, w_m, so that

$$w_m = \frac{m\lambda L}{d} \qquad \text{equation (4.5)}$$

Where m is the number of fringes counted.

Finally, we can determine the spacing of a pair of double slits, d, by measuring the spacing of the diffraction pattern and the equation:

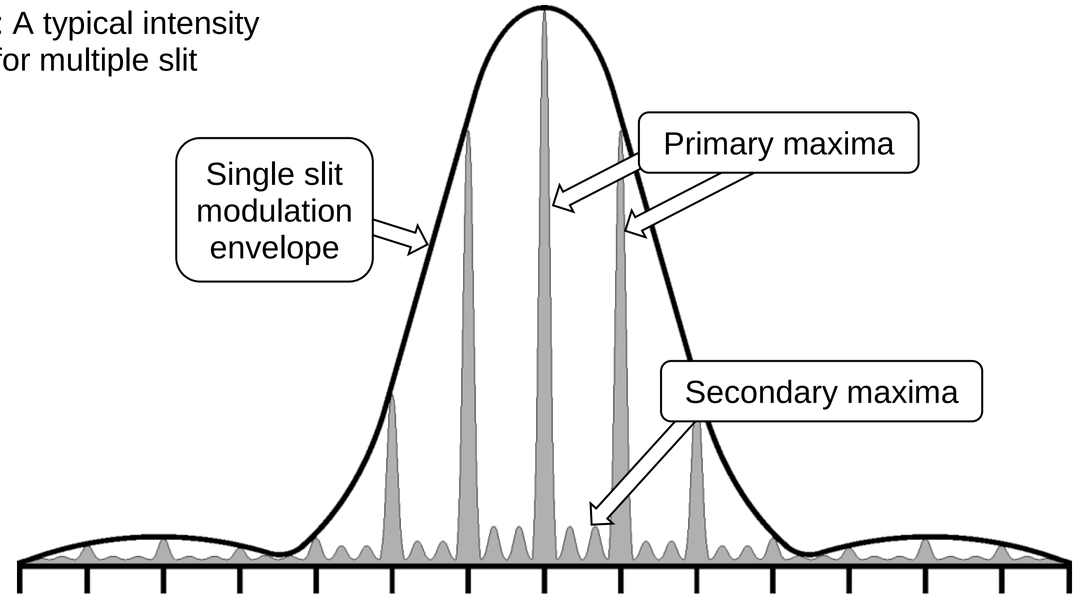
$$d = \frac{m\lambda L}{w_m} \qquad \text{equation (4.6)}$$

where w_m is the spacing between m diffraction fringes.

Multiple Slit Diffraction Pattern (Tipler 33-5).

For multiple slit combinations where the number of slits, p, is >2 there are additional secondary maxima between the primary maxima. As for the double slit, the intensity envelope is again controlled by the width of each individual slit, a, and the primary maxima from the separation between the slits, d. Additionally, there are also secondary maxima between the primary maxima, where the number of secondary maxima is (p - 2).

Fig 4.5: A typical intensity profile for multiple slit



This experiment will investigate how the width and intensity of the primary maxima change as the number of slits increases. Eventually as you increase the number of slits the maxima are very sharp and bright (and the secondary maxima are too small to be seen) and so such an assembly permits high-resolution separation of the maxima for different wavelengths. Such a multiple-slit is called a diffraction grating.

Experimental Procedure

Task 1: Setting up the apparatus

The first task is to set up the Optics Track so that the Laser beam travels parallel to the bench and arrives at the aperture bracket in the centre of the chosen slit.

1.1) Switch on the computer and log in. Move the Sensor assembly so it is in the middle of the Linear Translator Rack and select slit number 2 on the Aperture Bracket Wheel to start with as shown in the figure 4.6 below. In this arrangement, the light then enters the centre of the Light Sensor, which is located directly behind the aperture bracket.

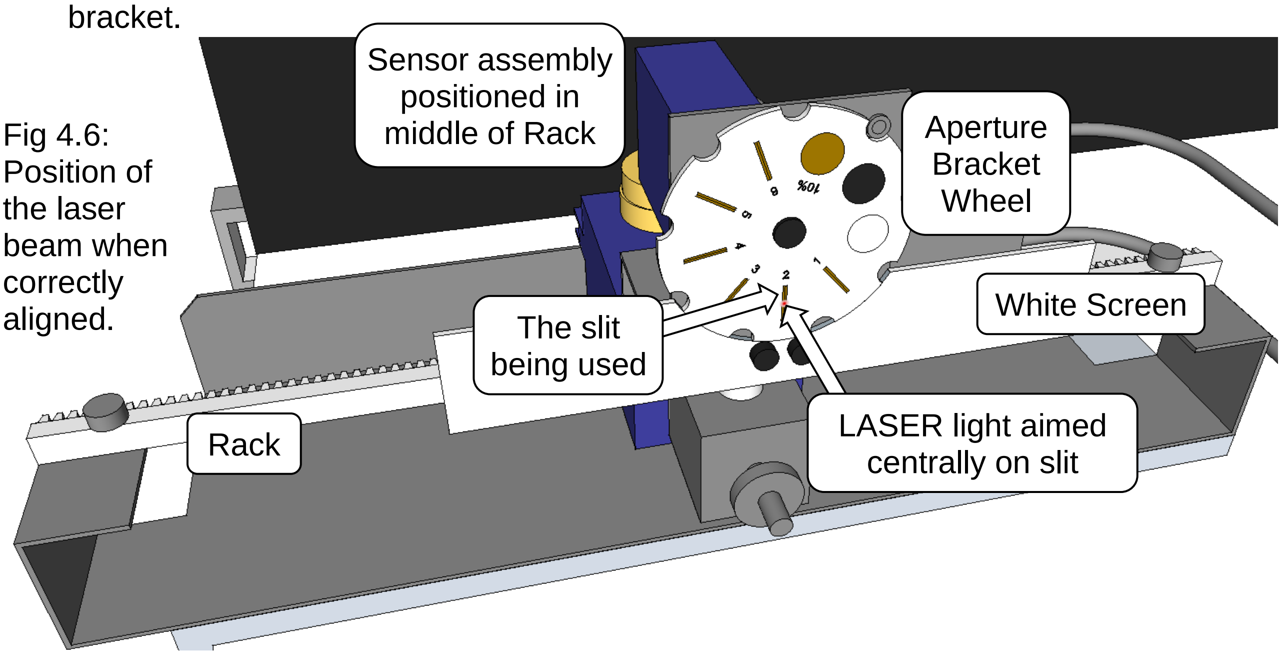


Fig 4.6: Position of the laser beam when correctly aligned.

1.2) Remove any Slide Holders from the Track and switch on the Laser (do NOT adjust its voltage). Then line up the Laser and Track so it is parallel to the edge of the bench and the Laser light is pointing at the middle of the slit being used on the Wheel as shown in the figure above. The distance between the Aperture Bracket Wheel and the Laser needs to be at least 1 metre. You may need to adjust the height of the track also, this can be done by screwing or unscrewing the 4 adjustable feet on each corner. You can lock the feet with the integral Collar, shown in figure 4.7a on the right. When adjusting the Track height, use the Spirit Level on both axes as shown in figure 4.7b below to check it is level in both directions. Once you have it nearly right, use the Laser Height Adjustment Screw to position the Laser in the centre of the Slit. Remove the Spirit Level once the Optics Bench is level and the Laser beam is illuminating the slit.

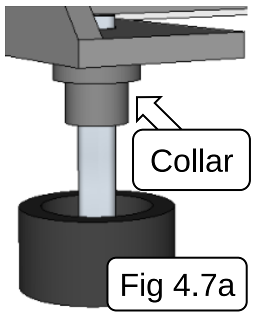


Fig 4.7a

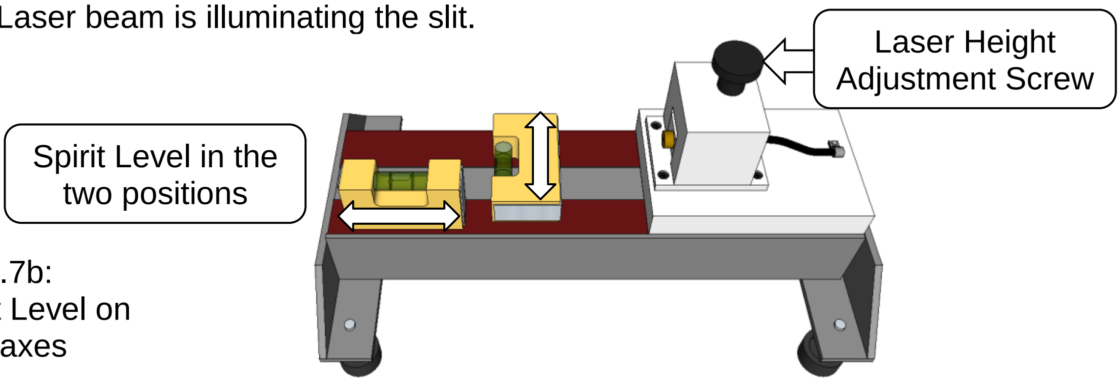


Fig 4.7b: Spirit Level on both axes

1.3) Switch on the Datalogger using the ON button which top left of the unit then launch the Pasco Capstone software . Then click on **Hardware Setup** on the left toolbar, you should see the Datalogger Interface connected to the Rotary Motion Sensor on channel 1 and the High Sensitivity Light Sensor on channel 2 and shown below in figure 4.8.

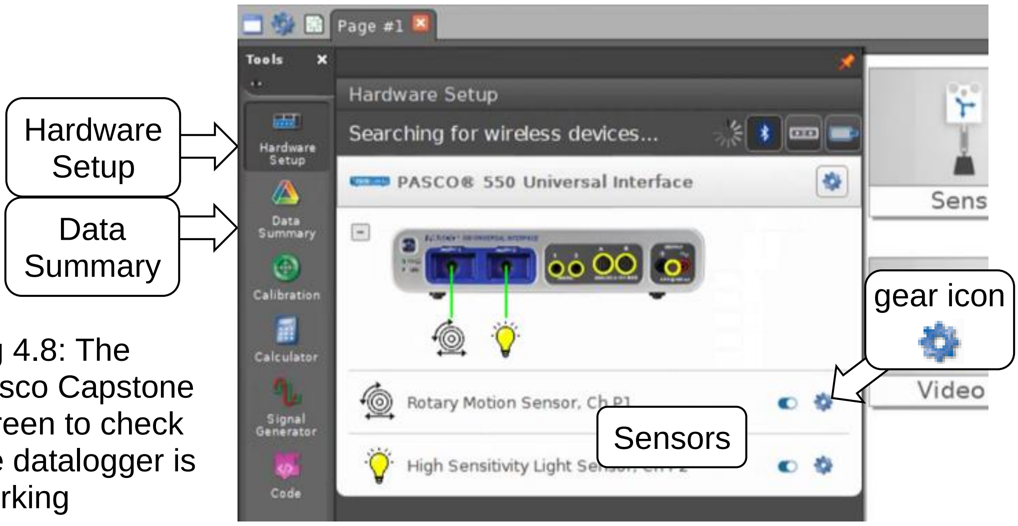


Fig 4.8: The Pasco Capstone screen to check the datalogger is working

1.4) Click the gear icon next to the Rotary Motion Sensor channel (as shown in figure 4.8 above) and under the Linear Accessory option click on the drop down menu and change it to **Rack and Pinion** and then click OK. Then click on **Data Summary** tab (shown in figure 4.8) and click on Position, then click the gear icon that appears to show its properties, click on Names and Symbols and then Default Units and change the position **units to mm**, then click OK and then click on Data Summary again to minimise the toolbar. If Position isn't showing under Data Summary then ask the Demonstrator.

1.5) Next set up a Graph for logging and analysing your diffraction pattern data. On the Displays Toolbar on the right, click on the Graph icon at the top of the right-hand toolbar and drag it in to the main window. This will show a graph covering a large chunk of the screen. Click on '**select measurement**' on the Y axis and select **Light Sensitivity (% of scale max)** and on the X axis do the same and select **position**.

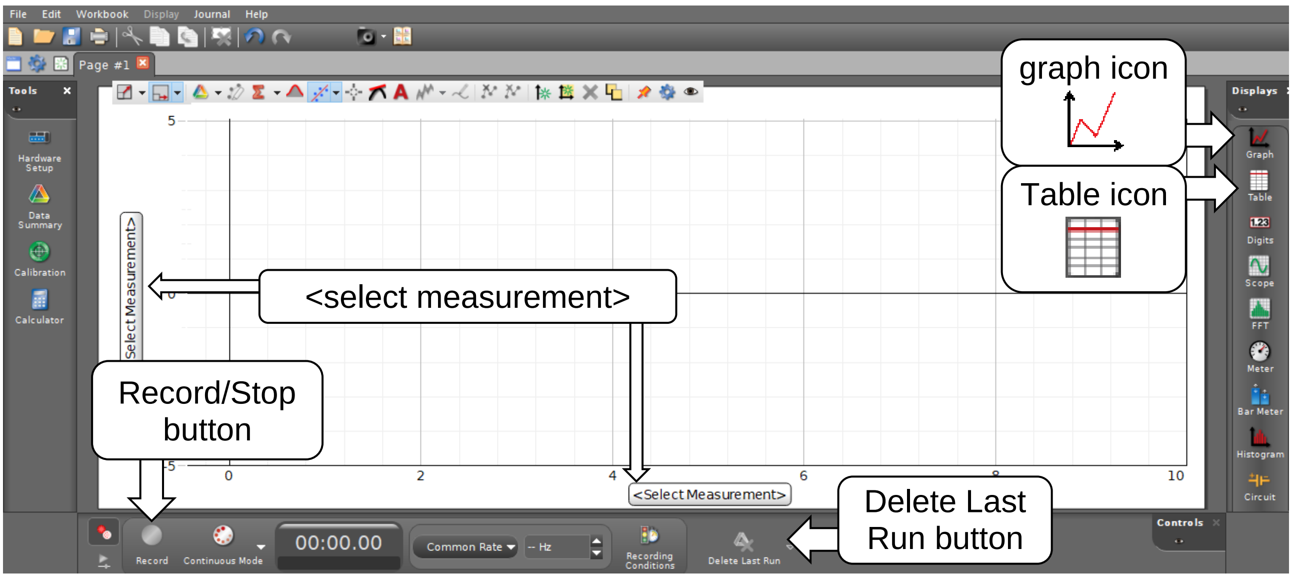
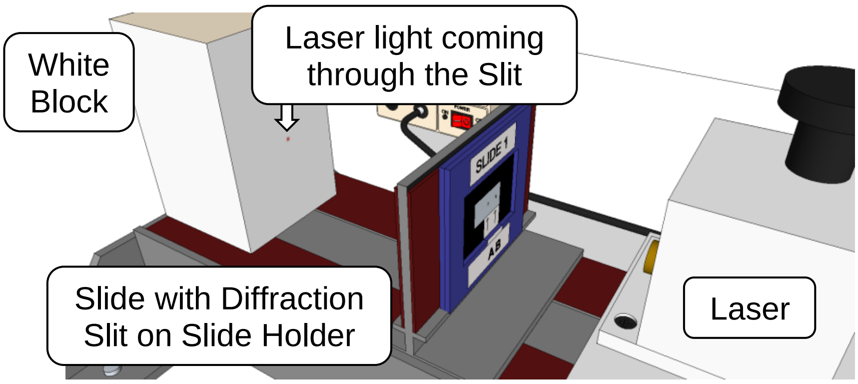


Fig 4.9: The Pasco Capstone Graph screen setup to log data.

Task 2: Measurement Procedure (The procedure is the same for each slit)

2.1) Place the Diffraction Slit you want to study on the Slit Holder and place it on the Track so it is between the Laser and the Light Sensor and then place the White Block as show in figure 4.10 below and adjust the Slide until you can see a good amount of Laser light coming through the Slit as shown in figure 4.10. Then remove the White Block.

Fig 4.10



2.2) Move the Sensor Assembly so that the diffraction pattern can be seen on the side White Screen, as shown on figure 4.11. If you do not see a diffraction pattern then adjust the Slit on the Slide Holder until the Laser light passes through it. The pattern shown in figure 4.11 is a typical one for double slit (and is the central large peak) from figure 4.4.

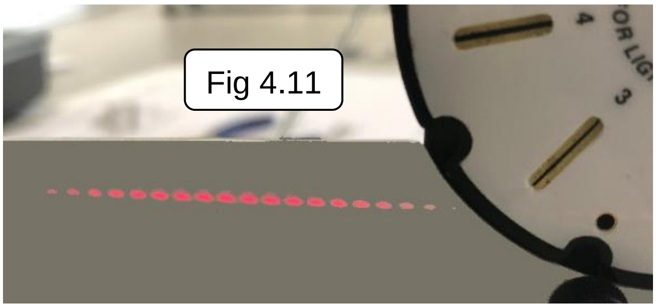


Fig 4.11

2.3) There are 3 buttons on the back of the Light Sensor facing away from you as shown in figure 4.13. These control the sensitivity of the Light Sensor. Press the **0 to 1** button (on the end nearest the Wheel) before you start to move the sensor.

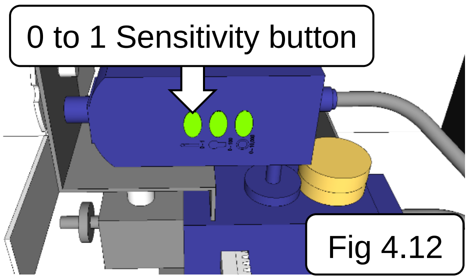
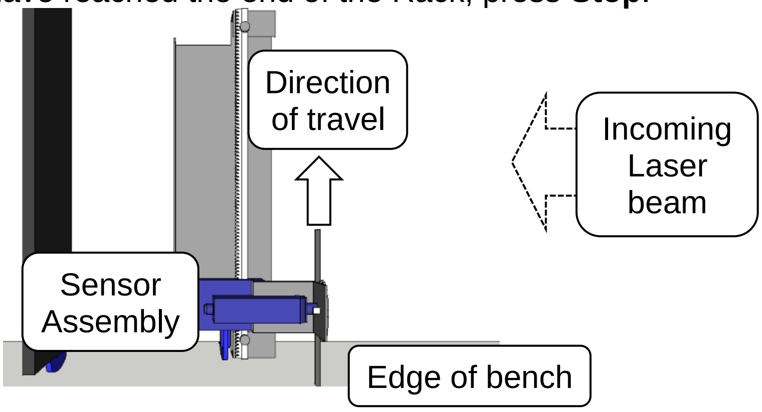


Fig 4.12

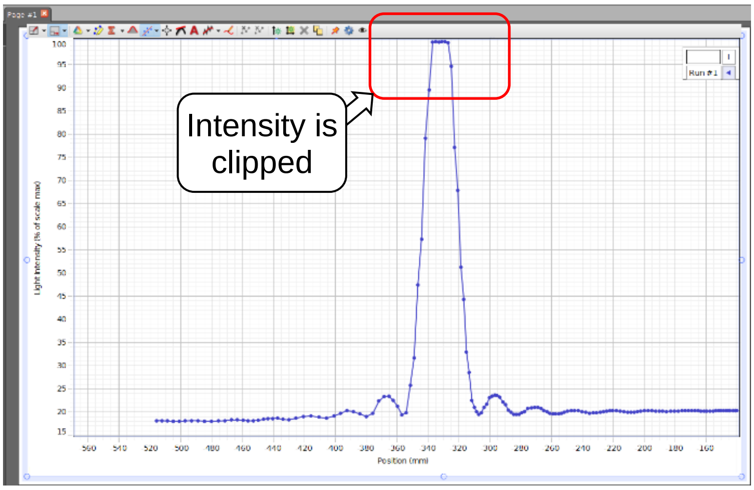
Move the Sensor assembly on the Rack so it is now near to the edge of the bench, then click **Record** (a shown in figure 4.13 below) and move the Sensor assembly at a slow reasonable pace along the Rack so the position changes and the sensor detects the diffraction pattern. Try not to press the sensitivity buttons while you are doing this. Once you have reached the end of the Rack, press **Stop**.

Fig 4.13: View from above of the Rack assembly start position and direction of travel.



2.4) An example spectra for a single slit is shown in figure 4.14a below. You can expand or contract the X and Y axes or move the data around to get the best display of your collected data using the mouse wheel Shift key (X axis) or CTRL (Y axis).

Fig 4.14a Graph of single slit diffraction, with its intensity clipped

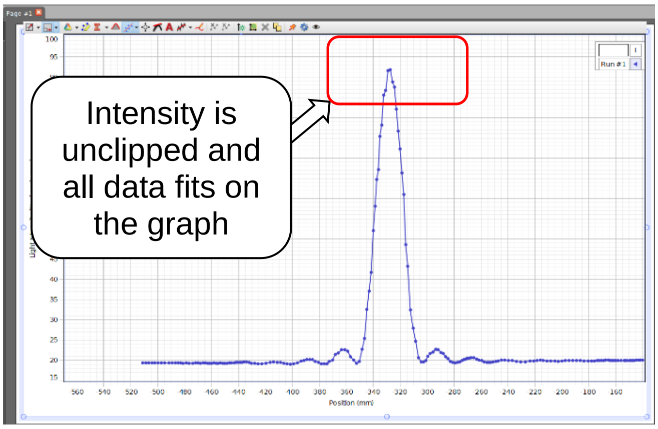


In this example in figure 4.14a, the intensity is clipped for the central fringe as the input of the high sensitivity Light Sensor has been exceeded. In order to get good data you need to have it all showing on the graph (unclipped). You have 3 options to fix this, pick which ever you think suits the Diffraction Slit you are using:

- Add the **Polariser** between the Light Sensor and Diffraction Slit to reduce the intensity of the Laser light. This can be rotated to provide varying degrees of polarization to reduce the intensity of the incoming Laser beam.
- Reduce the gain of the Light Sensor
- Reduce the slit width of the slit on the Aperture Wheel Bracket by rotating the Wheel to a narrower slit.

Experiment with these options by recording and then deleting your data (delete it using the Delete Last Run button) until you are content you have a good set of results. At this point it is good practise to save your data to your account on M:/ drive. Figure 4.14b below shows a final scan of figure 4.14a after a Polarizer has been added.

Fig 4.14b: scan image of figure 4.14a of single slit after Polarizer added.



Task 3: Taking Measurements

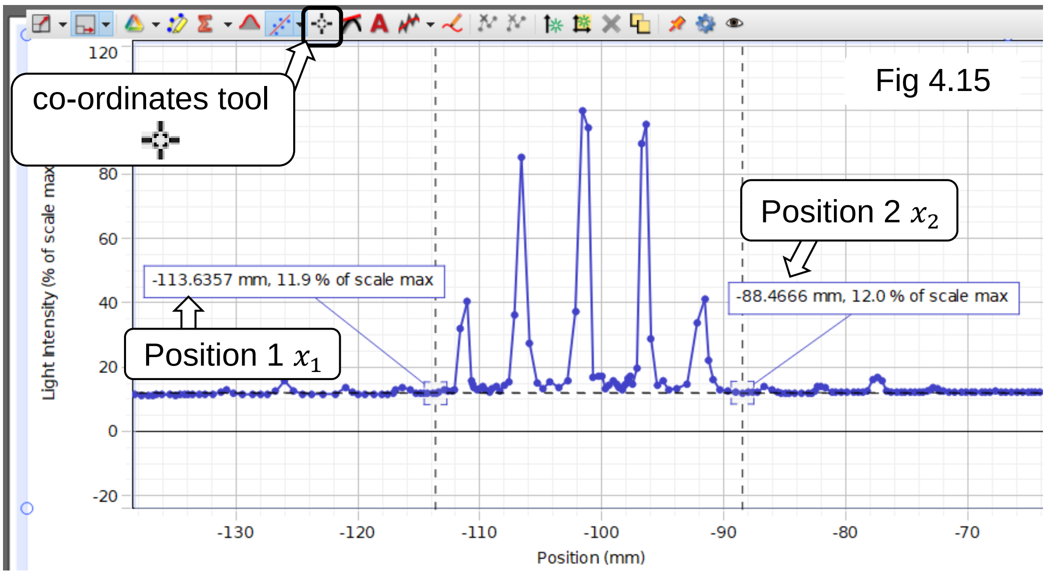
3.1) Move the Sensor Assembly to the middle of the Rack again and measure the distance between your chosen Slit and the Aperture Bracket Wheel, L, and record it in your lab notebook along with its uncertainty. Also open a new file in MS Excel to record your data later in the experiment.

3.2) Using the method set out in Task 2 and your chosen slit, obtain a graph with all the data for the diffraction pattern on it.

3.3) Make measurements of your diffraction pattern, specifically:
- the distance between the minima of the single slit envelopes
- the distance between any primary or secondary fringes

You can then compare these to the various enlarged picture of the actual slits (together with a suitable scale bar) which are available in the Lab.

The co-ordinates tool, as shown in figure 4.15 below, is a good way to make measurements from your diffraction pattern. In the example below the distance between two minima are measured. Click on the co-ordinates icon on the graph toolbar and select Add Coordinates/Delta Tool and a cursor will appear on screen. Click on the cursor and drag it to where the first minima is.



There are uncertainties on each position measurements (either the range over which you are confident you can find the position or the increment between each movement of the co-ordinate tool) and you can use the normal formulations to determine the uncertainties in the differences.

3.4) For instance, for two positions x_1 and x_2, with associated uncertainties Δx_1 and Δx_2, the difference will be given by

$$x = x_2 - x_1 \quad \text{equation (4.7)}$$

And the associated uncertainty $(\Delta x)^2 = (\Delta x_1)^2 + (\Delta x_2)^2$ equation (4.8)

3.5) Once you are happy with your data, capture the full screen as a picture (including all your calculations) by selecting **Display** from the top menu, and then **Copy Display**. You can then paste this captured image into MS Word or MS Excel. To obtain the raw data, you can click and drag the Table icon (as shown in figure 4.9) into the main area from the **Displays** menu on the right hand side of the screen as shown in figure 4.16. You can can then select the X Axis (Position) and the Y axis (Light Intensity), then select all data CTRL+A and then CTRL+C to copy and then CTRL+V to paste it into MS Excel.

Task 4: Measuring the interference patterns from the Diffraction Slits.

By measuring the interference patterns and particularly the spacing of the interference minima and maxima you will be able to determine the dimensions of each slit system and compare these to the expected values.

Task 4.1: Single Slits A and B

There are two single slits labelled A and B, each with a different width.

4.1) Set up the apparatus and software as described in Tasks 1 to 3 and collect and analyse the resulting interference patterns. The diffraction pattern should look like figures 4.3 and 4.4. You may not need to use the **Polariser** for the single slit measurements.

4.2) Using Slit A, take measurements of the first minima position either side of the central maxima and determine the slit width, a, with its uncertainty Δa. As the wavelength of the Laser light is given as 650nm then the uncertainty in a, Δa, will be given by:

$$\left(\frac{\Delta a}{a}\right)^2 = \left(\frac{\Delta L}{L}\right)^2 + \left(\frac{\Delta x}{x}\right)^2 \qquad \text{equation (4.7)}$$

Where L is the distance between the slits and the detector, and x is the distance between the central maxima and the first minima, or half the distance between the two minima either side of the central maxima (which is easier to measure).

4.3) Repeat step 4.2 but with Slit B.

4.4) Once you have determined $a \pm \Delta a$ for both slits, compare them to measurements taken from the laminated high magnification pictures available in the Lab (they also available on MINERVA under Learning Resources for this experiment). You will need to take measurements (along with their associated uncertainty) from these pictures.

Task 4.2: Double Slits, C and D

There are two double slits, C and D, with the same slit width a but with a different slit separation d.

4.5) **For each double slit:** Collect and analyse the diffraction patterns for each double slit like you did for the single slits. The diffraction patterns should look like figure 4.4 with closely spaced primary maxima underneath an envelope given by the single slit width.

4.6) Take measurements of the minima from the intensity envelope to determine the slit width, a, and its uncertainty, Δa. You can then compare this to single slits A or B from Task 4.1.

4.7) Then take measurements of the separation of the multiple primary maxima, w_m, (count over m fringes to increase your accuracy) and use this to calculate the slit separation along with its uncertainty. Compare these values to measurements taken from the laminated high magnification pictures available in the Lab (also available on MINERVA), as for the single slits. As before you will need to take measurements (along with their associated uncertainty) from these pictures.

Task 4.3: Multiple Slit Assemblies, E and F

There are two multiple slit assemblies: Slit E (3 slits) and Slit F (5 slits), to examine

4.8) Take measurements of these using the methods as described in previous Tasks. Do this for each slit.

Note: If time is running short towards the end of the Laboratory session, then take measurements of just one of these sets of slits (i.e. either E (3 slits) **or** F (5 slits).)

4.9) The diffraction patterns should look similar to figure 4.5. For comparison, a double slit D with the same slit width, a, as E and F is also provided as these three slit assemblies have a smaller slit width than in previous Tasks so that the Laser beam can illuminate them all evenly.

4.10) Collect and analyse the diffraction patterns for both Slit E and Slit F (or if you haven't time, then just one of those).

What to include in your Lab Notebook

1) A short Introduction describing the Experimental Aims.
2) A short method section with schematic diagrams of the apparatus.
3) A picture of the captured data for each of the 6 diffraction patterns.
4) Measurements taken from each diffraction pattern and calculations with their respective uncertainties of the slit width, $a + \Delta a$, and slit separations, $d + \Delta d$
5) Measurements of the actual slit geometries taken from the laminated high magnification pictures available in the Lab (also available on MINERVA in the appropriate folder) together with the uncertainties in these measurements.
6) A comparison Table for comparing your measurements.

Slit	Calculated Slit Width, a (m)	Calculated Slit Separation, d (m)	Expected Slit Width, a (m)	Expected Slit Separation, d (m)
A - Single				
B - Single				
C - Double				
D - Double				
E - Three				
F - Five				

7) As with all laboratory experiments, finish with a short Conclusion section, summarising all the key results and any comments or suggestions regarding the experimental method or apparatus. Use the following questions to aid in writing this section:
   a) How do the calculated slit widths and slit separations compare to those measured from the pictures of the slit assemblies, when the uncertainties in both are taken into account?
   b) How does the single slit diffraction pattern change as the slit width increases? Which slit gives the **broadest** diffraction pattern? Why?
   c) How does the double slit diffraction pattern change as the slit separation increases? From the diffraction envelope, which slit width (A or B) was used for the double slits?
   d) For the multiple slit diffraction patterns (E and F), answers to each of the four questions below:
      - How does the number of secondary maxima correlate with the number of slits?
      - Can you suggest where these secondary maxima come from? Can you use the separation in the diffraction patterns to compare to the physical distance on the actual slits?
      - What happens to the primary reflections (intensity and width) as number of slits increases?
      - What do you think the pattern would look like for a diffraction grating with 500 lines/mm?

8) Any suggested improvements to the apparatus or the experimental method.

Experiment 5

A Resonance Method of Estimating the Inter-Atomic in Copper

Experimental Aims:

- To measure Young's (Y), shear (S) and bulk (B) moduli of Copper (Cu).
- To measure the Spring Constant (k) for Cu and estimate the melting point (T_m) of Cu.

Learning Objectives:

- To become familiar with resonance, travelling waves and elastic moduli.
- To learn how to set up equipment carefully and safely.
- To learn how to use an oscilloscope to investigate resonance effects.
- To further develop your skills using an oscilloscope to take accurate measurements.
- To be able to critically evaluate the results of an experiment; to compare measured results with expected values and comment on the agreement within uncertainties.

VITALs

E1 a: Safely measure and record experimental data
E1 b: Keep a detailed laboratory notebook

Preparation:

You are expected to have done these things before you turn up to the lab session:

- **Watch the Online Supporting Video** (link is on Minerva) and become familiar with the experimental method and data analysis.
- Read this manuscript and become familiar with the physics behind this experiment.
- Read and understand these sections from Tipler: 12-7, 13-1, 14-1 and 14-5.
- Fill in the online Health & Safety form as described below.

Risk Assessment and Safety:

Read the Health and Safety information on the next page and fill in the online H&S form. The technician will check online that you have filled this in before you start. It can be reached either via this QR code, via the link on MINERVA or this weblink here: https://forms.office.com/e/aQXiJeGJcN

School of Physics & Astronomy	RISK ASSESSMENT RECORD
LOCATION:	Bragg Building, Room 4.08, 1st Year Physics Undergraduate Laboratory
DESCRIPTION OF ACTIVITY:	**Experiment 5: Inter-Atomic Forces in Copper**

SIGNIFICANT HAZARDS	**EXISTING CONTROL MEASURES**	**SEVERITY**	**LIKELIHOOD**	**RISK RATING**
		1 = minor, 2 = serious, 3 = major		
Strong Magnets	Take care when replacing the magnetic keepers to prevent trapping fingers/skin. Ask staff if you are unsure about doing this yourself.	1	2	2
Magnetic Fields	**Students with pacemakers and/or prosthetic implants should make this fact known to the laboratory convener before they start any lab work on this experiment.** Maximum 0.5mT and 1.0mT lines are indicated near each apparatus. The maximum static magnetic field generates is less than 25mT	1	2	2
Bars/coils become warm with use	After prolonged use, handle bars by their suspension thread only.	1	2	2
Electrical equipment	All equipment to have an up-to-date PAT test sticker. No such instrument should have its fuse or plug tampered with. If an item appears to be faulty, consult the Laboratory Technician.	1	1	1

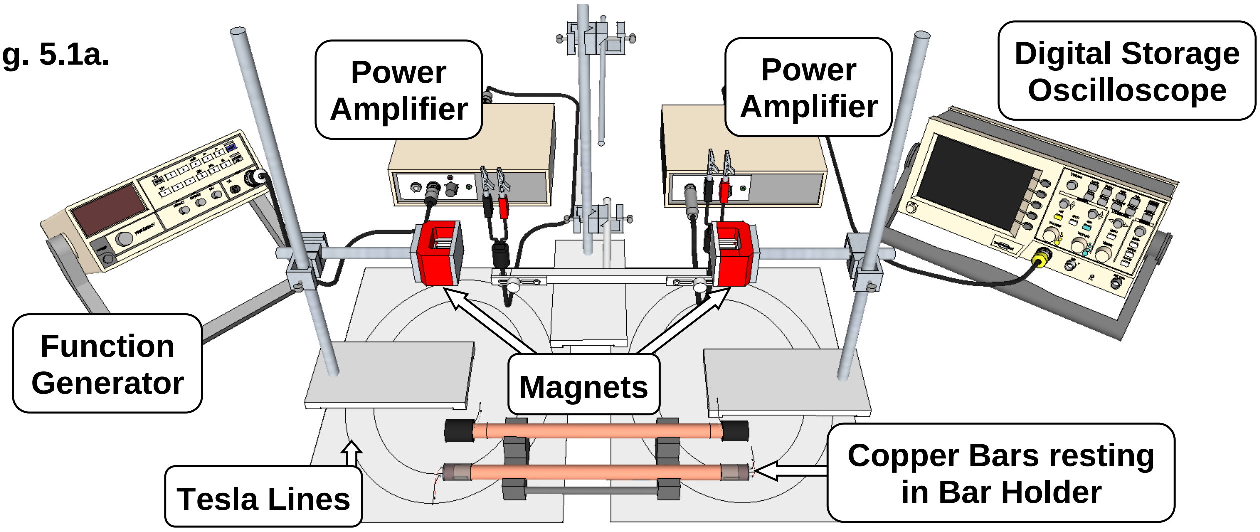
PEOPLE AT RISK	**ADVERSE EFFECTS**	**ACTIONS TO BE TAKEN & TIMESCALES**	**REFERENCES**
All students, demonstra-tors and staff members	Magnetic Fields	Students with pacemakers and/or prosthetic implants should make this fact known to the Lab Convener before they start any work on this experiment	Magnetic Fields: NRPB Document "Advice on Limiting Exposure to Electromagnetic Fields (0-300GHz) Volume 15 No. 2 2004 states in item 100 that restricting the time-weighted average magnetic flux density from static magnetic fields to 40mT for whole-body exposure is appropriate for the general public
	Trapped fingers	Take care when replacing the magnetic keepers.	
	Electrical shock	If an electrical item appears to be faulty, consult the laboratory technician.	

	Name	**Signature**	**Date**
ASSESSED BY:	Angela Beddows (Technician)	Angela Beddows	27/07/2022
GROUP HEAD:	Dr Peter Hine (Laboratory Convener)	P. J. Hine	27/07/2022
SAFETY SUPERVISOR:	Stuart Weston (Department Safety Officer)	S Weston	27/07/2022

Experimental Apparatus

In this experiment you will be finding and measuring the resonance peaks of two copper bars and using the results to find out properties of the material.

Fig. 5.1a.

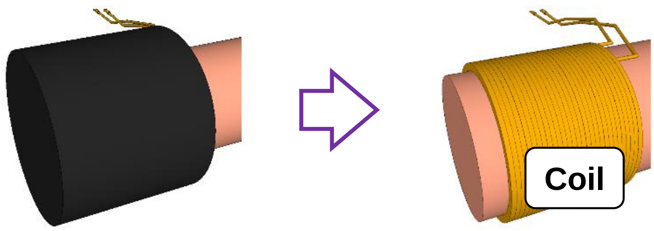


A **Function Generator** providing an alternating current is connected to an **Amplifier** which amplifies the signal to the coil in one end of the **copper bar** under investigation which has been suspended from a rod between the pole pieces of a permanent **magnet**. The magnetic field created by the current will try to align itself with the field of the permanent magnet thus applying a force to the bar. A similar coil and magnet at the other end of the bar acts as a detector. The e.m.f. generated by the flux change as the coil oscillates will be picked up and amplified by second **Amplifier** and then displayed on a **Digital Storage Oscilloscope**. There are two pieces of laminated paper showing the **Tesla Lines** of the magnets for health and safety reasons (see the Risk Assessment). When the bars are not in use they are placed on the **bar holder** to reduce damage to the coils. There are two types of **bar**, one with **circular coils** and one with **rectangular coils** (see figures 5.1b & c below). More detailed information on the apparatus and how to set it up is covered later in this script.

A close up of one end of each bar:

Fig 5.1b: **Bending mode bar: Circular coil**

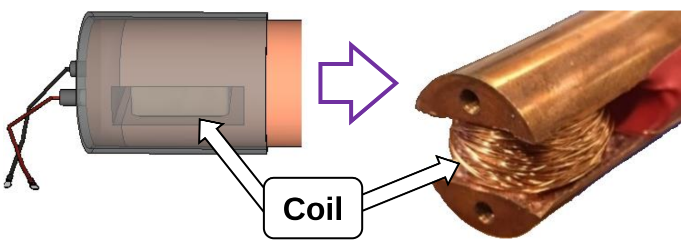
Circular coil covered in protective black plastic



How the Circular coil looks under the protective plastic

Figs. 5.1c: **Torsion mode bar: Rectangular coil**

Rectangular coil covered in protective clear plastic. You can see the coil here.



How the Rectangular coil looks under the plastic (during construction it is wound on a rectangular armature which is part of the bar)

Introduction and Background Theory

The elastic deformation of solid material to applied static or dynamic stress is of obvious importance to engineers. Such deformations clearly depend on the strength of the forces between neighbouring atoms and this experiment enables you to deduce the inter-atomic forces in copper. There are 3 main elastic moduli for bulk solids, these are:

1) Changes in length as a result of compressional or tensional forces **Young's Modulus** ($\boldsymbol{Y}$) = $\dfrac{\text{applied stress}}{\text{strain}} = \dfrac{\text{applied force / unit area}}{\text{fractional change in length}}$
2) Angular deformation as a result of shear forces. This is defined as the angular deformation of each cubic element in the sample as a result of the shear forces applied to it. **Shear Modulus** (or Rigidity Modulus) ($\boldsymbol{S}$) = $\dfrac{\text{applied shear stress}}{\text{angular deformation}}$
3) Change in volumes as a result of change in pressure. **Bulk Modulus** ($\boldsymbol{B}$) = **-** $\dfrac{\text{change in pressure}}{\text{fractional change in volume}}$

The three moduli are not independent but are related by the formula:

$$\frac{1}{B} = \frac{9}{Y} - \frac{3}{S} \qquad \text{equation (5.1)}$$

However, equation (5.1) is extremely sensitive to small changes in Y or S. Therefore, it is better to compare your results to those obtained by calculating B from one modulus

$$B = \frac{Y}{3(1-2\sigma)} \qquad \text{equation (5.1a)}$$

or

$$B = \frac{2S(1+\sigma)}{3(1-2\sigma)} \qquad \text{equation (5.1b)}$$

Where σ is known as Poisson's ratio which is **0.343 for Copper**.

Equation (5.1a) is of course equivalent to equation (5.1) but you may get better answers using one modulus in equation (5.1a) compared to using equation (5.1).

Measurement of Moduli by dynamic methods

In general, the strains are very small (fraction of 1%) and difficult to measure by the application of static stresses. However, solids having elastic resistance to a change in shape will transmit **transverse waves** (torsional and bending) and also longitudinal waves (compression waves). The velocity, v, of such waves is given by:

$$v = \sqrt{\frac{\text{appropriate elastic modulus}}{\text{density}}}$$

so that the different elastic moduli could be found by measuring the velocity of different types of deformation.

Thus, for example, as show in in equation (5.2) a torsional impulse will travel along a Copper bar of density ρ and Shear modulus S with a velocity, v

$$v = \left(\frac{S}{\rho}\right)^{\frac{1}{2}} \qquad \text{equation (5.2)}$$

On reaching the free end the impulse will be reflected back towards the initiating end where it is again reflected resulting in standing waves. If repeated torsional impulses are applied with just the right frequency the amplitude of the torsional oscillation will increase and a **resonant** condition will result, causing much larger deformations than for impulses applied at a different frequency (e.g. sound vibrations of an organ pipe which is open at both ends). Drawing a graph of amplitude (motion) of the bar against frequency as it increases it would look something like figure 5.2 below. As the drive frequency increases at some point around the resonant frequencies, we will get an increase in the amplitude. As we go up in frequency from the fundamental resonance it will decrease and then increase again around another harmonic resonance frequency.

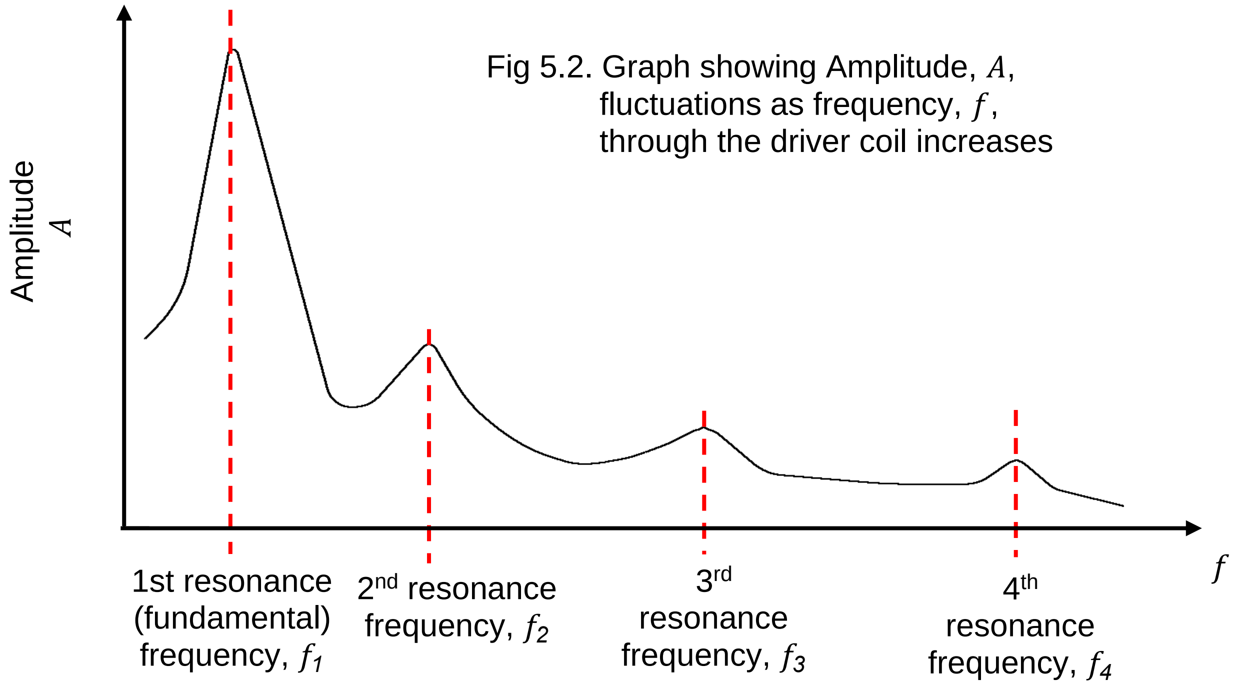


Fig 5.2. Graph showing Amplitude, A, fluctuations as frequency, f, through the driver coil increases

The amplitude decreases as you go up in frequency due to the relationship: $P \propto A^2 f^2$

Where: P = Power;
A = Amplitude (in this case half the peak-to-peak voltage on the oscilloscope V_{pp});
f = frequency

The power remains the same so as f increases then A must decrease. This makes the high frequency peaks harder to detect, so it helps if we can predict where they may lie by finding and using the Fundamental frequency, f_1, and relevant equations given in this manuscript for each type of bar.

The Bending Bar

Whilst the analysis for the bending resonant frequency modes is more complicated than for the torsional modes, since the free ends are not antinodes (see figure 5.3 below), it is easier to locate resonant frequencies whilst undertaking the experiment, which is why these are found first. Once you know what resonance looks like you can apply that knowledge to find the Torsional Bar resonant frequencies which are more difficult to spot. The lowest (fundamental) frequency ($n = 1$) for a solid bar in bending mode of length L and radius a will be as shown in figure 5.3:

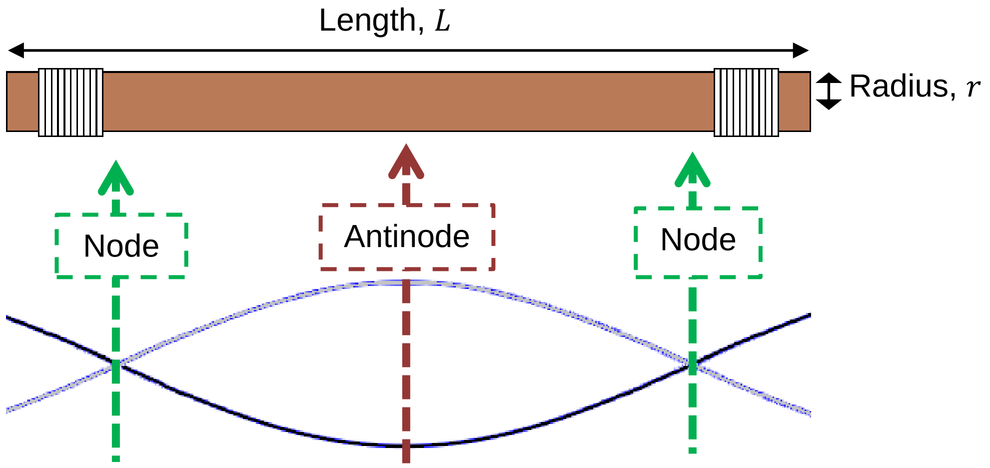


Fig 5.3

The relationship between the resonance peaks and Young's modulus, Y, for the bending bar can be shown by the following equation:

$$f_n = \frac{\pi r}{16L^2} \cdot (2n+1)^2 \cdot \left(\frac{Y}{\rho}\right)^{\frac{1}{2}} \qquad \text{equation (5.3)}$$

where:
f_n = frequency of harmonic, n
n = resonant harmonic = 1, 2, 3 etc.
ρ = density of Copper in kilogrammes per metre cubed
r = radius of bar in metres
L = length of bar in metres
Y = Youngs modulus

It follows from the equations above that if the fundamental resonance of a bar is known, then the other resonances may be easily estimated.

For example for f_2 in relation to f_1 is

$$\frac{f_1}{f_2} = \frac{9\cancel{\frac{\pi r}{16L^2}\left(\frac{Y}{\rho}\right)^{\frac{1}{2}}}}{25\cancel{\frac{\pi r}{16L^2}\left(\frac{Y}{\rho}\right)^{\frac{1}{2}}}}$$

As n = 1

As n = 2

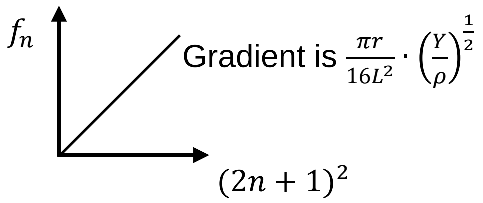
which yields:

$$f_2 = \frac{25}{9} f_1$$

and using the same method to predict f_3 and f_4 and so on.

Determining Young's Modulus, Y:

Use values of f_n from measurements, plot a graph of f_n versus $(2n+1)^2$ and find the gradient.



Use the gradient to find a value for Young's Modulus Y by rearranging equation (5.3) to give:

$$Y = \left(\frac{Gradient.16L^2}{\pi r}\right)^2 . \rho \qquad \text{equation (5.4)}$$

where:

Y = Youngs modulus in Pascals
r = radius of bar in metres
L = length of bar in metres
ρ = density of copper in kilogrammes per metre cubed

Calculating a value of the Bulk Modulus for the Bending Bar, B_1:
Using this calculated value for Young's Modulus Y and equation (5.1a) the Bulk Modulus, B_1 can be calculated.

The Torsional Bar

The lowest (fundamental) frequency ($n = 1$) for torsional oscillations in a bar of length L which is free at both ends as shown in figure 5.4.

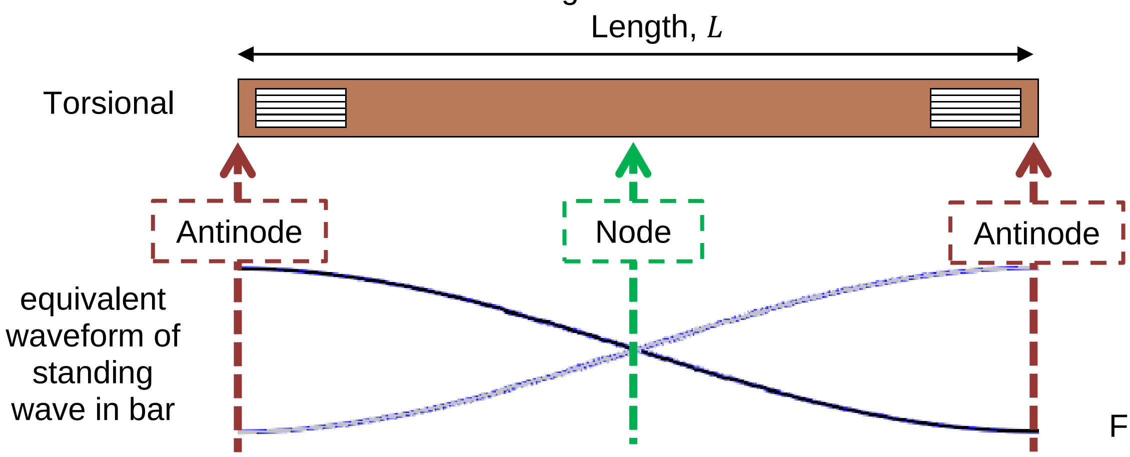


Fig 5.4

The largest resonant wavelength will be for $\lambda_1 = 2L$ and hence the corresponding lowest (or fundamental) frequency of wavelength λ travelling at velocity v will be:

$$f_1 = \frac{v}{\lambda_1} = \frac{1}{2L}\left(\frac{S}{\rho}\right)^{\frac{1}{2}}$$

and higher harmonics for the **torsion mode** will occur at frequencies:

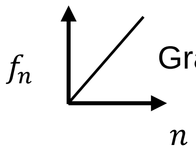
$$f_n = \frac{n}{2L}\left(\frac{S}{\rho}\right)^{\frac{1}{2}} \qquad \text{equation (5.5)}$$

where:
n = resonant harmonic = 1, 2, 3 etc.
L = length of bar in metres
S = shear modulus of copper in Pascals
ρ = density of Copper in kilogrammes per metre cubed

It follows from the equation above that if the fundamental resonance of a bar is known, then the other resonances may be easily estimated like with the Bending Bar but using equation (5.5) instead.

Calculating the Shear Modulus, S:

Using values of f_n from measurements, plot a graph of f_n versus n and find the gradient.



Gradient is $\frac{\left(\frac{S}{\rho}\right)^{\frac{1}{2}}}{2L}$

Use the gradient to find a value for the Shear Modulus S by rearranging equation (5.5) to give:

$$S = (2L.gradient)^2.\rho \qquad \text{equation (5.6)}$$

where:
S = Shear modulus of copper
L = length of bar in metres
ρ = density of bar in kilogrammes per metre cubed

Calculating a value of the Bulk Modulus for the Torsional Bar, B_2:

Using the calculated value for the Shear Modulus S and equation (5.1b), the Bulk Modulus, B_2 can be calculated.

Calculation of the inter atomic forces:

Spring Constant:

We know from X-ray diffraction that in a Copper crystal, the Cu atoms form the face-centred cubic lattice (find a picture of this lattice type in Tipler) with the distance along the cube edge for Copper being, a = 3.61Å, (1Å is called an Angstrom and is equal to 10^{-10}m). Longitudinal sound waves typically have a wavelength ~2a. This is related to the Spring Constant, k, by

$$k = \frac{aB\pi^2}{4} \qquad \text{equation (5.7)}$$

Where:
k = Spring Constant in Newtons per metre
a = 3.61Å = 3.61 x 10^{-10} m
B = Bulk Modulus in Pascals, which in this instance is the average value of the two Bulk Moduli you calculated.

The Spring Constant of Copper can be calculated using these values.

Melting Point of Copper:

The Lindemann criterion says that a solid will melt when the amplitude of the atomic motion is ~5% of the interatomic separation. The melting point is related to the Spring Constant by:

$$k_B T_m \approx \frac{1}{2} k x^2 \text{ which can be rearranged to: } T_m = \frac{kx^2}{2k_B} \qquad \text{equation (5.8)}$$

Where:
T_m = Melting point of Copper in Kelvin
k = Spring Constant in Newtons per metre
x = 5% of 3.61 x 10^{-10}m according to the Lindemann criterion = 1.805 x 10^{-11}m
k_B = Boltzmann Constant = 1.38 x 10^{-23} $m^2kgs^{-2}K^{-1}$

Using these values and the calculated value of the Spring Constant, the melting point of copper can be estimated. How does this estimate compare with the known melting point of Copper?

Experimental Procedure

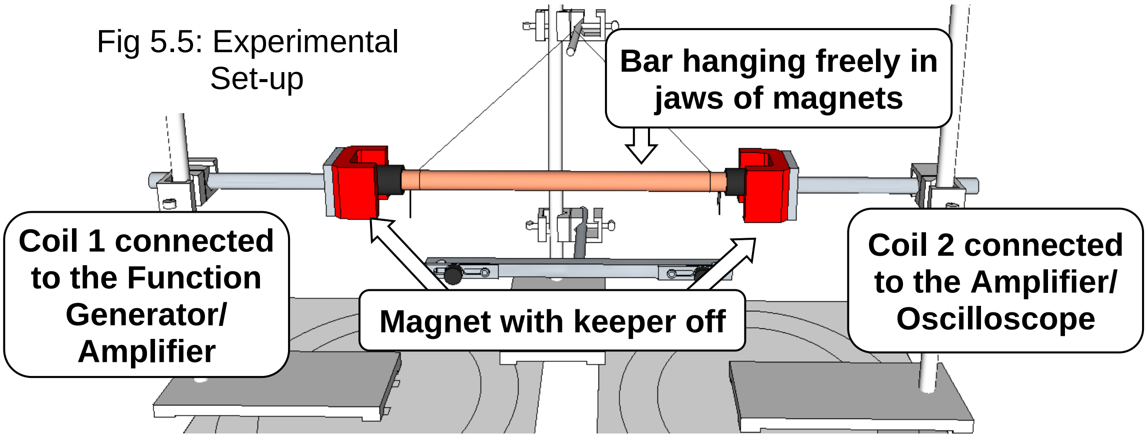
Before you start, please take note that the coils on the end of the bars are reasonably fragile so please handle them with care. They are very time consuming for the Technician to make so a bar holder is supplied to keep the bars off the desk which should minimise damage.

The same experimental setup is used for both bars.

1) Remove the keepers from the magnets before hanging the bar by **sliding** them off. **Do this carefully so as to avoid hand injury**. If you are having difficulty in removing the plates then ask the Lab staff.

2) Carefully pick up the bar and suspend it by the string on the bar provided and make sure it is **horizontal** (as well as you can) as indicated in like figure 5.5 below. Clip the four solder lugs that are on the ends of the leads on the bar into the small crocodile clips provided. It doesn't matter which way round the bar goes. Adjust the magnets positions and bar position so that the bar hangs freely just inside the jaws of the magnets so that it is free to perform oscillations. It should now look something like this:

Fig 5.5: Experimental Set-up



The Bar must **not** touch the magnets when under resonance. If it does touch the magnets then this will skew your readings.

3) Switch on the apparatus and set the Function Generator to the starting frequency for whichever bar you start with as indicated in each Procedure on the next two pages. When you have set it to the desired frequency, press the OUTPUT ON key and check that the LED above it is lit up. (This means you have a driver frequency going to the coil on the bar and you can start finding resonant frequencies).

4) When taking a measurement, find the first resonance frequency by adjusting the settings on the Function Generator and watching the Channel 1 trace. When you are close to the resonance frequency the amplitude should increase markedly. Once found, you can fine tune it. When you have found a resonant frequency, record the reading off of the Function Generator display. Using the correct equation for the bar calculate where the subsequent resonant frequencies can be found and search around those ranges, each time recording the value of the found resonant frequency from what is displayed on the Function Generator.

   When searching for the resonant frequency, first search for it in the tens of units range and then in single digits. It will be easier to spot this way. You will need to find at least 4 resonant frequencies for each bar.

5) When finished, disconnect the bar and place it back safely in its holder. Please remember to handle it by the string as the bar/coils will have become warm during the experiment as it has been twisting in the magnetic field.

Bending Mode Resonance

In the Bending mode with Circular Coils, figures 5.6a & 5.6b, current flowing through coil 1 produces a magnetic field which tends to align itself with that of the magnet thus producing a lateral bending of the bar.

Fig. 5.6a View from **above** of the bending mode bar.

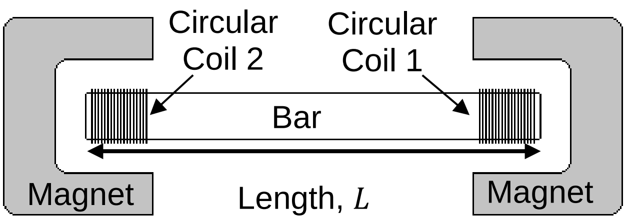
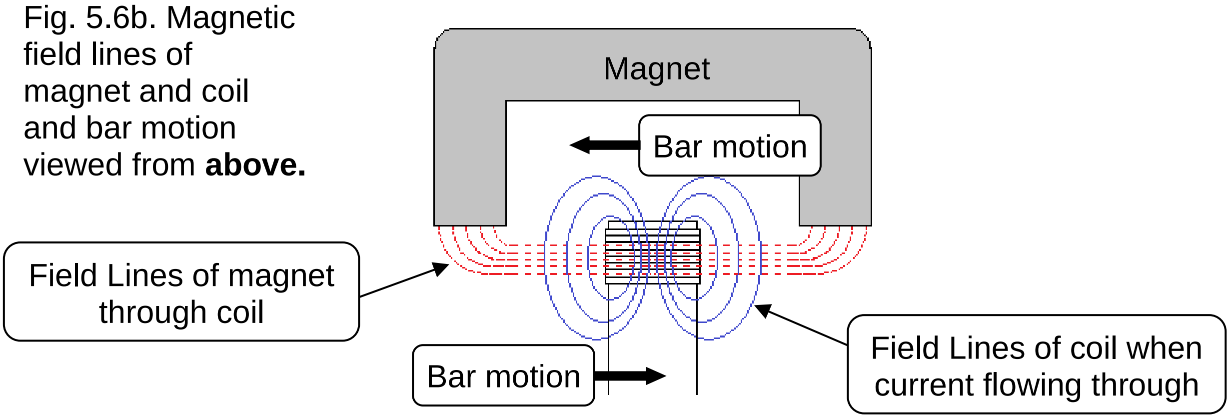


Fig. 5.6b. Magnetic field lines of magnet and coil and bar motion viewed from **above.**



Task 1: Bending Mode Procedure

1.1) Using the Bending bar and the experimental procedure shown on the previous pages on how to set up the apparatus, determine the fundamental resonance frequency which for this bar can be found between 500Hz and 600Hz, starting with the lower value.

1.2) Use equation (5.3) to calculate and predict where three additional resonant frequencies may be found between the range 600Hz to 10kHz. Use the apparatus to measure these 3 further resonant frequencies.

1.3) Repeat the previous steps of Task 1 a further 4 times so you have **5 values for each resonant frequency with their associated uncertainties**. Record each one and their associated uncertainties in your Lab Notebook. Calculate the average (with its uncertainty) for each of the resonant frequencies of f_n from your results.

1.4) Using your values of f_n of plot a graph of f_n versus $(2n+1)^2$ and find the gradient. Use the gradient to find a value for **Young's Modulus** Y and its uncertainty by using equation (5.4).

1.5) Using your calculated value for Young's Modulus Y and equation (5.1a) to calculate the **Bulk Modulus**, B_1.

Torsional Mode Resonance

In the torsional mode with Rectangular Coils, Fig. 5.7a & 5.7b below, current flowing through coil 1 produces a magnetic field which tries to align itself with that of the permanent magnet thus producing a torsional bending of the bar.

Fig. 5.7a. View from **above** of the torsional mode bar.

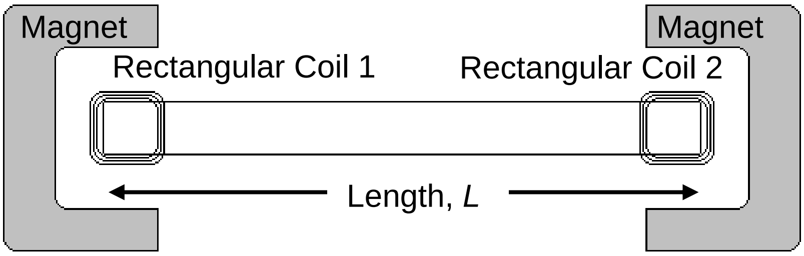
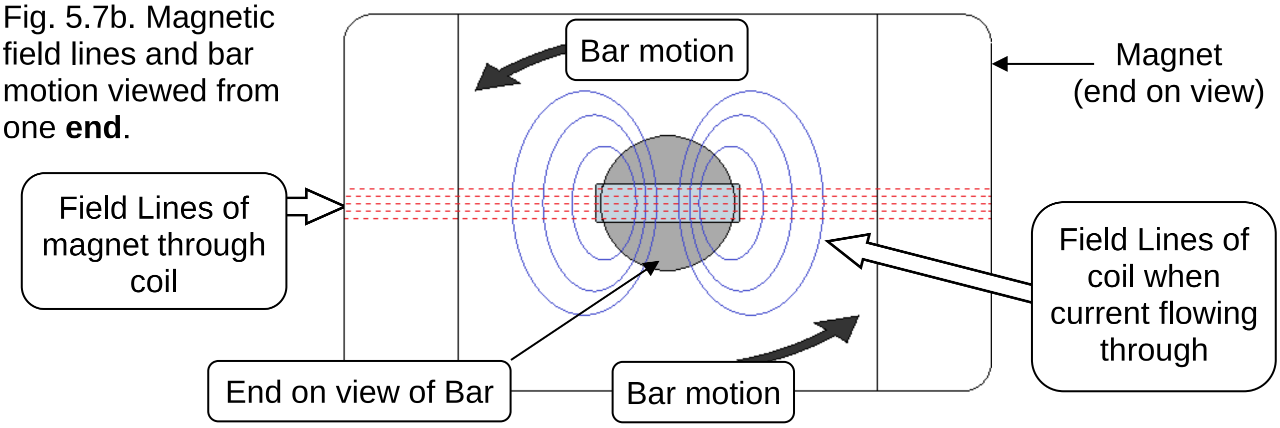


Fig. 5.7b. Magnetic field lines and bar motion viewed from one **end**.



Task 2: Torsional Mode Procedure

2.1) Using the Torsional bar and the experimental procedure shown on the previous pages on how to set up the apparatus, determine the fundamental resonance frequency of the bar, which can be found between 3.5kHz and 3.8kHz, starting with the lower value. **Make sure you hang this bar with the coils in the correct orientation**, as indicated in figure 5.6a and 5.6b otherwise your experiment will not work. (i.e. viewed from above the coils **must** be horizontal).

2.2) Use equation (5.5) to calculate and predict where three other resonant frequencies may be found between the range 3.7kHz to 18kHz.

2.3) Then use the apparatus to measure these 3 further resonant frequencies. The resonances for this bar can be quite narrow so that it is possible to miss them if you alter the frequency too rapidly.

2.4) Repeat steps 2.1 & 2.3 a further 4 times so you have **5 values for each resonant frequency with their associated uncertainties**. Calculate the average (with its uncertainty) for each of the resonant frequencies of f_n from your results.

2.5) Using your results and equation (5.6) deduce the value of the **Shear Modulus**, S, for Copper and estimate the uncertainty of your result.

2.6) Using equation (5.1b) calculate the **Bulk Modulus,** B_2, and its uncertainty. Poisson's ratio, σ, for copper is given as 0.343.

2.7) Using the average of your two values for the Bulk Modulus (B_1 and B_2) and equation (5.7) calculate the **Spring Constant**, k, for Copper.

2.8) Using your calculated value for the Spring Constant and the given values and equation (5.8) estimate the value of the **melting point**, T_m, of Copper and compare this to the known value.

What to include in your Lab Notebook

Bending mode:

1) A short Introduction with the Experimental Aims, including the expected target values and references. For some known quantities you may find a range of values,. If so, you should quote this range.
2) A short method section explaining what you did, also include labelled schematic diagrams of the apparatus.
3) Any key physics equations you used during the analysis including the uncertainty analysis.
4) Collect and tabulate data for the four resonant frequencies f_n with their associated uncertainties.
5) Calculate a mean frequency f_n (with it associated uncertainty) from your set of results for each resonant frequency mode.
6) Look up and record a value for the density of Copper. Record the values of the bar length given in the lab and measure and record the bar radius with its uncertainty.
7) Plot a graph of f_n versus $(2n+1)^2$ and find the gradient. Use the gradient to find a value for Young's Modulus Y and its uncertainty by using equation (5.4).
8) Compare your value of $Y + \Delta Y$ with the expected value and comment.
9) Using your value of Y, calculate the Bulk Modulus of Copper (B_1) and its associated uncertainty using equation (5.1a).

Torsion mode:

10) A short Introduction with the Experimental Aims, including the expected target values and references. For some known quantities you may find a range of values. If so, you should quote this range.
11) A short method section explaining what you did but it's not necessary to repeat detail covered in your Bending Mode write up as only the bar & frequency settings changed.
12) Any key physics equations you used during the analysis including the uncertainty analysis.
13) Collect and tabulate data for the four resonant frequencies f_n.
14) Calculate a mean frequency f_n (with its uncertainty) from your set of results for each resonant frequency mode.
15) Using your values of f_n, plot a graph of f_n versus n and find the gradient. Use the value of the gradient and equation (5.6) to calculate a value for the Shear Modulus, S, and its uncertainty.
16) Compare your value of $S + \Delta S$ with the expected value and comment.
17) Using your value of S, calculate the Bulk Modulus of Copper (B_2) and its associated uncertainty using equation (5.1b).

Calculation of the inter-atomic forces of Copper:

18) Create a table to show your 4 calculated values for Copper (Y, S, B_1 and B_2) and their associated uncertainties in comparison to the expected values (or range of values).
19) Using the average of your two values for the Bulk Modulus (B_1 and B_2) and equation (5.7) calculate the Spring Constant, k, for Copper.
20) Using your calculated value for the Spring Constant and equation (5.8) estimate the value of the melting point, T_m, of Copper and compare this to the known value.

To help form your conclusions, answer these questions:

- How do your results for Y, S, and B compare to the expected values when the uncertainties are taken into account?
- How did the two values of Bulk Modulus $B + \Delta B$ compare from the two deformation modes of bending and torsion?
- How does your value compare with the known Spring Constant, k, and melting point, T_m, of Copper?
- What is the best way to identify the uncertainties in the fundamental frequency?
- What are likely to be the largest sources of uncertainties?
- Any suggestions for improving the apparatus or the experimental method?

Experiment 6

Adiabatic and Isothermal Compression of Gases

Experimental Aims:

- To obtain an accurate value for the ratio of specific heats, γ

$$\gamma = \left[\frac{C_P}{C_V}\right]$$

  for both air and Argon (Ar).
- To demonstrate the difference between adiabatic and isothermal compressions and how to produce these changes for a fixed amount of gas.
- To measure the Spring Constant (k) for Cu and estimate the melting point (T_m) of Cu.

Learning Objectives:

- To learn how to use computer data collection software.
- To gain experience using MS Excel to analyse large data sets and plot graphs for selected regions of data.
- To be able to critically evaluate the results of an experiment; to compare measured results with expected values and comment on the agreement within uncertainties.
- To be able to evaluate the experiment and suggest plausible explanations for any differences between the measured and expected results.

VITALs

E1 b: Keep a detailed laboratory notebook
E1 d: Produce appropriate graphs or charts

Preparation:
You are expected to have done these things before you turn up to the lab session:

- **Watch the Online Supporting Video** (link is on Minerva) and become familiar with the experimental method and data analysis.
- Read this manuscript and become familiar with the physics behind this experiment.
- Derive a value for γ for isothermal compression (T constant) starting from the ideal gas law.
- Read sections 18.5, 18.6, 18.7, 18.8 and 18.9 in Tipler.
- Find out/calculate target values for γ for air (diatomic gas) and Ar (monotomic gas) – see Appendix 6.1 on page 119.
- Fill in the online Health & Safety form as described below.

Risk Assessment and Safety:
Read the Health and Safety information on the next page and fill in the online H&S form. The technician will check online that you have filled this in before you start. It can be reached either via this QR code, via the link on MINERVA or this weblink here: https://forms.office.com/e/G0NiRPzv9v

Appendices at the end of this script:
Appendix 6.1: Calculating γ for Adiabatic Processes (page 119)
Appendix 6.2: The volume of the thin ring of air between the base of the piston and the rubber seal.(page 119)

School of Physics & Astronomy	RISK ASSESSMENT RECORD
LOCATION:	Bragg Building, Room 4.08, 1st Year Physics Undergraduate Laboratory
DESCRIPTION OF ACTIVITY:	**Experiment 6: Adiabatic Expansion**

SIGNIFICANT HAZARDS	EXISTING CONTROL MEASURES	SEVERITY (1 = minor, 2 = serious, 3 = major)	LIKELIHOOD (1 = minor, 2 = serious, 3 = major)	RISK RATING
Argon (gaseous)	Argon is an asphyxiant. Do not breathe in the Argon gas provided in the balloon.	2	1	2
Heavy masses	Take care when handling the heavy masses. Keep feet from under the masses at all times.	2	1	2
Electrical equipment	All equipment to have an up-to-date PAT test sticker. No such instrument should have its fuse or plug tampered with. If an item appears to be faulty, consult the Laboratory Technician.	1	1	1

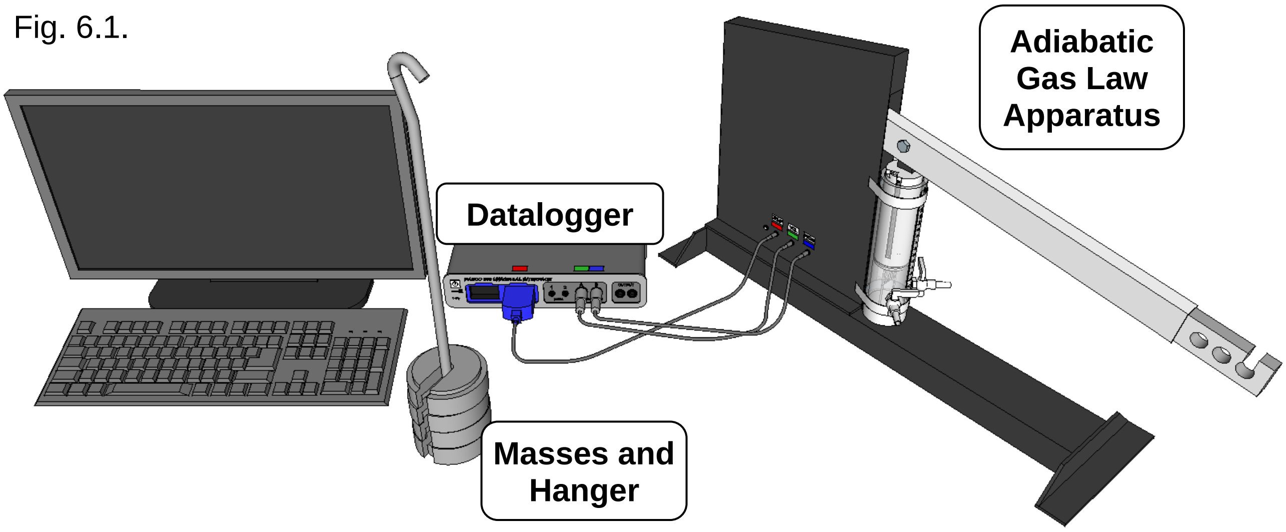
PEOPLE AT RISK	ADVERSE EFFECTS	ACTIONS TO BE TAKEN & TIMESCALES
All students, demonstrators and staff members	Lack of oxygen	Do not breathe in the Argon gas provided in the balloon.
	Injury	Take care when handling the heavy masses.
	Electrical shock	If an electrical item appears to be faulty, consult the laboratory Technician.

	Name	Signature	Date
ASSESSED BY:	Angela Beddows (Technician)	Angela Beddows	27/07/2022
GROUP HEAD:	Dr Peter Hine (Laboratory Convener)	P. J. Hine	27/07/2022
SAFETY SUPERVISOR:	Stuart Weston (Department Safety Officer)	SWeston	27/07/2022

Experimental Apparatus

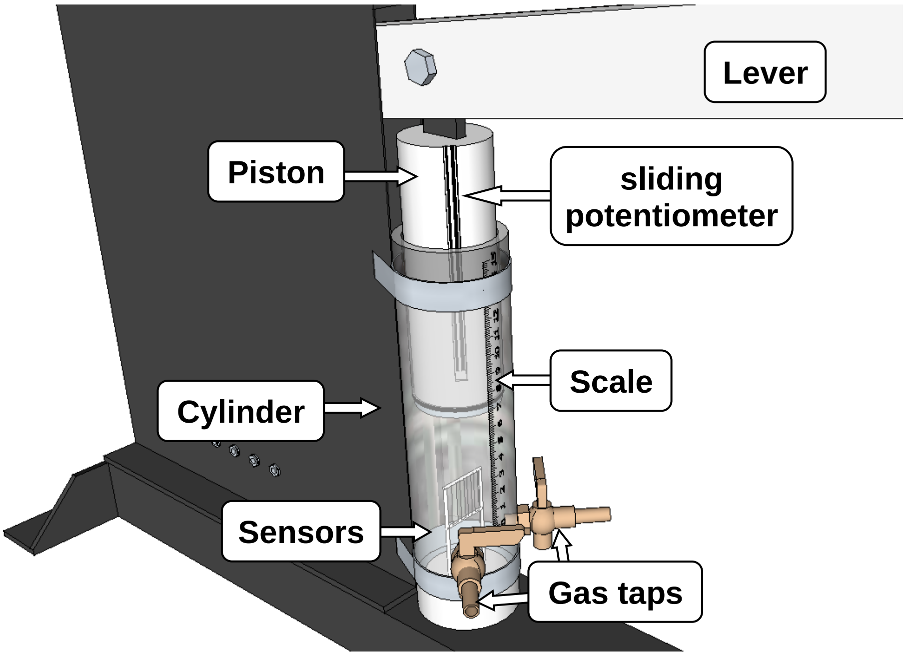
In this experiment, gas is compressed in a cylinder and sensors allow the chamber volume, pressure and temperature to be measured simultaneously using a Datalogger.

Fig. 6.1.



The **Adiabatic Gas Law Apparatus** is connected to a **Datalogger** which is connected a **PC**. Heavy **masses and their hanger** are used later in the experiment to hang off the arm of the Adiabatic Apparatus in order to compress the gas contained in the cylinder. A Balloon (not shown) with a rubber tube and valve attached is filled up with Argon (Ar) on request.

Fig. 6.2: Parts of the Adiabatic Apparatus



The Adiabatic Gas Law Apparatus comprises of a **Cylinder** containing a **Piston** and also a **Lever** to move piston. The fragile temperature and pressure **Sensors** sit inside the piston cylinder. Two **Gas Taps** allow the piston cylinder to be closed off when compressing the gas under investigation. Mounted on the side of the piston is a **Sliding Potentiometer** to measure its volume by the position of the piston along with the transparent millimetre **Scale**.

Introduction and Background Theory

An adiabatic process is defined as one where no heat enters or leaves the system, which is shown by the first law of thermodynamics as:

$$Q = \Delta U + W = 0 \qquad \text{equation (6.1)}$$

where Q, is the heat entering or leaving the system, ΔU is the change of internal energy and W work done (on or by) the system. Taking the work done as $P\Delta V$ where P is the Pressure and ΔV is the change in volumes and the change in internal energy as a product of the specific heat at constant volume (C_V) and the change in temperature (ΔT), the first law becomes

$$C_V \Delta T + P\Delta V = 0 \qquad \text{equation (6.2)}$$

For an ideal gas $PV = nRT$, which gives

$$C_V \Delta T + nRT\frac{\Delta V}{V} = 0 \qquad \text{equation (6.3)}$$

and rearranging yields

$$\frac{\Delta T}{T} + \frac{nR}{C_V}\frac{\Delta V}{V} = 0 \qquad \text{equation (6.4)}$$

Noting that $C_P - C_V = nR$, equation (6.4) can be rewritten as

$$\frac{\Delta T}{T} + \frac{(C_P - C_V)}{C_V}\frac{\Delta V}{V} = 0 \qquad \text{equation (6.5)}$$

Taking $\frac{(C_P - C_V)}{C_V} = \frac{C_P}{C_V} - 1 = \gamma - 1$, where g is the ratio of the specific heat capacities, gives:

$$\frac{\Delta T}{T} + (\gamma - 1)\frac{\Delta V}{V} = 0 \qquad \text{equation (6.6)}$$

Integrating gives $\ln(T) + (\gamma - 1)\ln(V) =$ constant equation (6.7)

Rearrangement yields $\ln\left(TV^{(\gamma-1)}\right) =$ constant equation (6.8)

Or $TV^{(\gamma-1)} =$ constant equation (6.9)

Substituting the ideal gas law into equation (6.9) gives

$$\frac{PV}{nR}V^{(\gamma-1)} = \text{constant} \qquad \text{equation (6.10)}$$

which can be written as

$$PV^{(\gamma)} = \text{constant} \qquad \text{equation (6.11)}$$

Equation (6.11) holds for an ideal gas and an ideal adiabatic process from state 1 to state 2.

$$P_1V_1^{(\gamma)} = P_2V_2^{(\gamma)} \qquad \text{equation (6.12)}$$

Experimental Procedure

Task 1: Calibration of the Cylinder Volume

1.1) Log in to the PC and load the PASCO Capstone software. Click on the **Hardware Setup** on the Tools bar and it should show the datalogger connected.

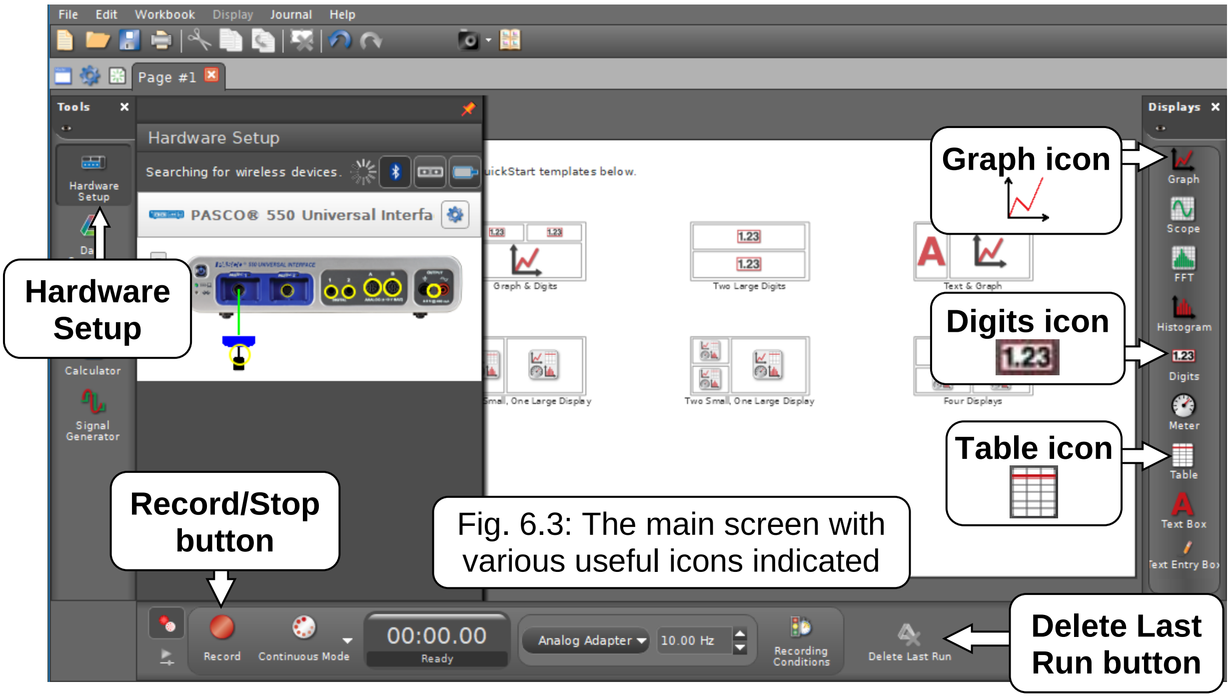


Fig. 6.3: The main screen with various useful icons indicated

1.2) Before carrying out any compression experiments, the Cylinder volume is to be calibrated. This is done by a Sliding Potentiometer which is attached to the side of the Cylinder. It measures the position, x, of the Piston and hence the cylinder volume (C) as shown in figure 6.4 below.

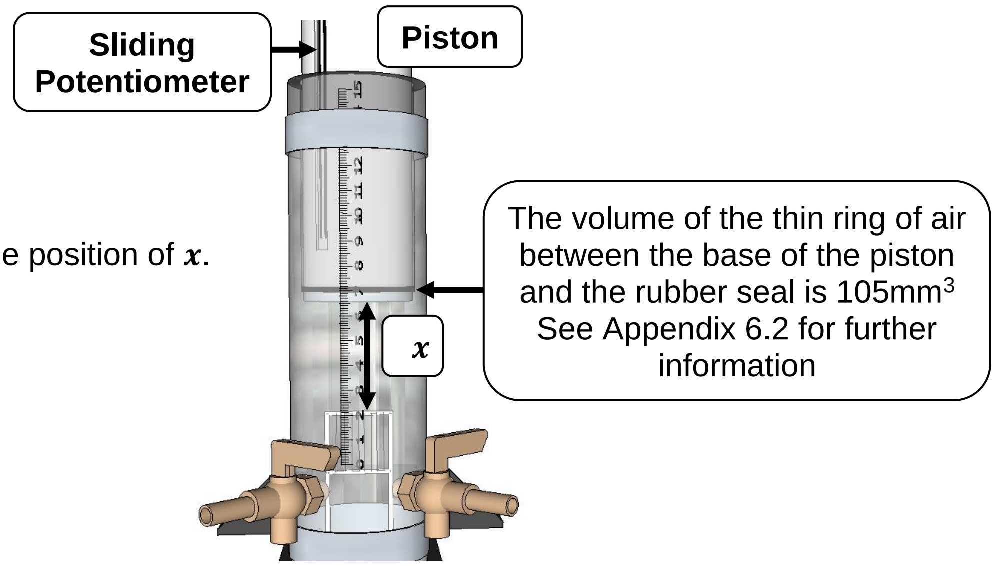


Fig. 6.4: the position of x.

The sensor for this is connected to Channel A and to calibrate the cylinder you will use the Datalogger as a voltmeter. Click on the yellow circle highlighting Channel A on the image of the Datalogger in the Hardware Setup screen. It will produce a menu, scroll down and select **Voltage Sensor** as shown in figure 6.5a below, it should then show as in figure 6.5b. Then click on Hardware Setup again to minimise the setup window.

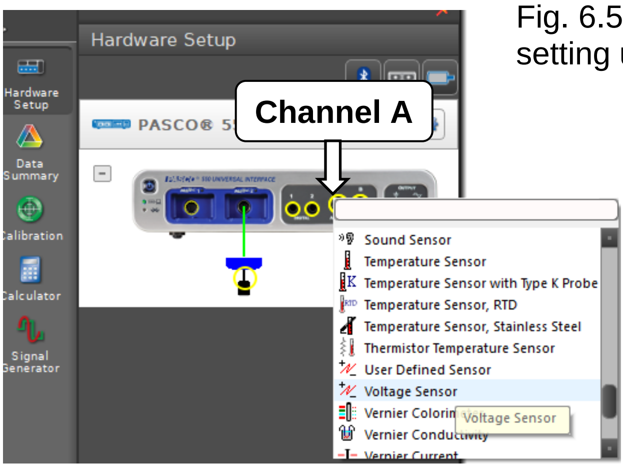
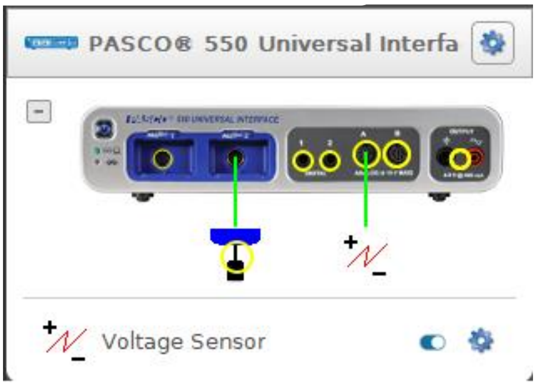


Fig. 6.5a and 6.5b:
setting up a channel



1.3) Click on the **Digits** icon (as shown in figure 6.3) and drag and drop it on to the main screen to bring up the digits display, click on **<select measurement>** and select **Voltage (V)**.

1.4) Press **Record** (as shown in figure 6.3) and this will show a live reading of the voltage. It will vary as the lever is adjusted. If it does not, then tell the Demonstrator or Technician. Open one Gas Tap and whilst moving the Lever, vary the piston position and take measurements of Voltage vs. piston position (x) in ~1cm intervals between 14cm and 6cm and record these in your lab book along with their uncertainties. **At each position** close the Gas Taps so the Lever doesn't move whilst you are taking a reading. **Read the measurement x from where the rubber seal on the Piston touches the Cylinder.**

1.5) Using MS Excel or Origin, plot a graph of x versus Voltage to determine the value of the best fit coefficients a and b in the following equation.

$$x = \alpha \times \text{Voltage} + \beta \qquad \text{equation (6.13)}$$

A calibration equation for the cylinder volume V (in cm^3) can then be determined as:

$$V = \pi r^2 x = \frac{\pi}{4} d^2 (\alpha \times \text{Voltage} + \beta) \qquad \text{equation (6.14)}$$

where d represents the Cylinder Internal Diameter (CID) which can be found on the front of the Adiabatic Apparatus. When you have completed this task, click on the STOP button (which is where the **Record Button** was).

The uncertainty equations for these values are:

$$\Delta V = \frac{\pi d^2}{4}\sqrt{\Delta A^2 + \Delta\beta^2} \qquad \text{and} \qquad \frac{\Delta A}{A} = \sqrt{\left(\frac{\Delta\alpha}{\alpha}\right)^2 + \left(\frac{\Delta V}{V}\right)^2} \qquad \text{where} \qquad A = \alpha V$$

Task 2: Air - Adiabatic Compression - Fast

The first compression experiment to be carried out is a fast (adiabatic) compression of air.

2.1) First you need to add the 2 remaining sensors to the Datalogger (as you have already added the Volume sensor to Channel A). Do the same for the **Temperature Channel** and the **Pressure Channel B** by clicking on them like before so their menus appear and select Voltage Sensor from the list for both channels. It should then look like figure 6.7b. Then click on Hardware Setup again to minimise the setup window. (If the software doesn't detect the sensors you may have to restart the software with all 3 connected. If you do so, the calibration will be unaffected).

2.2) On the Displays menu on the right hand side click and drag the Graph icon (as shown in figure 6.3) to open up a graph. Click on **<Select Measurement>** on the Y-axis and select the first channel **Voltage Sensor Ch P2 (V)** so the graph then shows that channel (Temperature) versus Time on the X-axis. Then click on the **Add New Plot Area** icon twice (as shown in figure 6.6 below) to add the other two channels. Click on <Select Measurement> for the middle graph and select **Voltage Ch A (V)** for the Volume and similarly for the bottom graph click on <Select Measurement> and **select Voltage Ch B (V)** for the Pressure.

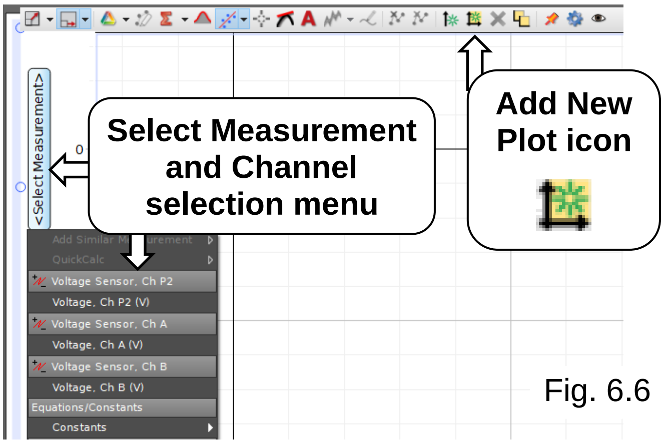
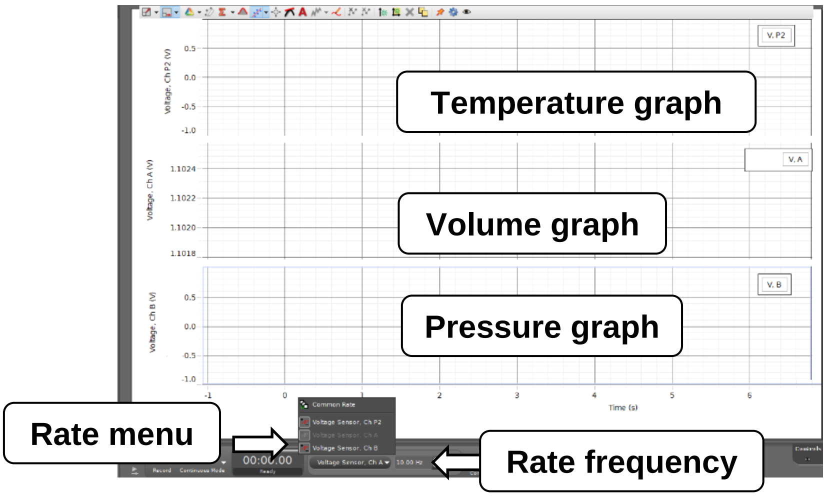


Fig. 6.6

2.3) The screen should then look something like figure 6.7 below. Set each channel to log at the same rate by clicking on the **Rate menu** as shown in figure 6.7 below and select **Common Rate**. Then set the **Rate Frequency** to 200Hz.

Fig. 6.7



2.4) You also need to bring up the data in Table form. Go to the **Displays** menu on the right click and drag the **Table** icon (as shown in figure 6.3) across to reduce the size of the graph so the Data Table can fit. Click on **<Select Measurement>** for the first column and change that to **Time**. Then add two more columns by clicking on the **Insert Column** icon twice as shown in figure 6.8 below. Select and change the second column to the **Temperature** Channel, the third column to the **Volume** channel and the fourth column to the **Pressure** Channel. Now you can see the absolute values as well as seeing them on the graph.

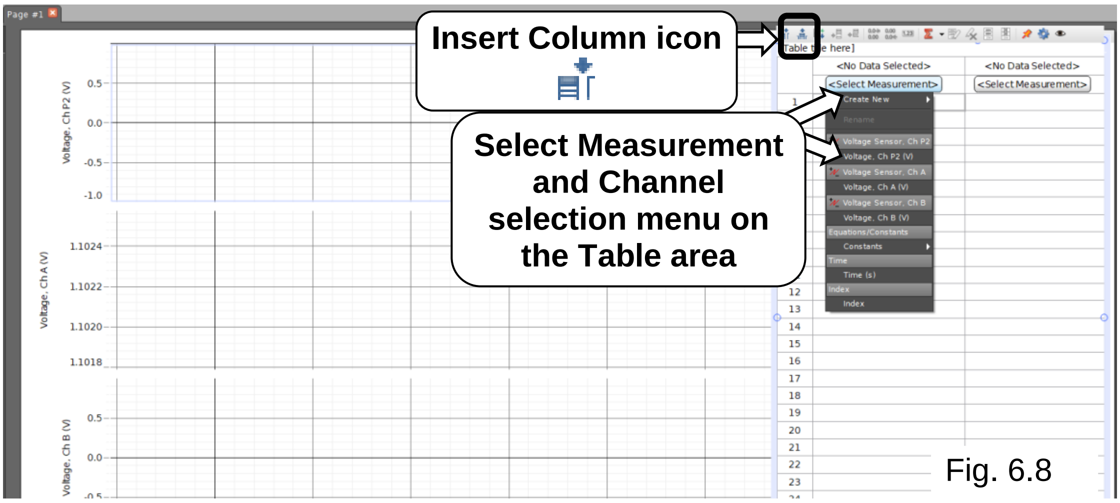


Fig. 6.8

2.5) The equipment should now be ready to record data. First check that the **Lever** is all the way up and that **you have both gas taps CLOSED.** If they aren't closed then this may result in damaging the apparatus when you push the lever for this measurement.

2.6) When you are ready to take the data, press the **Record** button. Then compress the gas in the piston as **quickly** as possible by pushing down on the Lever. Press the **Stop** button to stop data collection.

There should now be a full set of data in the table and 3 completed graphs. To copy the data into MS Excel, click on one of the cells of the Table, then press CTRL+A then press CTRL+C to copy it, then paste it into an MS Excel spreadsheet using CTRL+V. If you want a copy of the graphs on the screen, on the menu bar at the top, press **Display** which should drop a menu down and click on 'Copy Display'. Then you can paste this into your spreadsheet. Then save your spreadsheet.

2.7) Now you have your data, use the two calibration equations given on the front of the Adiabatic Apparatus for Temperature and Pressure, plus the Volume equation determined in the first part of the experiment to compile a **table** for Temperature, Volume and Pressure as shown below.

Time (s)	Temperature (K)	Volume (cm^3)	Pressure (kPa)	$\frac{PV}{T}$

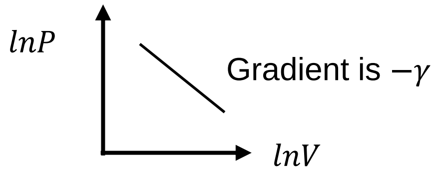
2.8) In the final column calculate $\frac{PV}{T}$ to see how well the results fit the perfect gas law.

Comment on the results

2.9) Taking natural logs from equation (6.11) gives:

$$lnP = -\gamma \; lnV + c \qquad \text{equation (6.15)}$$

Plot a graph of lnP (Pressure) vs. lnV (Volume) using MS Excel or Origin and determine γ from the gradient of the line of best fit.



Task 3: Air – Isothermal

To further reinforce this point, carry out an isothermal test where the temperature is allowed to return to its original value after each small compression step.

CAUTION: Be careful when handling the masses. Do NOT drop the masses on your foot!

3.1) Firstly, click on **Delete Last Run** to clear the data from Task 2. Also reduce the Rate Frequency to 2Hz. Then raise the Lever to its highest position and again **<u>close</u> both gas taps**. Move the Adiabatic Gas Law Apparatus so the Lever overhangs the bench (and the base <u>doesn't</u>). **Press Record** and attach the Mass Hanger without any masses on it to the end of Lever (the mass hanger itself weighs 1kg). It should now look like figure 6.9 below

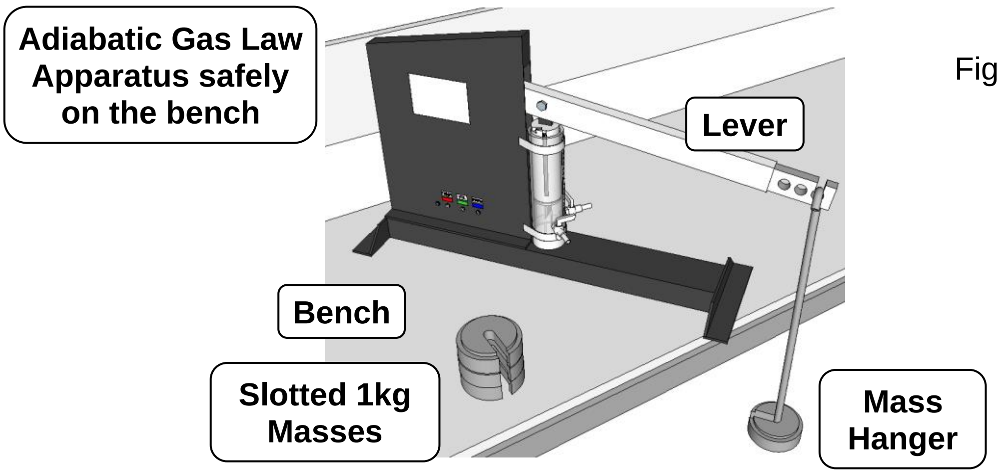


Fig. 6.9

3.2) After 30 seconds add the next 1Kg Mass and repeat until up to 5kg has been added. Once you have added the 4 masses, press Stop and copy the data/images of the graphs into MS Excel like you did in Task 2.

Check the data to make sure the temperature did not rise significantly during the compression experiment (i.e. close to isothermal).

3.3) As in Task 2, turn the Channel data into Temperature, Volume and Pressure and plot a graph of lnP (Pressure) vs. lnV (Volume) and determine the gradient.

Comment on the value obtained and compare to the value expected for an ideal isothermal process.

Task 4: Argon (Ar) – Adiabatic Compression - Fast

To investigate how the atomic structure of the gas affects the value of , carry out a fast compression test using Argon in the cylinder.

4.1) Ask the Demonstrator or Lab Technician to fill the balloon with Argon. The balloon has a rubber tube with a valve attached to it. To fill the piston cylinder, start with the lever at the lowest position and both gas taps closed. Attach the balloon to one of the gas taps then:
- Open the gas tap connected to the balloon.
- Then open the valve on the rubber tube and raise the cylinder, thereby drawing Argon into the cylinder (the balloon should partly deflate).
- Then close both the valve on the rubber tube **and** the gas tap the balloon is connected to.
- Then open the other gas tap on the cylinder. Compress the lever (expelling Argon) and then close the gas tap.
- Repeat this process at least four times to make sure the cylinder is full of Argon.

4.2) Press **Record** and collect data as a fast compression like you did in Task 2.

4.3) Determine a value of γ like you did for air but this time for Argon and compile a table of all your results and comment on the all results.

Creating your lab notebook: ideally it should include:

1) A short introduction describing the Experimental Aims, including the target values and references.

2) A short method section with schematic diagrams of the apparatus. You may also want to develop the key physics equations as a reminder of what you will measure and how you will do the analysis.

3) For each set of measurements include:
   - A table of the measurements and calculations for the various parameters.
   - A graph of lnP (Pressure) vs. lnV (Volume) to determine γ.

4) Create and overall summary Table to present your three values of gamma and their associated uncertainties. Compare these to the expected values and comment.

	Air		Argon	
		Book Value		Book Value
Adiabatic fast				
Isothermal				

5) A final Conclusion section with a discussion of the results and answers to the following questions:
   - How did your values compare with those expected?
   - Did they lie within your calculated uncertainties or not?
   - Any random or systematic uncertainties that could be identified?
   - Did the background physics prove appropriate?
   - Any suggested changes to the apparatus or experimental method?

Appendix 6.1: Calculating γ for Adiabatic Processes

For an ideal gas, the internal energy U, for each degree of freedom, is given by

$$U = \frac{1}{2}nRT \qquad \text{equation (6.15)}$$

From the Introduction,

$$C_V = \frac{dU}{dT} = \frac{1}{2}nR \qquad \text{equation (6.16)}$$

Or

$$= \frac{q}{2}nRT \qquad \text{equation (6.17)}$$

where q is the number of degrees of freedom

Also from the Introduction $$C_P - C_V = nR \qquad \text{equation (6.18)}$$

Therefore

$$\gamma = \frac{C_P}{C_V} = \frac{nR + \frac{q}{2}nR}{\frac{q}{2}nR} = \frac{q+2}{q} \qquad \text{equation (6.19)}$$

- A monotonic gas has three degrees of freedom (three translational).
- A diatomic gas has five degrees of freedom (three translational and two rotational).
- A polyatomic gas has six degrees of freedom (three translational and three rotational although this is not always the case (e.g. for CO_2).

Note: $\gamma = 1$ for isothermal processes.

Appendix 6.2: The volume of the thin ring of air between the base of the piston and the rubber seal

Piston Diameter = 44.5mm ∴ Piston Radius = 22.25mm;
Base of Piston area = 1,590.43mm^2

Inner Cylinder Diameter = 45mm ∴ Inner Cylinder radius = 22.50mm;
equivalent Base of Cylinder area = 1,555.28mm^2

1,590.43mm^2 - 1,555.28mm^2 = 35.14 mm^2

Distance of rubber seal from bottom of piston = 3mm

35.14 mm^2 x 3 = 105.43mm^3

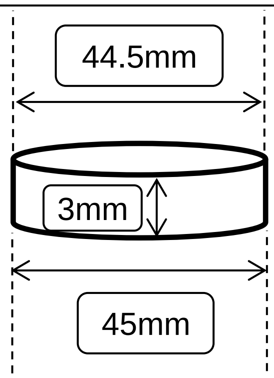


Fig. 6.12**.** Diagram to show the thin ring of air between the base of the piston and the rubber seal

Experiment 7

Experiments in Newtonian Mechanics

Experimental Aims:

- To measure the acceleration due to gravity, g, and the coefficient of friction, μ.
- To demonstrate the validity of Newton's Second Law of Motion.

Learning Objectives:

- To learn how to use computer data collection software.
- To further develop analysis skills, in particular extracting accurate information from graphs.
- To be able to determine the uncertainty in final measurements and use these to evaluate the results of an experiment.
- To be able to critically evaluate the experiment and suggest plausible explanations for any differences between the measured and expected results.

VITALs

E1 b: Keep a detailed laboratory notebook
E1 e: Determine the overall uncertainty in a final value

Preparation:
You are expected to have done these things before you turn up to the lab session:

- **Watch the Online Supporting Video** (link is on Minerva) and become familiar with the experimental method and data analysis.
- Read this manuscript and become familiar with the physics behind these experiments.
- Read the section in Tipler on Newton's Laws, Chapter 4 and 5 and Examples 5-2 and 5-4.
- Fill in the online Health & Safety form as described below.

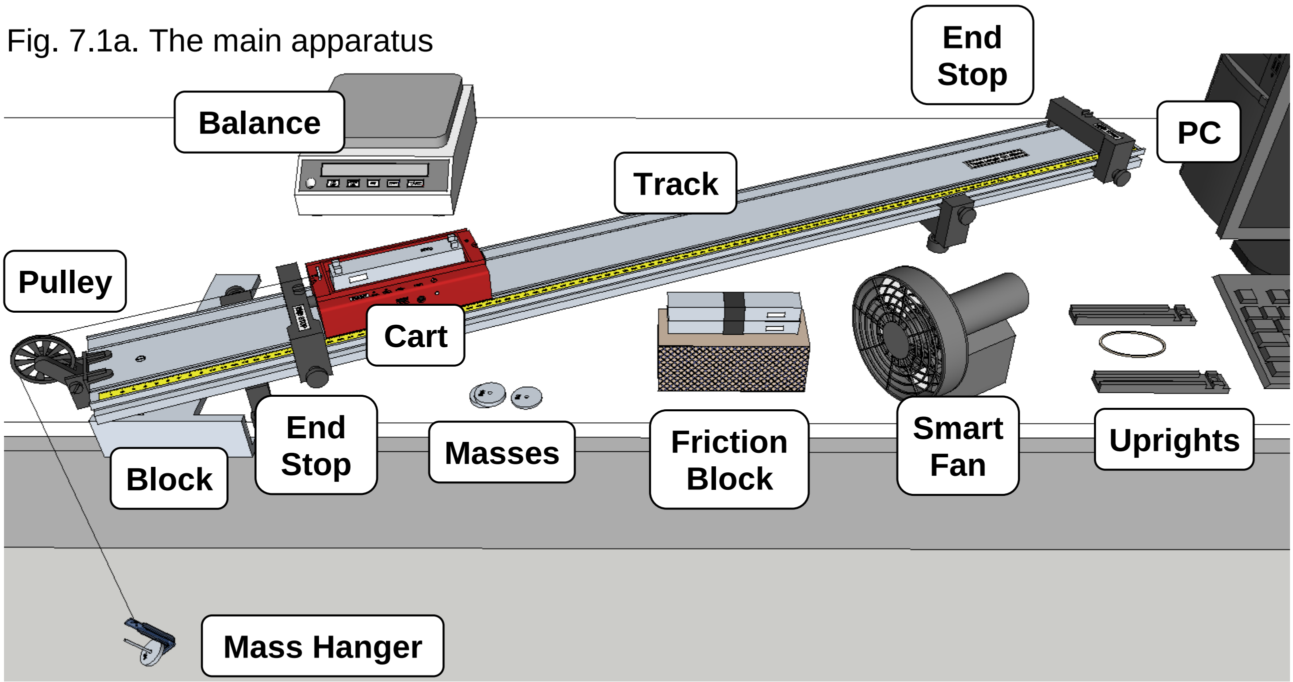
Risk Assessment and Safety:
Read the Health and Safety information on the next page and fill in the online H&S form. The technician will check online that you have filled this in before you start. It can be reached either via this QR code, via the link on MINERVA or this weblink here: https://forms.office.com/e/e8HtpetiuY

<table>
<tr><th colspan="2">School of Physics & Astronomy</th><th colspan="3">RISK ASSESSMENT RECORD</th></tr>
<tr><td>LOCATION:</td><td colspan="4">Bragg Building, Room 4.08, 1st Year Physics Undergraduate Laboratory</td></tr>
<tr><td>DESCRIPTION OF ACTIVITY:</td><td colspan="4">Experiment 7: Newtonian Mechanics</td></tr>
<tr><td rowspan="2">SIGNIFICANT HAZARDS</td><td rowspan="2">EXISTING CONTROL MEASURES</td><td>SEVERITY</td><td>LIKELIHOOD</td><td rowspan="2">RISK RATING</td></tr>
<tr><td colspan="2">1 = minor, 2 = serious, 3 = major</td></tr>
<tr><td>Masses</td><td>Do not drop the 250g masses.</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>Spring loaded plunger</td><td>The cart has a spring-loaded plunger. Should it become depressed whilst operating then take great care when deploying the spring-loaded plunger. Do not look directly at the end of the cart whilst deploying it. Keep fingers away from deployment area when deploying the plunger.</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>Electrical equipment</td><td>All equipment to have an up-to-date PAT test sticker. No such instrument should have its fuse or plug tampered with. If an item appears to be faulty, consult the Laboratory Technician.</td><td>2</td><td>1</td><td>2</td></tr>
<tr><td>PEOPLE AT RISK</td><td>ADVERSE EFFECTS</td><td colspan="3">ACTIONS TO BE TAKEN & TIMESCALES</td></tr>
<tr><td rowspan="3">All students, demonstrators and staff members</td><td>Electrical shock</td><td colspan="3">If an electrical item appears to be faulty, consult the laboratory technician.</td></tr>
<tr><td>Dropping masses</td><td colspan="3">Take care when handling the masses and carts.</td></tr>
<tr><td>Spring loaded plunger</td><td colspan="3">Take care when deploying the plunger.</td></tr>
</table>

	Name	Signature	Date
ASSESSED BY:	Angela Beddows (Technician)		27/07/2024
GROUP HEAD:	Dr Peter Hine (Laboratory Convener)		27/07/2024
SAFETY SUPERVISOR:	Stuart Weston (Department Safety Officer)		27/07/2024

Experimental Apparatus

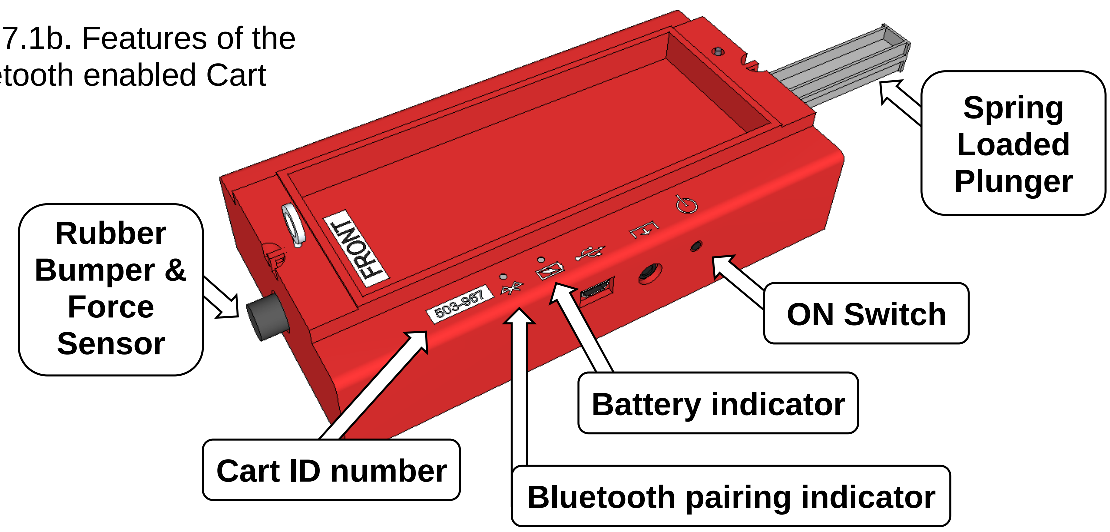
Fig. 7.1a. The main apparatus



The apparatus consists of a **Track** and two **End Stops**, on which a **Cart** is able to move in either direction. The cart is Bluetooth enabled which allows the cart's data to be measured wirelessly. The Cart also has an on-board Force sensor, located behind the rubber bumper as shown in figure 7.1b below.

In Task 1 a **Smart Fan** is attached to the Cart, enabling a constant (or variable) thrust to be generated. In Task 2 a **Pulley Wheel** is added and the Fan is removed. A **Mass Hanger** is attached to the Cart via fishing line passing over the Pulley Wheel. A 250g mass is also added to the Cart. For both tasks a **Block** attached to the bench prevents the Track from coming off the table when the experiments are underway. Small **Masses** are added to the 5 gram **Mass Hanger** throughout the experiment. In both tasks, the PC allows the acceleration of the **Cart** to be determined via a Bluetooth connection to the Cart. The End Stops prevents the **Cart** from coming off the end of the track. In Task 3 the Force sensor located behind the cart bumper is used to evaluate the friction of a **Friction Block** with differing surface roughness.

Fig. 7.1b. Features of the Bluetooth enabled Cart



Task 1: Part 1: Investigating Newton's Second Law

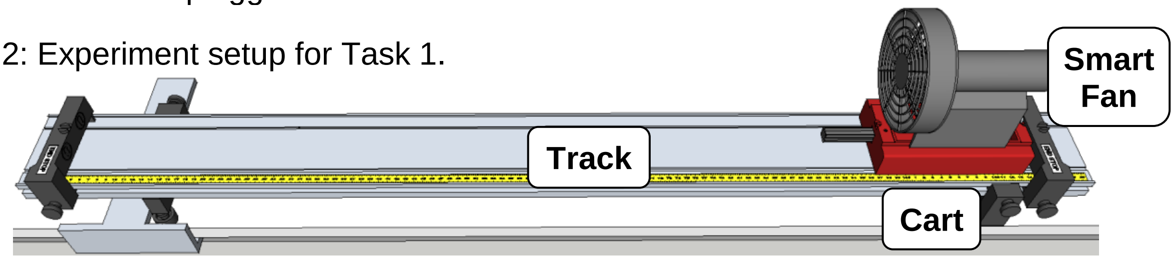
The aim of this first part of the experiment is to verify Newton's Second Law of Motion,

$$F = ma \qquad \text{equation (7.1)}$$

where F = Force; m = mass and a = acceleration.

The track should already be set up as shown in figure 7.2, horizontally with track feet at both ends and two end stops. The Smart Fan Accessory should be clipped to the top of the Smart cart and plugged in to the Cart.

Fig. 7.2: Experiment setup for Task 1.



1.1) First, measure and record the total combined mass of the Cart and Fan using the balance provided (and its uncertainty) as this will form the target value for this experiment.

1.2) Login to the PC and switch the Bluetooth (✱) on the Cart (**ON** switch shown in figure 7.1b). The red LED will flash to show Bluetooth is unpaired.

1.3) Load the PASCO Capstone software and click on **Hardware Setup** tab (as shown in figure 7.3 below). Your wireless Cart ID number should appear in the Available Wireless Devices, click on it. (Make sure it has the **correct** ID number shown on the top of the Cart (as indicated in figure 7.3) so you do not connect to someone else's Cart). Once the Bluetooth is paired, the LED on top of the Cart will flash green. Also whilst in the Hardware Set up tab, click on the Settings Icon next to the Force Sensor to show its Properties. Tick the box that says 'Zero Sensor measurement at Start' so it will be zeroed before each experiment run. When logging the force you may prefer this to be a positive value, so click the 'change sign' icon above the zero force box if you prefer this. Click on the Hardware Setup tab again to minimise it.

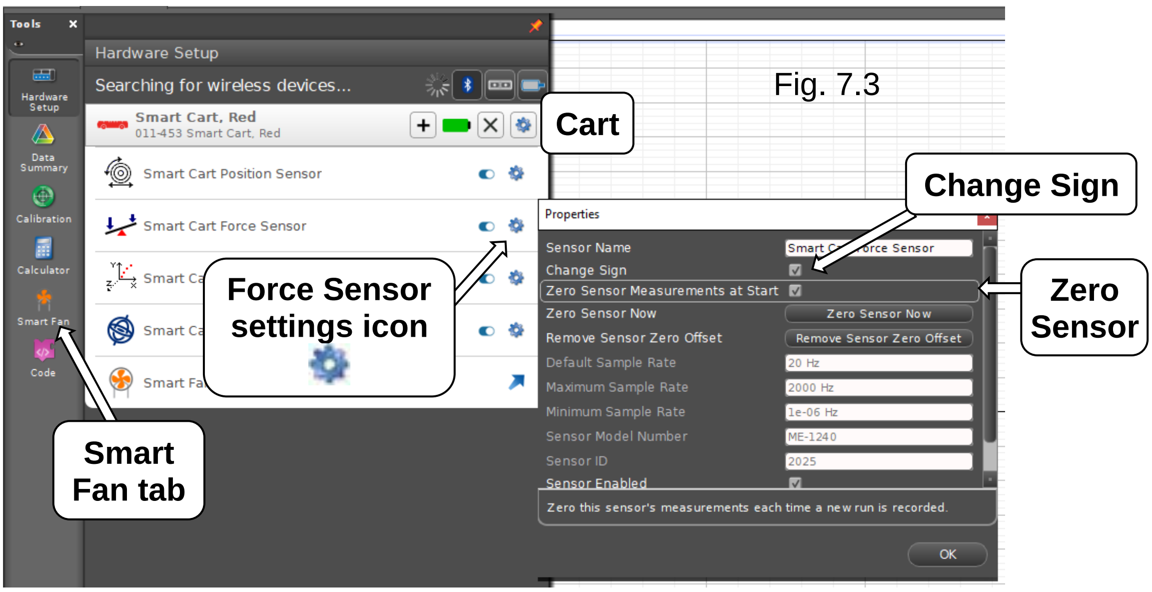


Fig. 7.3

1.4) Click on and drag the **Graph Icon** from the Displays sidebar and drop it into the central area. It should look similar to the screen as shown in figure 7.4.

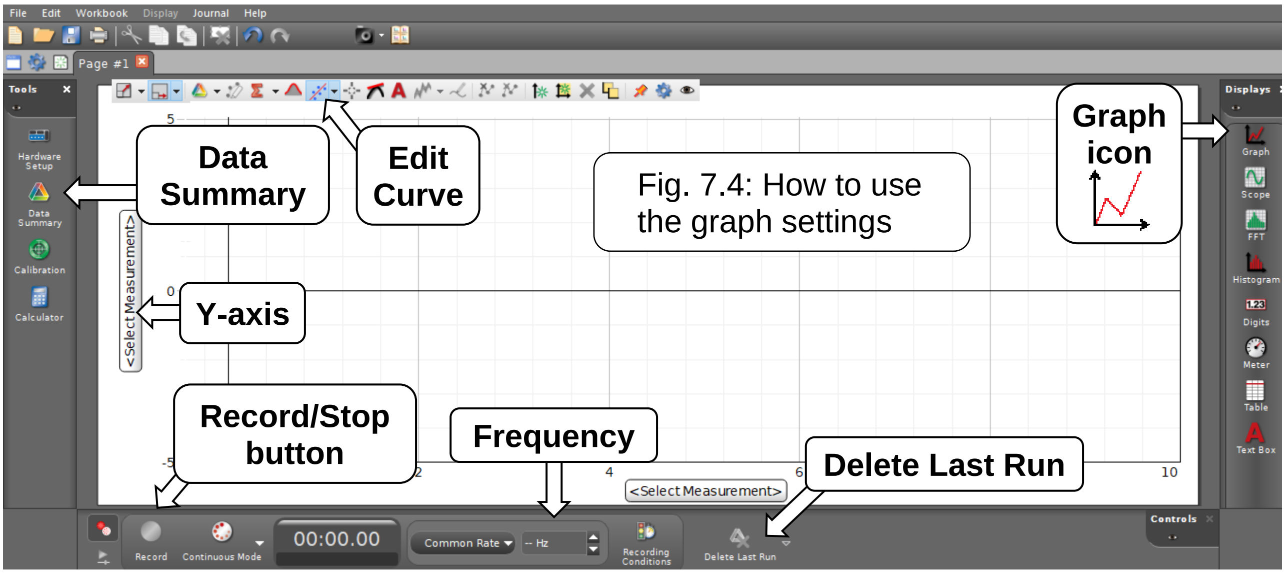


Fig. 7.4: How to use the graph settings

1.5) On the **Y-axis** click on <select measurement> (shown in figure 7.4) and select **Force**. Change the X-axis to time (seconds) if it hasn't automatically changed.

Select your measurement **Frequency** (shown in figure 7.4) to 40Hz. This is how often the software takes a reading.

1.6) Bring up the Smart Fan Tab on the Tools bar (shown in figure 7.3). Set the Thrust to 45 for the first measurement (shown in figure 7.5).

Then click on the **Advanced Options Menu** and switch both Start and Stop conditions to Measurement based (shown in figure 7.5) as this then sets the fan to Start/Stop when you press Record/Stop then Close the menu.

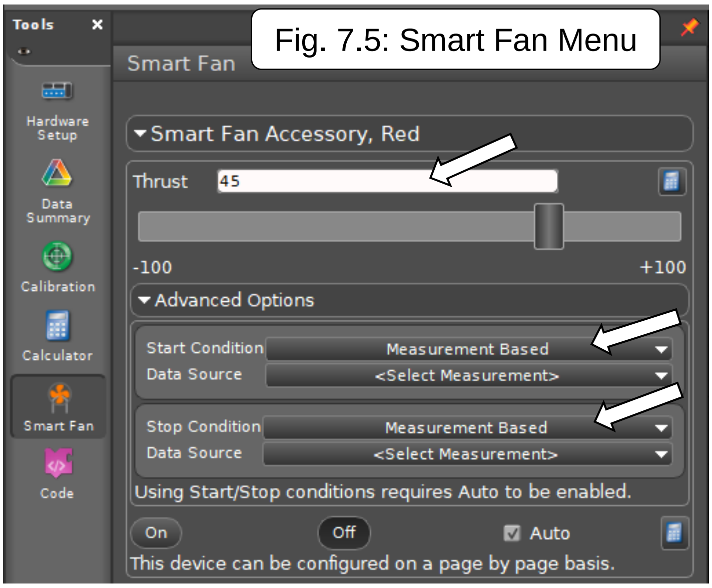


Fig. 7.5: Smart Fan Menu

1.7) Click on the **Data Summary** tab (shown in figure 7.4), click on the Force (N) settings icon under Smart Cart Force Sensor and change the number of decimal places for the Force measurement to '3' as shown in figure 7.6. Close the menu and click on the tab again to minimise it.

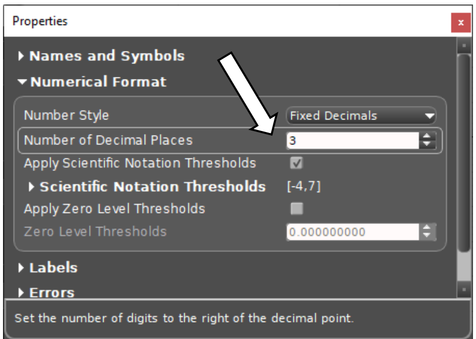


Fig. 7.6: Cart Sensor Settings

1.8) Create a table in your Lab Notebook like the one below:

Thrust	Average Force	Standard Deviation
45		
50		
55		
60		
65		
70		

1.9) Before you start, make sure the Cart has its bumper against the **End Stop** (as seen in figure 7.7) with the Spring Loaded Plunger facing away from the End Stop. Press Record, this should start the Fan on and then start the experiment. You will see that the force will rise from zero to a constant value once the fan has spun up to a constant speed (this will take longer as the thrust is increased). Stop recording after at least 10 seconds.

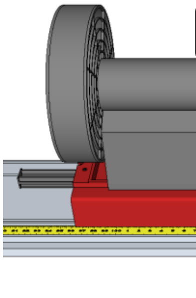


Fig. 7.7

1.10) A graph of typical results is shown in figure 7.8 below (you need to zoom in to see it on the PC). Click the Highlighter icon on the top toolbar and then select the region of the Force trace which is roughly constant and then use the Stats Icon that comes up when you click in this box to determine the average Force and the standard deviation which is the measurement uncertainty. Record these in the table in your Lab Notebook then click ‘Delete Last Run’ (shown in figure 7.4)

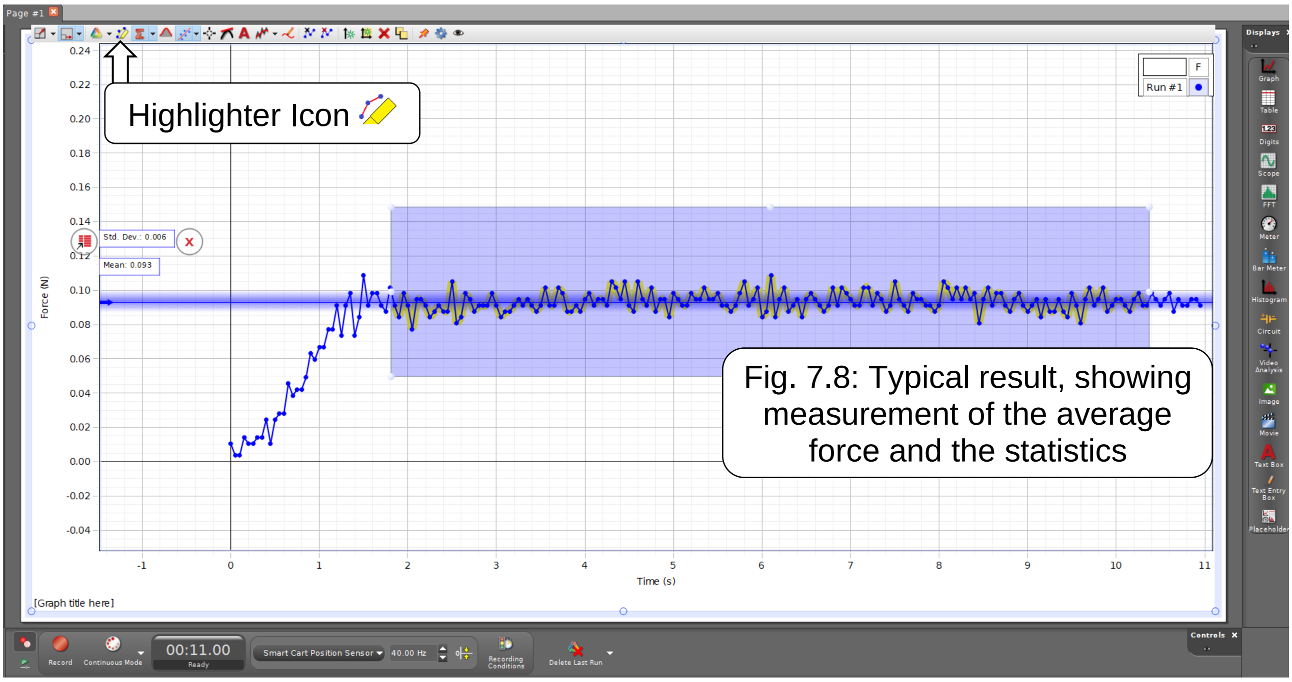


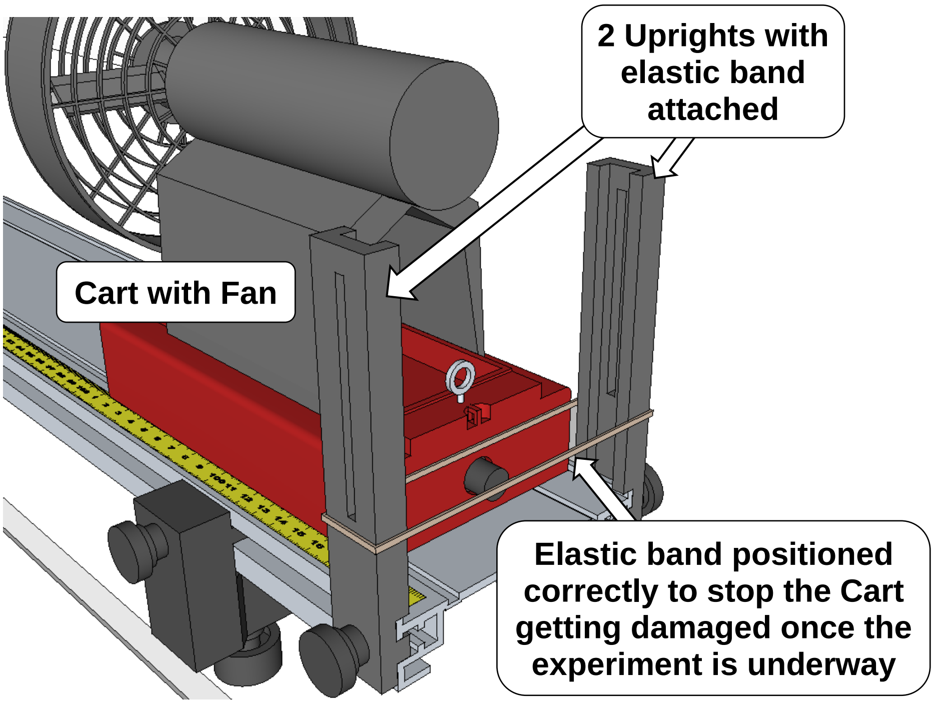
Fig. 7.8: Typical result, showing measurement of the average force and the statistics

1.11) Repeat this for thrusts of 50, 55, 60, 65, 70 and 80 and record the mean thrust with its uncertainty each time. Plot a graph of Force versus Thrust and fit a straight line using LINEST using MS Excel (as explained on pages 38 & 39). The equation of the line (the intercept and gradient and their associated uncertainties) is then the calibration equation for the next part of this experiment.

In the next part of the experiment, you will measure the acceleration of the Cart at thrust settings of 45, 50, 55, 60 65 and 70 and then correlate the average cart acceleration with the Force measured earlier in the experiment.

1.12) Remove the End Stop nearest the computer and replace it with the 2 Uprights with an Elastic Band wrapped around both as shown in figure 7.9. Arrange the elastic band so it is level with the back of the cart just above the bumper.

Fig. 7.9: Uprights set up with the elastic band setup



1.13) Create a table as below but in your Lab Notebook (or on MS Excel) to record your results, being mindful of the units used for measurement.

Total mass (cart, plus fan plus mass)	$(m \pm \Delta m)$ (g)					
Thrust setting	45	50	55	60	65	70
Force from equation from earlier $F \pm \Delta F$ (N)						
acceleration of Run 1 a_1 (cm/s^2)						
acceleration of Run 2, a_2 (cm/s^2)						
acceleration of Run 3, a_3 (cm/s^2)						
Average acceleration, of 3 Runs, a (m/s^2)						
Standard deviation, σ_{n-1}						
Standard uncertainty ${\sigma_{n-1}}/{\sqrt{3}}$						

1.14) Change the graph to measure **Velocity** on the Y-axis and move the Cart to the opposite end of the track to the Uprights. Set the Fan to a thrust of 40 and press Record. Stop recording once the Cart hits the elastic band. You should have a graph similar to the one in figure 7.10 on the next page.

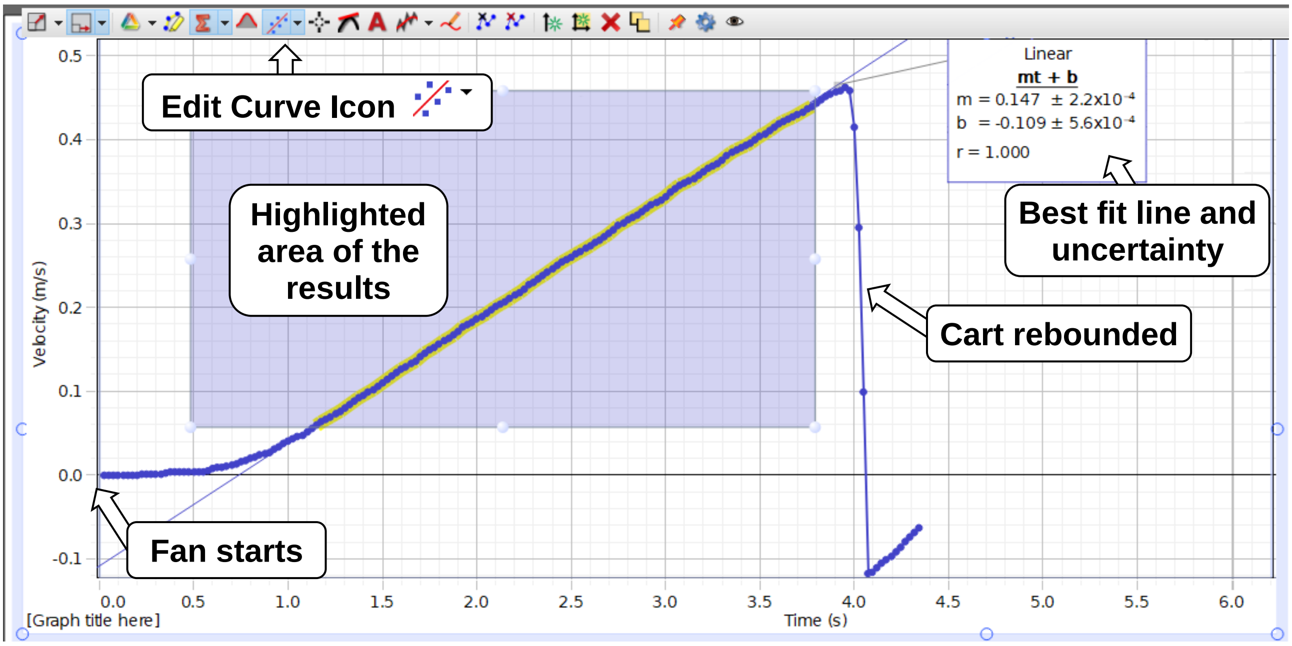


Fig. 7.10 Typical captured velocity versus time data with highlighted region and fitted linear regression.

1.15) Once the data is collected, highlight the region of the curve you would like to fit a linear curve to. Click on the Edit Curve icon as shown in figure 7.10 and select **linear:mt +b** from the dropdown menu. This will give a readout of the **best fit line** to the slope and show the gradient (constant acceleration) and its uncertainty, record this in your Lab Notebook.

1.16) Using the same thrust, repeat this again two more times so you have 3 values for acceleration for this value of Thrust remembering to Delete Last Run after you have recorded the results of each run. Record these results in the table along with their uncertainties and calculate the average acceleration along with its uncertainty.

1.17) Repeat this three times for each value of Thrust indicated in the table on the previous page so you have 3 readings of acceleration and associated uncertainties for each Thrust.

1.18) Plot a graph of Force versus Acceleration and find the gradient of the graph and its uncertainty using LINEST. This value is the predicted mass of the cart assembly (if Newton's second law holds), compare this to the mass measured earlier using the electronic balance and comment on the comparison within the calculated final uncertainty.

Task 2 starts on the next page.

Task 2: Newton's 2nd Law and measurement of the acceleration due to gravity, g.

Introduction and Background Theory

The aim of this part is to use Newton's Second Law of Motion to determine the acceleration due to gravity, g. To determine the acceleration, you will release the cart from rest whilst it is attached to hanging mass.

The driving force is the gravitational force on the hanging mass (m_2) which then accelerates the combined mass ($m_2 + m_1$).

balancing force gives $$m_2 g = (m_2 + m_1)a \qquad \text{equation (7.2)}$$

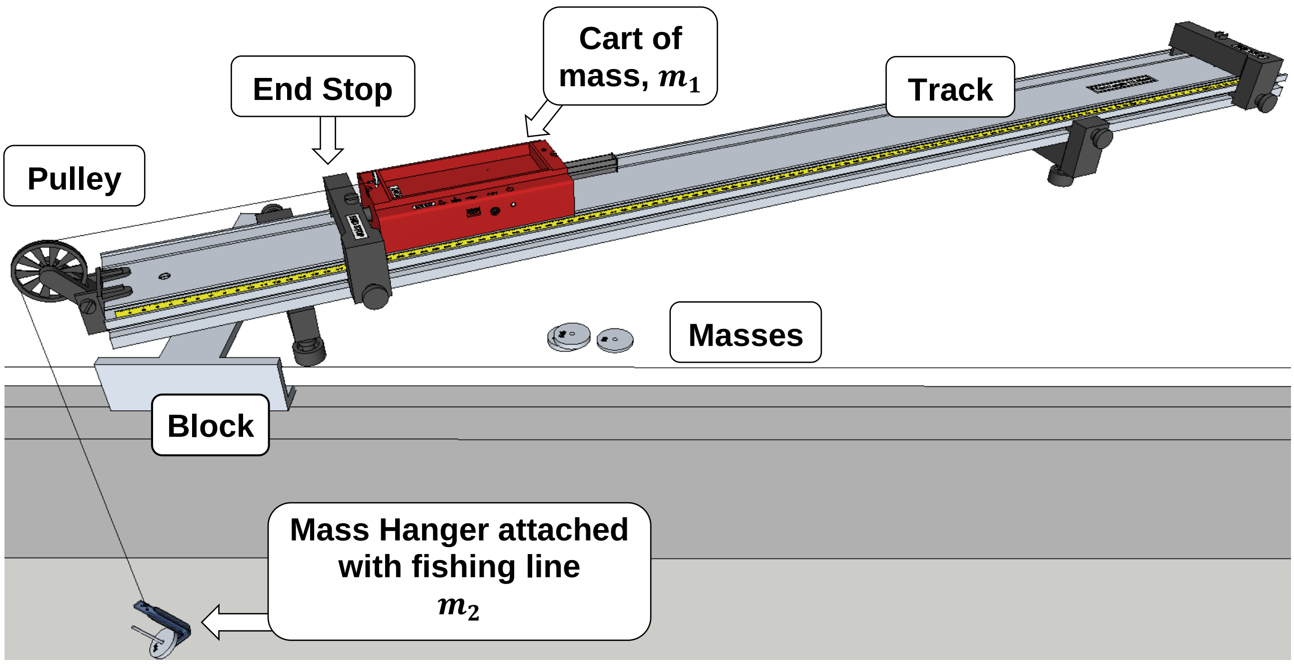
Or rearranging $$a = \frac{m_2}{(m_2 + m_1)} g \qquad \text{equation (7.3)}$$

Procedure for Task 2

2.1) Set up the apparatus as shown below by moving the End Stop nearest the Block to around 30cm from the end. Remove the Smart Fan attachment from the Cart and add the fishing line to the hook on the Cart so it goes over the Pulley Wheel and adjust the track so this hangs off the bench. The setup should now look like figure 7.11 below. The feet of the Track need to be all on the bench and one end needs to be up against the block, this is so the Track doesn't go off the bench during the experiment.

You will be doing the same experiment repeatedly but changing the combined hanging mass each time using masses of 10g, 15g, 20g, 25g and 30g respectively.

Fig. 7.11 Set up for Task 2

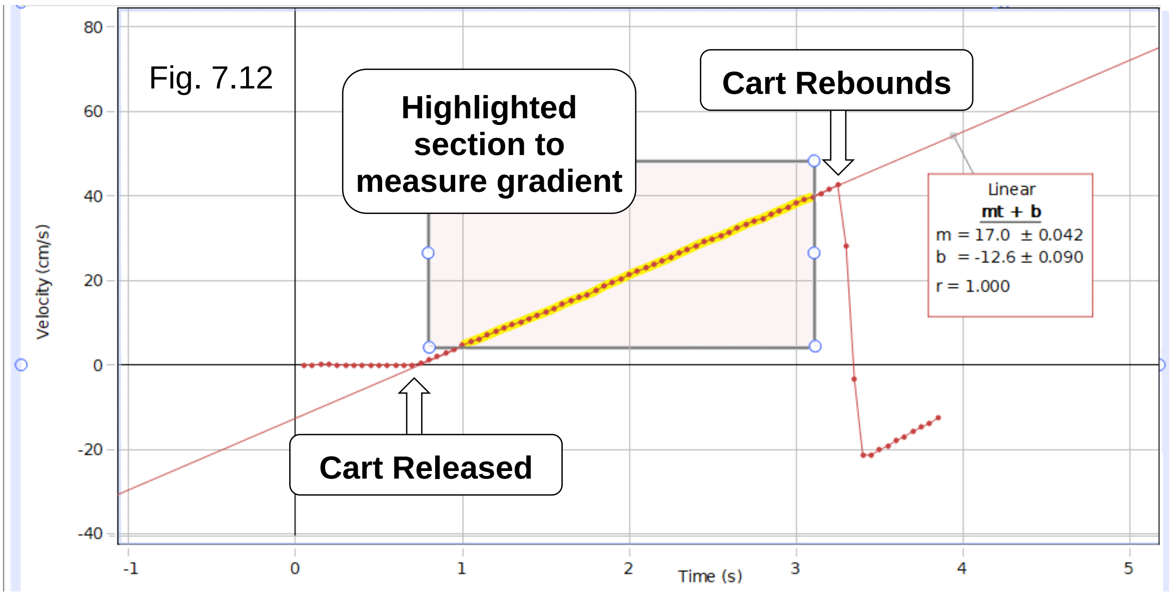


2.2) Capstone will already be setup from Task 1 to measure a Velocity vs Time graph but change the **measurement frequency** to 200Hz.

2.3) Create the table below but in your Lab Notebook (and in MS Excel)

Total Cart mass (m_1) (g)					
Combined hanging mass (m_2) (g)	10	15	20	25	30
acceleration of Run 1 a_1 (cm/s^2)					
acceleration of Run 2, a_2 (cm/s^2)					
acceleration of Run 3, a_3 (cm/s^2)					
acceleration of Run 4, a_4 (cm/s^2)					
acceleration of Run 5, a_5 (cm/s^2)					
Average acceleration of all Runs, a (cm/s^2)					
Standard deviation, σ_{n-1}					
Standard uncertainty ${}^{\sigma_{n-1}}/_{\sqrt{5}}$					

2.4) Add the 5g mass to the mass hanger (so its 10g total combined) and pull the cart back about 30cm from the End Stop near the Pulley and hold it. Press **Record** and then after a couple of seconds release the Cart. After it has rebounded **Stop** the recording. You should now have data on your graph which looks like figure 7.12 below.



2.5) As in Task 1, use **Highlighter** and **Edit Curve** to fit a linear curve to the results to determine the acceleration and its uncertainty from the gradient. Record these values in the table. Repeat this until you have 5 measurements in total for the 10g mass.

2.6) Once you have finished your measurements for the 10g mass, increase the mass, m_2 so it is 15g and take another 5 measurements and so on for masses of 20g, 25g, & 30g. Also record the mass of the Cart along with its associated uncertainty which are printed onto the Cart.

Analysis of Task 2:

1) Create this table in your Lab Handbook and in MS Excel. Calculate the function of the Masses $\frac{m_2}{(m_2 + m_1)}$ and also calculate the average acceleration from your results:

Cart mass (m_1)	Hanging mass (m_2)	$\frac{m_2}{(m_2 + m_1)}$	Average a (cm/s^2)
	10		
	15		
	20		
	25		
	30		

2) Plot a graph of the measured acceleration of the cart, a, against the function of masses, $\frac{m_2}{(m_2 + m_1)}$

The gradient of this graph gives the value of the acceleration due to gravity, g. Use the LINEST function in MS Excel to calculate the slope and intercept, and their uncertainties.

3) Answer the following questions:

a) Compare to the expected value of g of 9.81 m/s^2 and comment on your results.

b) Did the results show a linear relationship, and if so, how does this verify $F = ma$?

c) Did the best fit line pass through the origin? If not, what could be the reason for the discrepancy?

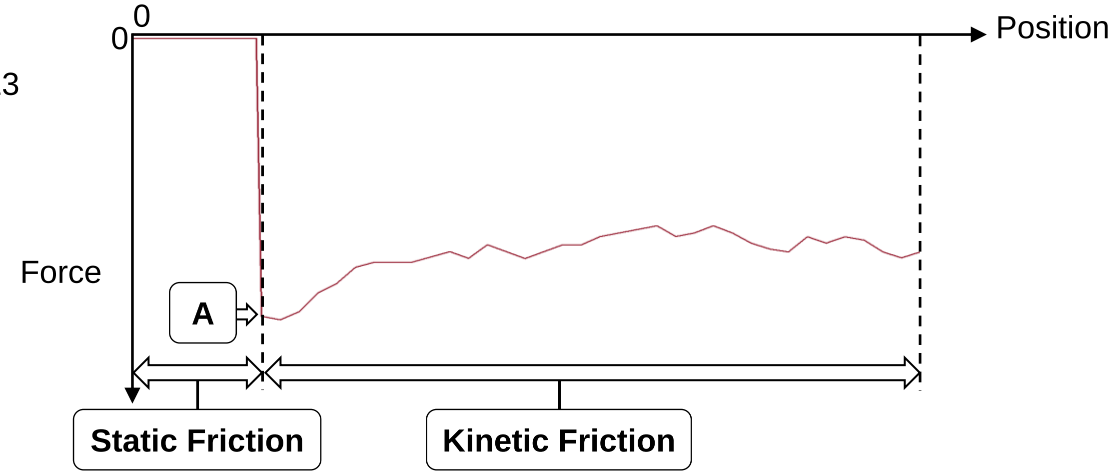
Task 3 is on the next page.

Task 3: Static and Kinetic Friction

Introduction and Background Theory:

Static friction is friction between two or more solid objects that are not moving relative to each other. For example, static friction can prevent an object from sliding along a level surface. The static friction force must be overcome by an applied force before an object can move. The friction increases as the applied force increases until the object moves (denoted by position A). After the object moves, it experiences **kinetic friction** as indicated in figure 7.13 below, which is less than the maximum static friction.

Fig 7.13



The coefficient of friction μ is the ratio between friction force F and normal force (which is the mass of the object m_{object} multiplied by the accepted value for the acceleration due to gravity, g) as shown in equation (7.4) below.

$$\mu = \frac{F}{m_{object}\ g} \qquad \text{equation (7.4)}$$

Because the friction force and normal force are both measured in Newtons, the coefficient of friction is dimensionless. The coefficient of friction has different values for static friction, μ_s and kinetic friction, μ_k. In static friction, the frictional force resists force that is applied to an object, and the object remains at rest until the force of static friction is overcome. In kinetic friction, the frictional force resists the motion of an object. The coefficient of static friction μ_s is usually higher than the coefficient of kinetic friction μ_k.

Task 3: Procedure

3.1) Detach the fishing wire assembly from the Cart and store it safely in the blue tray. Take the Cart off the Track and place it next to (but not yet touching) the Friction Block on the bench somewhere it won't roll off as in figure 7.14 with the Bumper end nearest the Friction Block. The Friction Block has two sides, a smooth one and a rough one. Start with the **smooth side** facing down.

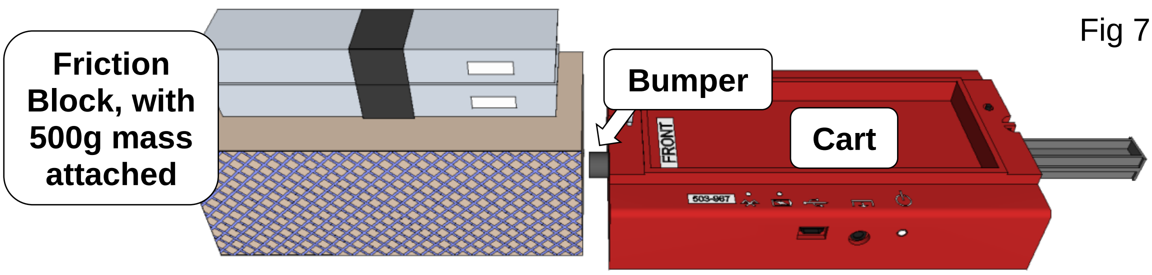


Fig 7.14

3.2) If you have not done this yet, click on Change Sign on the Smart Cart Force Sensor settings so it is ticked. On your graph from Task 2 delete the last data run and change the Y-axis to **Force** (in Newton) and the X-axis to **Position** (in Metres). Drag and drop the Table icon onto the graph to open up a table and select Force for column 1 and Position for column 2.

3.3) Make sure the Cart's Bumper is not touching anything and then zero the Force sensor by clicking on the icon (which is near Delete Last Run).

3.4) Starting with the **smooth side** of the Friction Block in contact with the bench, position the Cart so it will push the Friction Block around the midpoint of its end. Press Record, then very slowly push the Cart towards the Friction Block until it starts to move and then push it steadily across the table for about 30cm. Then press Stop. Copy the data from the table into MS Excel (using CTRL+A in the Table area to highlight it, then CTRL+C to copy and pasting it into MS Excel using CTRL+V).

3.5) Create a table like the one below but in you Lab Notebook and record the result along with its associated uncertainty.

Friction Block side	Smooth side		Rough side	
Speed	slow	fast	slow	fast
Run	Run 1	Run 2	Run 3	Run 4
Maximum Force (static)				
Average Force (kinetic)				
Static Friction μ_s				
Kinetic Friction μ_k				

Using your data, determine:

a) the **maximum force** required to push the Friction Block. This is an indication of the static friction

b) calculate the **average force** whilst the Friction Block was moving. This is an indication of the kinetic friction

3.6) Repeat task 3.4 but push the Friction Block and Cart at a faster speed once it breaks loose and again record the maximum force required to push the object and calculate the average force whilst it was moving.

3.7) Repeat task 3.4 but with the **rough side** of the Friction Block in contact with the bench and again record the maximum force required to push the object and calculate the average force whilst it was moving at both slow and fast speed.

3.8) Find the mass of the Friction Block using the Balance provided and record the value in the table along with its uncertainty. Calculate the coefficients of Static Friction μ_s and Kinetic Friction μ_k for each run using equation (7.4) and record those also.

3.9) **Answer these three questions:**
What effect does speed have on the static and kinetic friction?
How does the static and kinetic friction depend on the block surface?
Do the coefficients of static and kinetic friction change?

Creating your lab notebook: ideally it should include:

1) A short introduction describing the Experimental Aims, including any target values with references.

2) A short method section with schematic diagrams of the apparatus. You may also want to develop the key physics equations as a reminder of what you will measure and how you will do the analysis for each task.
   For this experiment, where there are three separate tasks, it can sometimes be better to split your lab notebook into tasks, and then within each task have a short method, key equations, data, graphs etc and then a short Conclusion before proceeding to the next task.

3) Document and tabulate all your recorded measurements using the tables suggested in the lab script and supporting video.

4) Graphs for Task 1 and Task 2 showing the best-fitted line, uncertainty bars etc. A typical graph for Task 3 showing the result of a friction experiment.

5) For Tasks 1 and 2 tasks, calculate your final values with their uncertainties and compare to the expected values.

6) A conclusion section answering the following questions (plus your own) as a template:
   - For Task 1, was Newtons Second Law validated?
   - For Task 2, was the graph for determining 'g' linear and so did the measured data confirm Newtons Second Law? Did the graph best fit lines pass through the origin? If not why not? Did the value of $g \pm \Delta g$ agree with the expected value? If not, any suggested reasons to investigate in a follow-on experiment by another researcher?
   - Any suggested improvements to the apparatus or the experimental method for future researchers for tasks 1 or 2?
   - For Task 3 what was the relationship between static and kinetic friction? What was the effect of speed or block surface?

Experiment 8

Determination of Planck’s Constant

Experimental Aims:
- To measure Planck's constant, h.
- To demonstrate that the intensity of a black-body radiator depends on Planck’s constant.

Learning Objectives:
- To learn how to solder electrical components together to build a simple circuit.
- To further develop skills in using digital multimeters to measure the potential differences and current at different points in an electrical circuit.
- To practice complex data analysis skills to determine the final value and the uncertainty in this value.
- To be able to critically evaluate the results of an experiment; to compare measured results with expected values and comment on the agreement within uncertainties.

VITALs

E1 b: Keep a detailed laboratory notebook
E1 c: Perform appropriate calculations

Preparation:
You are expected to have done these things before you turn up to the lab session:
- **Watch the Online Supporting Video** (link is on Minerva) and become familiar with the experimental method and data analysis.
- Read this manuscript and become familiar with the physics behind these experiments.
- Read Appendix 8.2 on how to solder. **You must read this entire section before starting to solder**
- Fill in the online Health & Safety form as described below.

Risk Assessment and Safety:
Read the Health and Safety information on the next page and fill in the online H&S form. The technician will check online that you have filled this in before you start. It can be reached either via this QR code, via the link on MINERVA or this weblink here: https://forms.office.com/e/AjZKtTV1N1

Appendices at the end of this script:
Appendix 8.1: Example data (page 144)
Appendix 8.2: How to solder.(page 145)

School of Physics & Astronomy	**RISK ASSESSMENT RECORD**
LOCATION:	Bragg Building, Room 4.08, 1st Year Physics Undergraduate Laboratory
DESCRIPTION OF ACTIVITY:	**Experiment 8: Determination of Planck’s Constant**

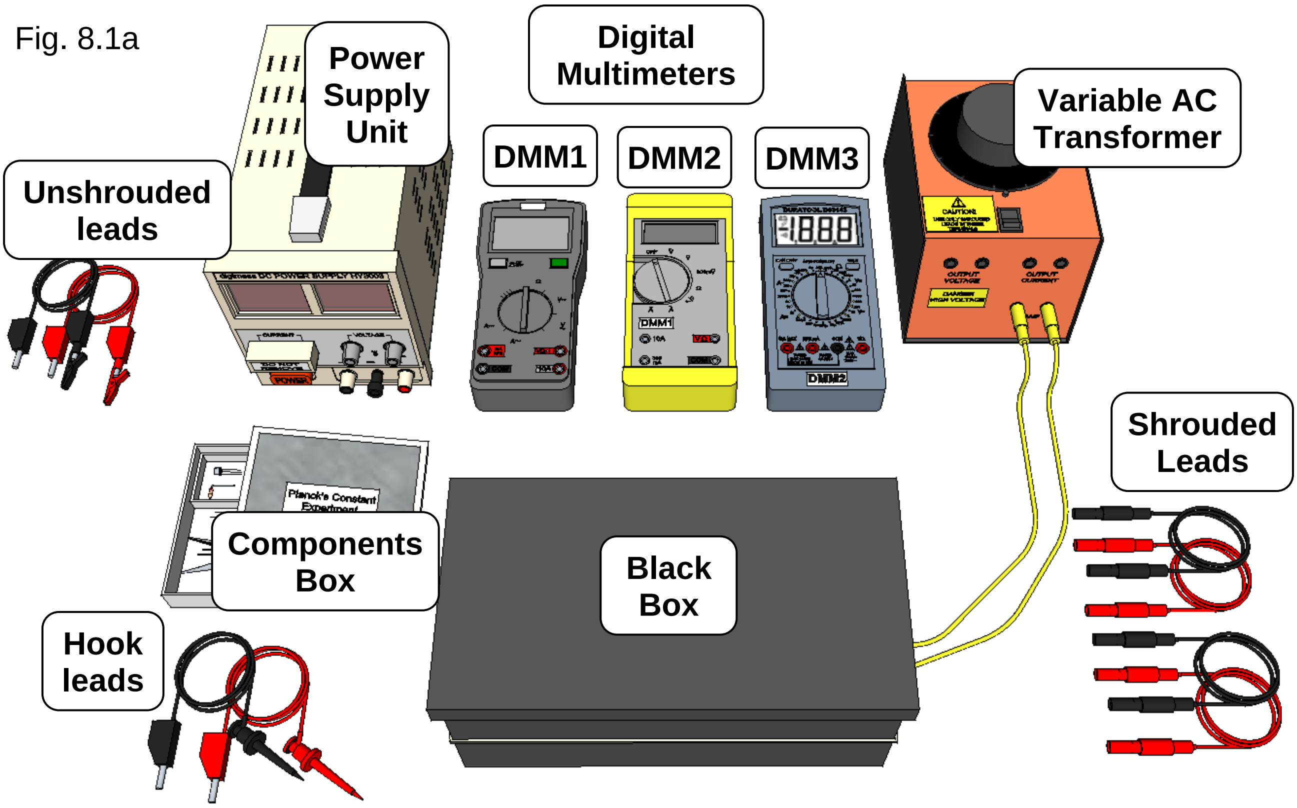
SIGNIFICANT HAZARDS	**EXISTING CONTROL MEASURES**	**SEVERITY**	**LIKELIHOOD**	**RISK RATING**
		1 = minor, 2 = serious, 3 = major		
Electrical Shock	When connecting the Digital Multimeter/Variable AC Transformer circuit **shrouded** leads **MUST** be used. If incorrect leads are used, user is at risk of electric shock.	2	2	4
Soldering Iron tip at 400ºC	Do **not** touch the tip of the soldering iron. Soldering Iron **MUST** be placed back in its holder when not in use.	2	2	4
Solder (Lead & Roisin free)	Use pliers to handle the solder. Wash hands after use. Use the goggles provided when soldering.	1	1	1
Solder fumes	Do not breathe the solder fumes: use the Fume Extractor provided.	1	1	1
Bulb gets hot during use	Do not touch the bulb in the black box.	2	1	2
Electrical equipment	All equipment to have an up-to-date PAT test sticker. No such instrument should have its fuse or plug tampered with. If an item appears to be faulty, consult the Laboratory Technician.	2	1	2

PEOPLE AT RISK	**ADVERSE EFFECTS**	**ACTIONS TO BE TAKEN & TIMESCALES**
All students, demonstrators and staff members	Electrical shock Burning Noxious substance Noxious Fumes	If an electrical item appears to be faulty, consult the laboratory technician. Use shrouded leads where appropriate. Do not touch the tip of the soldering iron. Do not touch the bulb. Use pliers to handle the solder. Wash hands after use. Use the extractor fan provided.

	Name	**Signature**	**Date**
ASSESSED BY:	Angela Beddows (Technician)	Angela Beddows	27/07/2022
GROUP HEAD:	Dr Peter Hine (Laboratory Convener)	P.J. Hine	27/07/2022
SAFETY SUPERVISOR:	Stuart Weston (Department Safety Officer)	[illegible]	27/07/2022

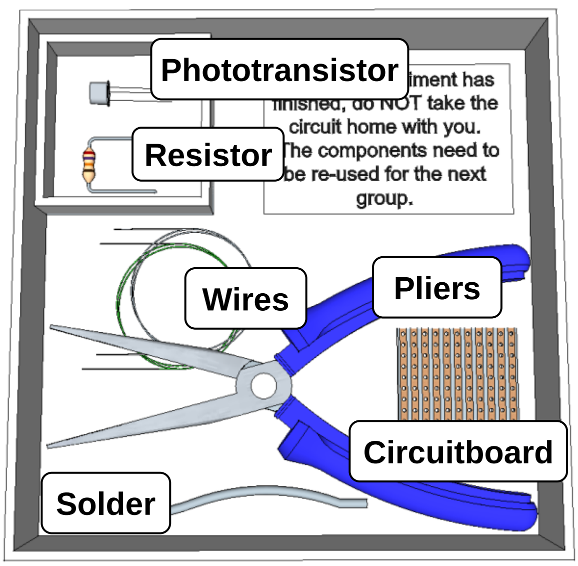
Experimental Apparatus

Fig. 8.1a



Two **Digital Multimeters (DMM 1 and DMM3)** are connected to a **Variable AC Transformer** (using **Shrouded Leads**) so accurate voltage and current readings can be taken. A **Black Box** with a 40W Bulb mounted inside is also connected to the Variable AC Transformer. All the components that are needed to build the smaller circuit are contained in the **Components Box** (explained below). Once the smaller circuit is soldered, it is attached to the Black Box using an elastic band. The **Phototransistor** is inserted into the small hole at the opposite end to the box to the bulb. The two leads coming off the smaller circuit are attached to the **Low Voltage Power Supply Unit** using the **Unshrouded Leads**. A **Digital Multimeter (DMM2)** is then attached to the resistor on the smaller circuit using the **Hook Leads** to measure the voltage across it once the experiment is underway.

Fig. 8.1b



The **Components Box** contains:

- Pliers,
- a piece of Circuitboard
- a Phototransistor*
- a 160Ω Resistor
- 2 pieces of single core wire
- some Solder

*All Phototransistors are checked before the lab session by the Technician to make sure they work.

You will NOT be allowed to take your circuits away with you when you have finished. The components need to be reused for the next group.

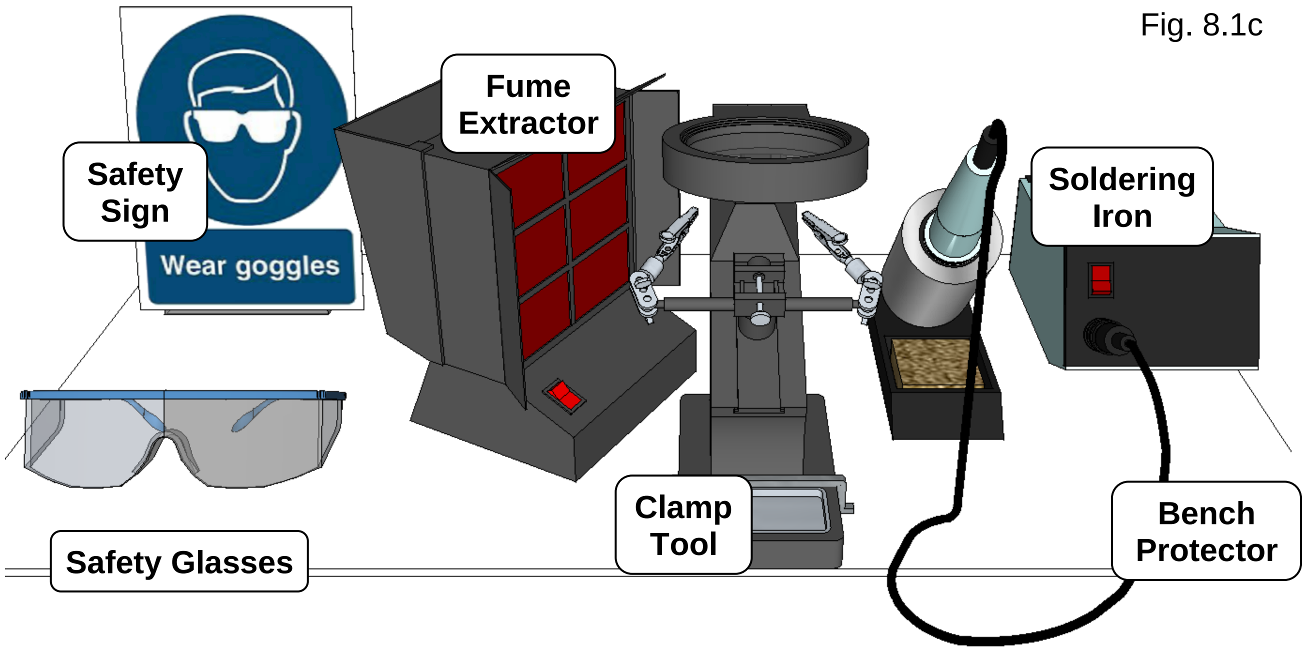


Fig. 8.1c

The smaller circuit is constructed using the components and the **Soldering Iron**. A pair of **Safety Glasses MUST** be worn when soldering. A **Fume Extractor** is provided to reduce the chance of breathing in the solder fumes, this must be positioned near to the circuit when you are soldering so the fumes are taken in by it. There is also a **Clamp Tool** with board clip and adjustable crocodile clips provided to hold the **Circuitboard** and components whilst soldering, it also has a light which can be switched on at the side and a magnifier. All this rests upon a **Bench Protector**.

If you do not know how to solder then watch the 'How to Solder' video on MINERVA. There are also several instructional videos on how to solder available on the internet.

Safety note with regards to leads.

It is important you use the correct leads with the Variable AC Transformer. You **MUST** use the shrouded leads otherwise you are at risk of an electric shock.

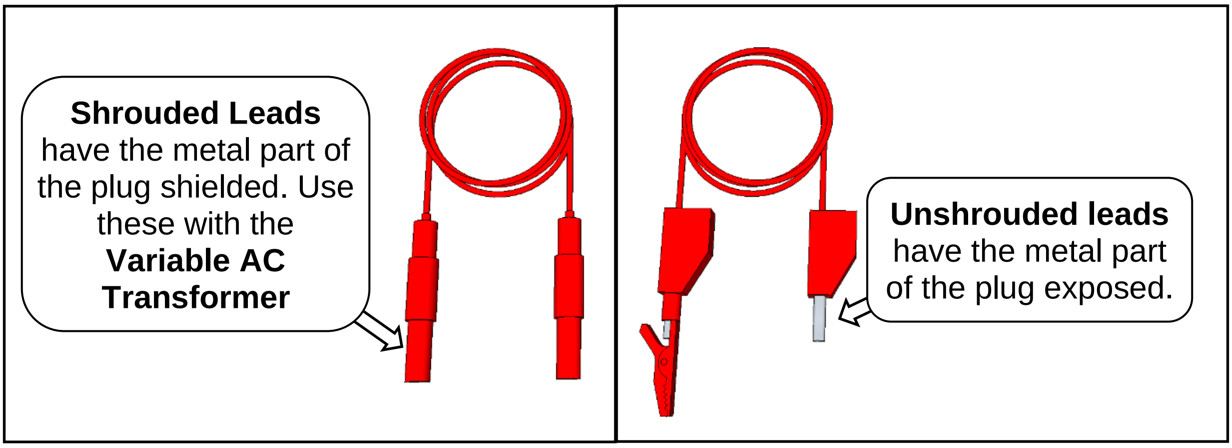


Fig. 8.1d the difference in shrouded and unshrouded leads.

Introduction and Background Physics

Planck's law gives the intensity of black-body radiation I at a single frequency υ as

$$I(\upsilon, T) = \frac{8\pi h}{c^3} \frac{\upsilon^3}{\exp\left(\frac{h\upsilon}{k_B T}\right) - 1} \qquad \text{equation (8.1)}$$

Where:
I = the intensity of black-body radiation
υ = frequency
T = the absolute temperature of the emitter
h = Planck's constant.
c = the speed of light
k_B = the Boltzmann constant

The intensity ratio, measured at the same frequency and at two temperatures T_1 and T_2, is expressed as follows:

$$\frac{I_1}{I_2} = \frac{\exp\left(\frac{h\upsilon}{k_B T_2}\right) - 1}{\exp\left(\frac{h\upsilon}{k_B T_1}\right) - 1} \qquad \text{equation (8.2)}$$

where I_1 represents the intensity at temperature 1 and I_2 the intensity at temperature 2.

For conditions like those in this experiment when $h\upsilon >> k_B T$, equation (8.2) can be approximated as

$$\frac{I_1}{I_2} = \frac{\exp\left(\frac{h\upsilon}{k_B T_2}\right)}{\exp\left(\frac{h\upsilon}{k_B T_1}\right)} \qquad \text{equation (8.3)}$$

To facilitate an estimate of Planck's constant, equation (8.3) is rewritten as

$$\ln\left[\frac{I_1}{I_2}\right] = \frac{-h\upsilon}{k_B}\left[\frac{1}{T_1} - \frac{1}{T_2}\right] \qquad \text{equation (8.4)}$$

It is important to note that this equation is based on the ratio between two intensities and the relative difference between their temperatures. To emphasise this point, equation (8.4) is rewritten in terms of a reference intensity, I_{Ref} , at a reference temperature, T_{Ref} , as follows:

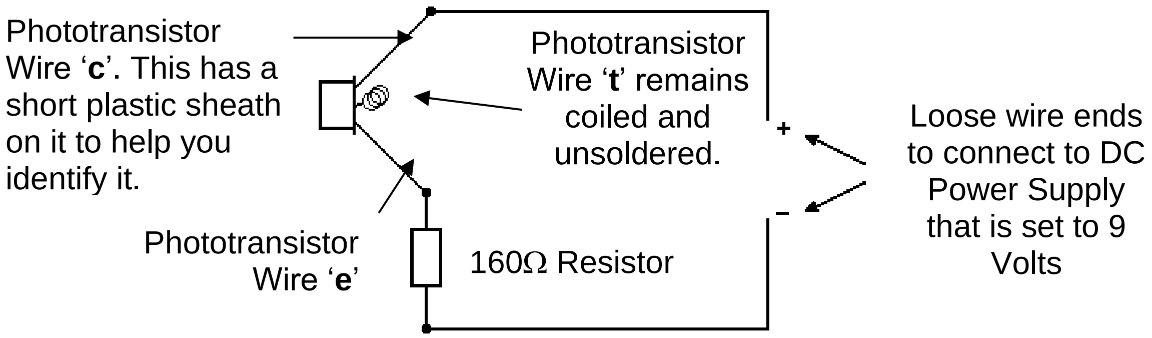
$$\ln\left[\frac{I_{\text{Ref}}}{I}\right] = \frac{-h\upsilon}{k_B}\left[\frac{1}{T_{\text{Ref}}} - \frac{1}{T}\right] \qquad \text{equation (8.5)}$$

Experimental Procedure

Task 1: Building the Smaller Soldered Circuit
Using a small piece of circuitboard, components and solder supplied, build the circuit in figure 8.2 below which contains the phototransistor, the 160Ω resistor and the 2 pieces of single core wire.

You will be shown how to solder and use circuitboard by the Demonstrator, there are also instructions in Appendix 8.2 which starts on page 145 which are also available as a handout in the lab. You could also look up 'How to solder' online as preparation for this lab, there are a number of videos available which cover the basics. There will be some old circuitboard and loose wire in the lab for you to practise with if you want to before you solder your circuit for this experiment. **When soldering ALWAYS WEAR THE GOGGLES PROVIDED**.

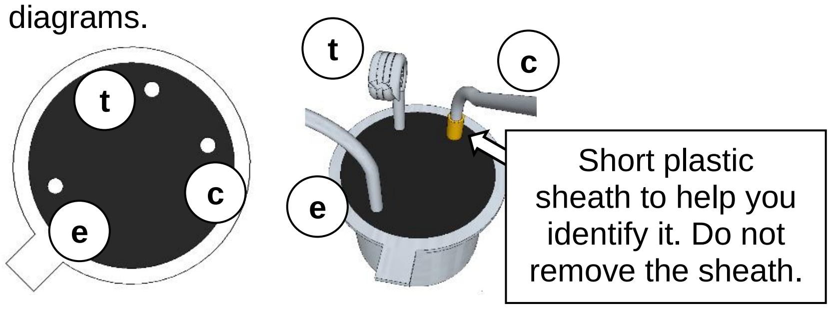
Fig. 8.2 The circuit to be built using the circuitboard.



The phototransistor wire 't' **should be left coiled** up not soldered to anything. Also, make sure that you keep the phototransistor wires 'c' and 'e' long so that the head of the phototransistor can be easily pushed through one side of the black box that houses the lightbulb.

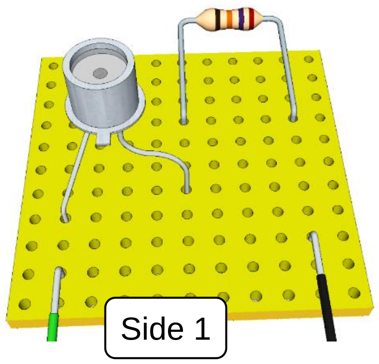
To properly identify each of the phototransistor wires, point the wires towards you and make reference to the following diagrams.

Fig. 8.3. The Phototransistor wires viewed from the bottom. Identification diagram and corresponding picture



When the circuit is finished it should look something like this in figures 8.4a and 8.4b:

Fig. 8.4a.



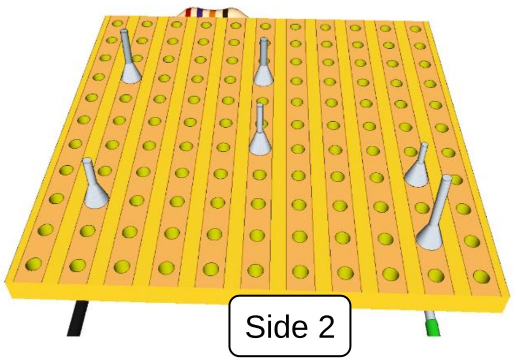


Fig. 8.4b

If your circuit is soldered incorrectly, the experiment will not work. When in use if you think your soldered circuit may be faulty then tell your Demonstrator immediately. Only as a last resort you can use a pre-constructed/tested working circuit so you can do the experiment without spending and inordinate amount of time soldering.

Task 2: Setting up the Larger Circuit.

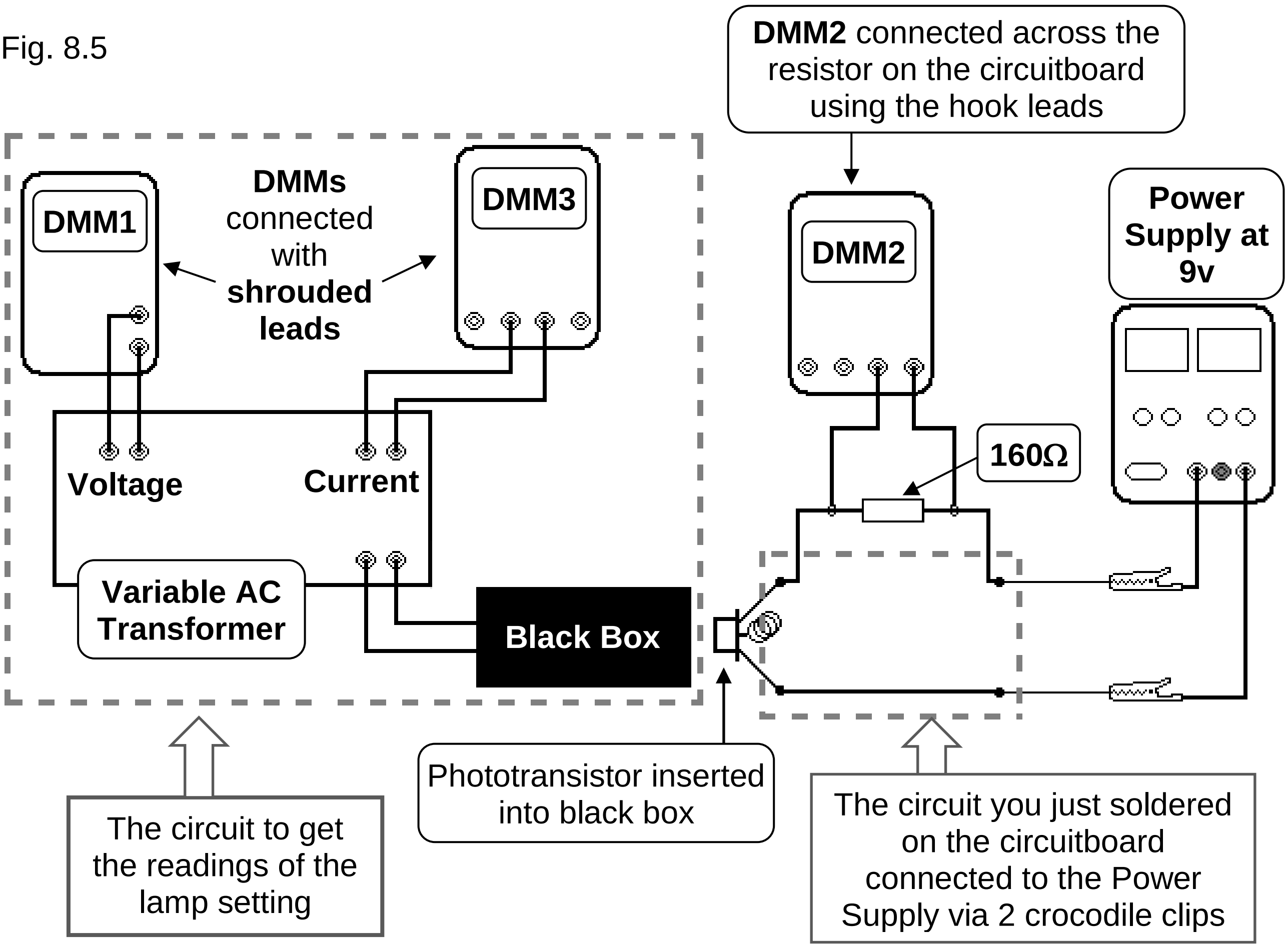
Set the equipment up as indicated in figure 8.5 below. **Please note that if either circuit is wired up incorrectly, the experiment will not work.**

SAFETY: It is **VERY** important that DMM1 and DMM3 are connected to the Variable Transformer **using the shrouded leads provided**. If you use the wrong leads, you are at risk of an electric shock.

Build the circuit on the left of figure 8.5 using the Variable AC Transformer, 2 Digital Multimeters (DMM1 & DMM3) and the Black Box. Connect DMM1 to the Voltage terminals and connect DMM3 to the Current terminals using the **Shrouded Leads** provided.

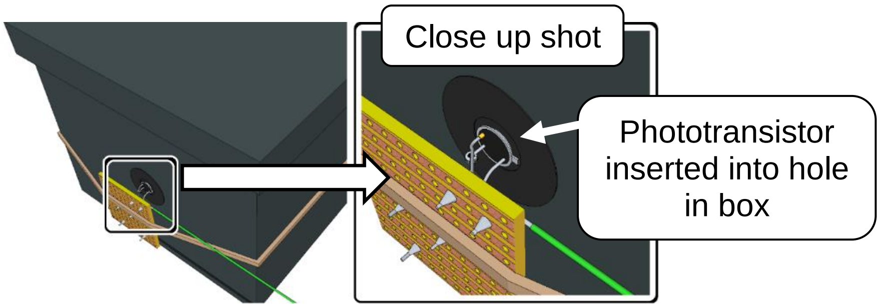
Then build the circuit on the right of figure 8.5 by setting the Power Supply Unit to 9V using Digital Multimeter (DMM2) to check the output before wiring that up as shown. Then connect the circuit you just soldered to the Power Supply Unit using the Unshrouded Leads and the crocodile clips. Attach Digital Multimeter (DMM2) to the 160Ω Resistor using the Hook Leads.

Fig. 8.5



The circuit you soldered on the circuitboard should be inserted into the black box like this:

Fig. 8.6.



Once you have built these circuits, ask the Demonstrator to check you have wired them up correctly before continuing.

Task 3: Takings Readings and Calculating Planck's Constant

3.1) Create a table in your lab notebook as shown below. Please note in the table the set voltages that you need to use on the Variable AC Transformer. **Please note that the dial on this instrument does not reflect the actual output voltage, the output dial shows a % of 240V. The actual output voltage should be read from the Digital Multimeter DMM1.**

V	i	P	R	T		i_p
Set and Measure	**Measure**	**Calculate**	**Calculate**	**Calculate**	**Measure**	**Calculate**
AC lamp voltage applied, in (V)	AC lamp Current, in (A)	Lamp Power, in (W)	Lamp resistance, in (Ω)	Lamp temperature, in (K)	Resistor DC Voltage in (V)	Phototransistor Current, in (A)
60						
70						
80						
90						
100						
110						
120						
130						
140						
150						
160						
170						
180						

3.2) Take measurements of the AC lamp current on DMM3 and the Voltage across the Resistor on DMM3 as you vary the Variable AC Transformer voltage, and also record the AC Voltage on DMM1, along with their associated uncertainties and record these in the table.

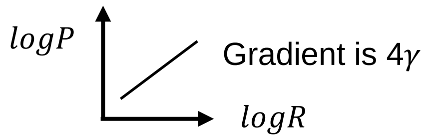
3.3) Calculate the Lamp Power and Lamp Resistance from your results using $P = iV$ and $R = V/i$. Pay attention to the units used.

$$P = A\sigma T^4 \qquad \text{equation (8.6)}$$

Stefan's Law is invoked to relate the lamp's emitted power, P, to the lamp's temperature, T, where A is the surface area of the emitter and σ is Stefan's constant. If it is assumed that $T \approx R^{\gamma}$, where R is the Lamp Resistance then Stefan's law can be rewritten as

$$P = A\sigma R^{4\gamma} \qquad \text{equation (8.7)}$$

Plotting the logarithm of the **calculated** lamp power versus the logarithm of the lamp resistance gives a straight-line graph where the gradient is 4γ



This allows you to generate the empirical equation

$$T = \left[\frac{R}{R_0}\right]^{\gamma} T_0 \qquad \text{equation (8.8)}$$

where T_0 = 463K and R_0 = 182.6Ω.

3.4) Plot a graph of $\log P$ versus $\log R$ from your results and find your value of γ (along with its uncertainty $\Delta\gamma$) from the gradient.

3.5) Using your value of γ, calculate the lamp temperatures T from the lamp resistances R for all your values using equation (8.8)

3.6) Calculate the Phototransistor Current from your measurements of the Voltage across the 160Ω Resistor. Assuming the intensity of the radiation I is proportional to the phototransistor current i_p as explained earlier in this script, plotting a graph of $\ln\left[\frac{(i_p)_{\text{Ref}}}{i_p}\right]$ versus $\left[\frac{1}{T_{\text{Ref}}} - \frac{1}{T}\right]$ will give a straight line with $(i_p)_{\text{Ref}}$ and T_{Ref} being the measurements at 60V. The gradient is then $\frac{-h\upsilon}{k_B}$ as shown in equation (8.5)

3.7) Calculate a value of Planck's Constant h along with its uncertainty using the value of gradient of your graph and the frequency value υ of 3.41 x 10^{14} Hz which corresponds to the peak response frequency value for the phototransistor.

What to include in your Lab Notebook

1) A short Introduction describing the Experimental Aims and including any target values with references.
2) A short method section with schematic diagrams of the apparatus. You may also want to develop the key physics equations as a reminder of what you will measure and how you will do the analysis.
3) A table of the measurements and calculations for the various parameters.
4) A graph of Log(P) vs Log(R) to determine γ.
5) A graph of $ln\left[\frac{(i_p)_{\text{Ref}}}{i_p}\right] = -\frac{h\upsilon}{k_B}\left[\frac{1}{T_{Ref}} - \frac{1}{T}\right]$ to determine h.

6) A final Conclusion section with a discussion of the results and answering the following questions:
   - Were both graphs linear, and so did the measured data confirm our original hypotheses?
   - Did the calculated value of Planck's constant h agree with the expected value when the uncertainty in the final calculated value, Δh, was taken into account?
   - If not any suggestions for the reason? Random uncertainties, a systematic uncertainty or incorrect physics?
   - Any suggested improvements to the apparatus or the experimental method for future researchers.

Appendix 8.1: Example data

To help you understand how to interpret your data in terms of an estimate of Planck's constant, you could undertake this exercise before doing the experiment.

Within this experiment you will be monitoring the current output by a phototransistor that is illuminated by a domestic light bulb. The light bulb filament is considered to be the source of radiation with intensity I at a temperature T. Assume that you have performed the experiment with the following results where the intensity of the light emitted from the filament is directly proportional to the phototransistor current.

Phototransistor Current (in A)	Temperature of the light bulb filament (in K)
2.75E-04	1430
4.20E-04	1496
6.54E-04	1558
9.64E-04	1614
1.35E-03	1668
1.81E-03	1718
2.36E-03	1766
3.01E-03	1809

The choice of the reference point is arbitrary and a convenient choice for $(i_p)_{\text{Ref}}$ would be your first phototransistor current data point and its temperature for T_{Ref}. Fill-in the remaining elements of the following table in your lab book using the raw data above and the first element in this table as the reference.

$\ln\left[\frac{(i_p)_{\text{Ref}}(T_{\text{Ref}})}{i_p(T)}\right]$	$\frac{1}{T_{\text{Ref}}} - \frac{1}{T}$
0.00	0.00
etc…	etc…

NOTE: Do not read $i_p(T)$ as the product of the current, i_p, and the temperature, T. Rather, $i_p(T)$ denotes the current as a function of temperature.

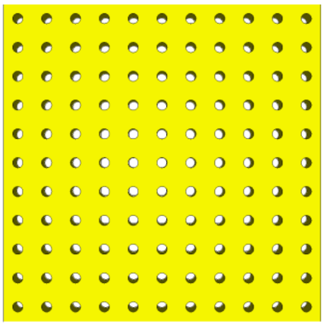
Plot the first column versus the second column and determine a value of h with the help of equation (8.5). For this exercise and the rest of the experiment, you should assume that υ in equation (8.5) is 3.41 x 10^{14} Hz which corresponds to the frequency of the peak response for the phototransistor.

Appendix 8.2: How to solder. Before soldering, read this entire section.

HOW TO USE CIRCUITBOARD

You will be using Circuitboard to solder your components onto in order to make the circuit. It has two different sides, one of which has thin copper strips etched onto it. These copper strips will from part of the circuit so it is important that you solder onto that side and not the blank side. In between the strips is a non-conductive area. It is important when soldering not to let the solder into that non-conductive area or the circuit you build may be faulty.

Side 1 is blank



Side 2 with the copper strips and non-conductive areas. This is the side the solder goes on.

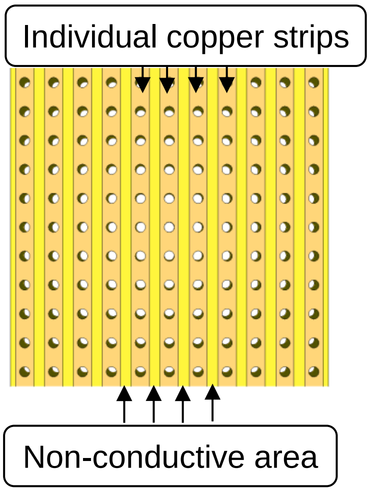
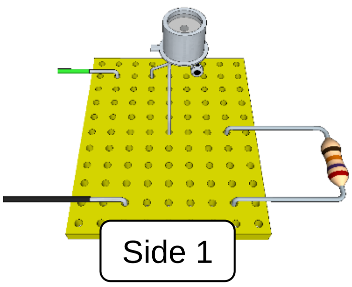
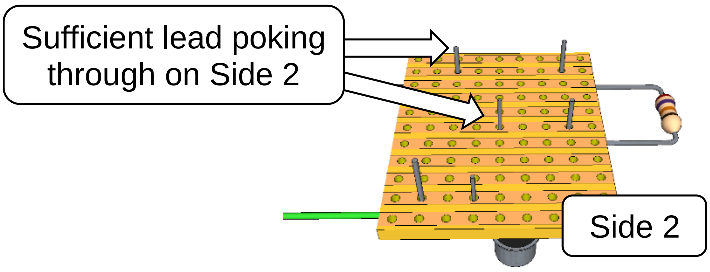


Fig 8.7a and 8.7b Circuitboard sides

When inserting components to be soldered make sure you insert them through Side 1 and that the leads needing to be soldering are sticking out of Side 2. Like so:

Fig 8.8a and 8.8b lead positions

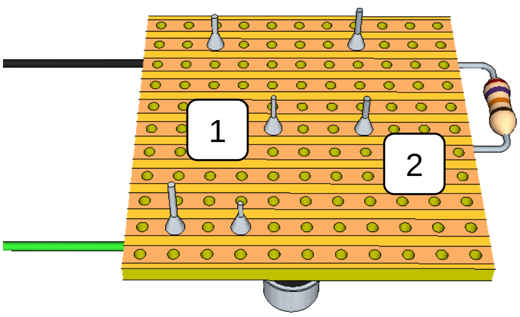


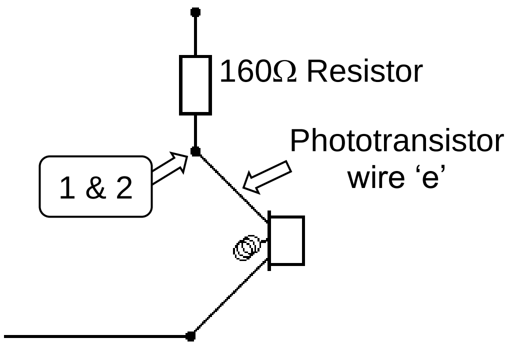


You can then solder the component to the copper strip on Side 2.

It is important that you understand the function of the copper strips on the circuitboard. They act just like a connecting lead between two components. For instance, in this circuit below in figure 8.9a, you can see that the leads soldered into holes 1 & 2 connect one of the ends of the resistor to the emitter 'e' lead of the phototransistor, as in figure 8.9a on the right:

Fig 8.9a and 8.9b





How To Solder

There will be scrap circuitboard and wire available so you can practise soldering before you make your circuit for this experiment if you would like to. We assume that no one knows how to solder before they arrive at university so if you need help then ask.

Read through this section entirely before beginning to solder.

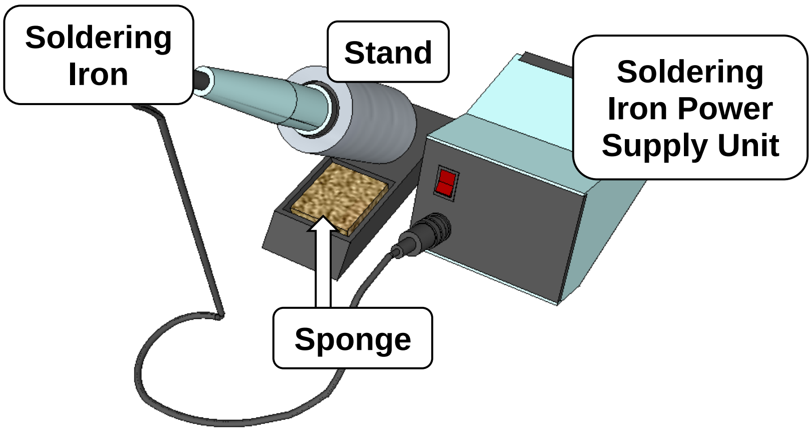


Fig 8.10 Parts of Soldering Iron

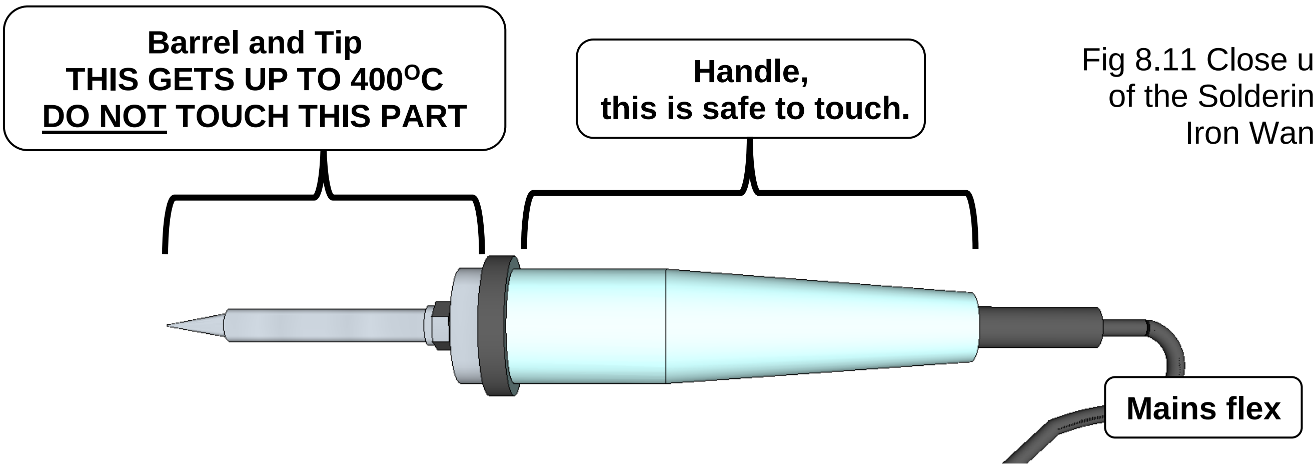


Fig 8.11 Close up of the Soldering Iron Wand

FIRST A FEW SAFETY PRECAUTIONS:

- Never touch the **Barrel** or **Tip** of the soldering iron as shown in figure 8.11. When it is on, these parts get very hot (about 400°C) and will give you a nasty burn if you touch them.
- Take great care to avoid touching the **mains flex** with the tip of the iron.
- **Always return the soldering iron to its stand when not in use. Never put it down on your workbench, not even for a moment!**
- When soldering **ALWAYS WEAR THE GOGGLES PROVIDED**.

Preparing the soldering iron:

1) Dampen the **Sponge** in the stand. The best way to do this is to lift it out the stand and hold it under a cold tap for a moment, then squeeze to remove excess water. It should be damp, not dripping wet.
2) Switch the Soldering Iron on and wait for a few minutes. The Iron needs time to reach its operating temperature of about 400°C.

Preparing the joint to be soldered:

3) Clamp the Circuitboard with the copper strips facing upwards using the clamping tool. This will leave your hands free to solder the joint.

4) Insert the component(s) you want to solder into the Circuitboard into the correct strips. You can use the magnifying lens on the clamp tool if you are having trouble seeing the joint you are soldering.

You are now ready to start soldering. To solder:

5) Hold the Soldering Iron Wand **Handle** like a pen which is indicated in figure 8.11 on the previous page.

6) Wipe the tip of the **Iron** on the damp **Sponge**. This will clean the tip.

7) In your other hand you should have the length of the **Solder** provided **held in a pair of Pliers**. It will get hot when you solder, so it's best not to hold it in your bare hands.

8) Touch the **Soldering Iron** onto the joint to be made as indicated below. **Make sure it touches both the component lead and the track**. Hold the tip there for a few seconds and...

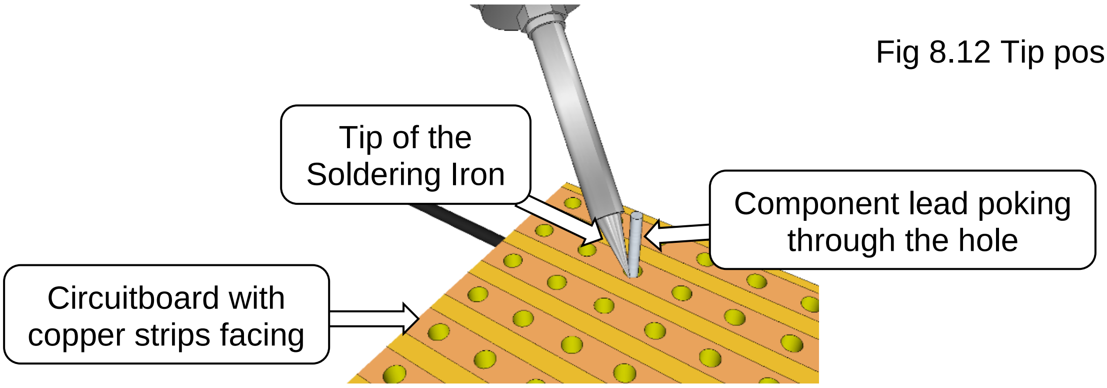


Fig 8.12 Tip position

feed a little solder onto the joint applying the solder to the **joint**, not the tip of the Iron. It should flow smoothly onto the component lead and copper track. Ideally it should form a volcano shape as shown in figure 8.13 below. Apply only as much as is needed. Too little solder and joint will be dry, too much and you risk spreading it onto a neighbouring copper track. Either way it may cause a faulty circuit. Once you have a good join, remove the solder held in the pliers, then the soldering iron, while keeping the joint still. Allow the joint a few seconds to cool before you move the circuitboard or solder another joint.

9) Inspect the joint closely. It should look shiny and have a 'volcano' shape as shown in figures 8.13 and 8.14. If not, you will probably need to reheat it and try soldering it again, check with your demonstrator. A good joint volcano shaped and the solder does not flow onto neighbouring tracks. The component is held firm by the soldering joint.

Fig. 8.13.
good soldering

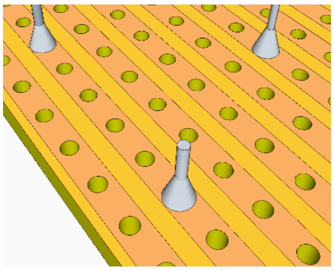
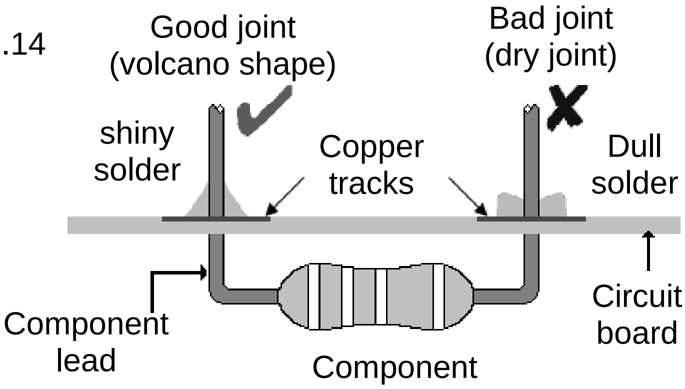


Fig. 8.14



Experiment 9

Measurement of e/m_e of an Electron

Experimental Aims:

- To measure the charge to mass ratio for an electron using a fine beam gas tube inside a constant magnetic field.
- To show the effect of electric and magnetic fields on charged particles and demonstrate the validity of the Lorentz expression.

Learning Objectives:

- To develop skills in making careful observations and taking accurate measurements.
- To further develop skills in using digital multimeters to measure the potential differences and current at different points in an electrical circuit.
- To learn how to compare the equations underpinning the experiment with the equation of a line in order to decide how to present and analyse data graphically.
- To be able to critically evaluate the results of an experiment; to compare measured results with expected values and comment on the agreement within uncertainties.

VITALs

E1 b: Keep a detailed laboratory notebook
E1 d: Produce appropriate graphs or charts

Preparation:
You are expected to have done these things before you turn up to the lab session:

- **Watch the Online Supporting Video** (link is on Minerva) and become familiar with the experimental method and data analysis.
- Read this manuscript and become familiar with the physics behind these experiments.
  - Read the sections on ‘The Force Extended by a Magnetic Field and Motion of a Point Charge in a Magnetic Field in The Magnetic Field’ chapter in Tipler.
  - Make a note of the accepted value for e/m_e from a data book, or a standards bureau website or equivalent.
  - Fill in the online Health & Safety form as described below.

Risk Assessment and Safety:
Read the Health and Safety information on the next page and fill in the online H&S form. The technician will check online that you have filled this in before you start. It can be reached either via this QR code, via the link on MINERVA or this weblink here: https://forms.office.com/e/ZctDcn5V7h

Appendices at the end of this script:
Appendix 9.1: Uncertainty Equations (page 157)

School of Physics & Astronomy	RISK ASSESSMENT RECORD
BUILDING:	Bragg Building, Room 4.08, 1st Year Physics Undergraduate Laboratory
DESCRIPTION OF ACTIVITY:	**EXPERIMENT 9: MAGNETIC FIELDS AND MEASUREMENT OF *e/m* FOR ELECTRONS**

SIGNIFICANT HAZARDS	**EXISTING CONTROL MEASURES**	SEVERITY 1=minor/2=serious/3=major	LIKELIHOOD 1=low/2=medium/ 3=high	RISK RATING
Magnetic Fields	**Students with pacemakers and/or prosthetic implants should make this fact known to the laboratory convener before they start any lab work on this experiment.** Maximum 0.5mT and 1.0mT lines are indicated near each apparatus. The maximum static magnetic field generates is less than 25mT	1	2	2
Evacuated Glass Tube	Do **not** touch the evacuated glass tube.	2	1	2
Hot Coils	Do **not** touch the Helmholtz coils when the Power Supplies are switched on as they become hot during use.	1	1	1
Electrical equipment	All equipment to have an up to date PAT test sticker. No such instrument should be tampered with or have its plug or fuse replaced. If an electrical item appears to be faulty, consult the Laboratory Technician.	2	1	2

PEOPLE AT RISK	**ADVERSE EFFECTS**	ACTIONS TO BE TAKEN & TIMESCALES
All students, demonstrators and staff members	Electrical shock Implosion of evacuated glass tube Burning Magnetic Fields	If an electrical item appears to be faulty, consult the laboratory technician. Do not touch the glass tube. Do not touch the coils as they become hot during use Students with pacemakers and/or prosthetic implants should make this fact known to the Lab Convener before they start any work on this experiment

	Name	**Signature**	**Date**
ASSESSED BY:	Angela Beddows (Technician)		27/07/2024
GROUP HEAD:	Dr Peter Hine (Laboratory Convener)		27/07/2024
SAFETY SUPERVISOR:	Stuart Weston (Department Safety Officer)		27/07/2024

Experiment Apparatus

Fig 9.1a Fine-Beam Tube Apparatus

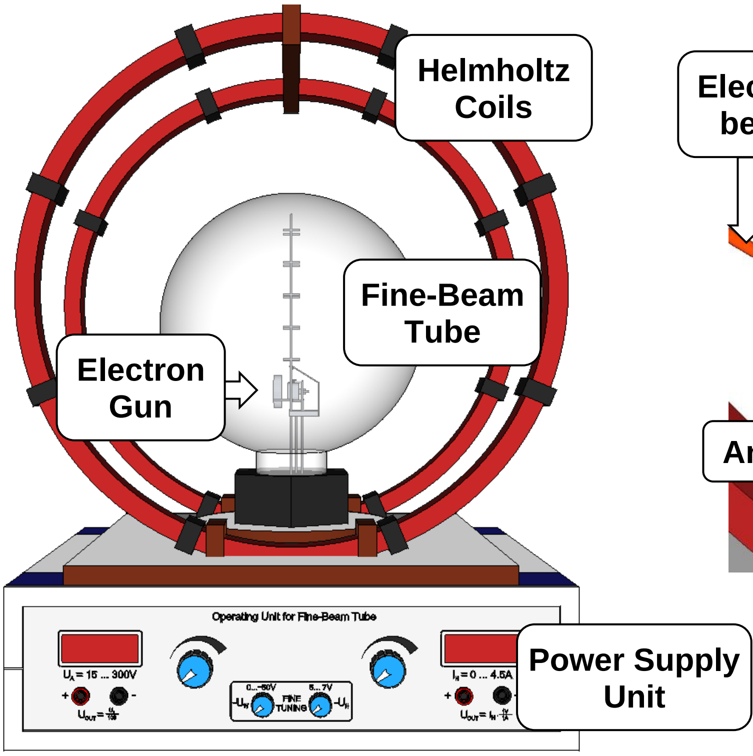
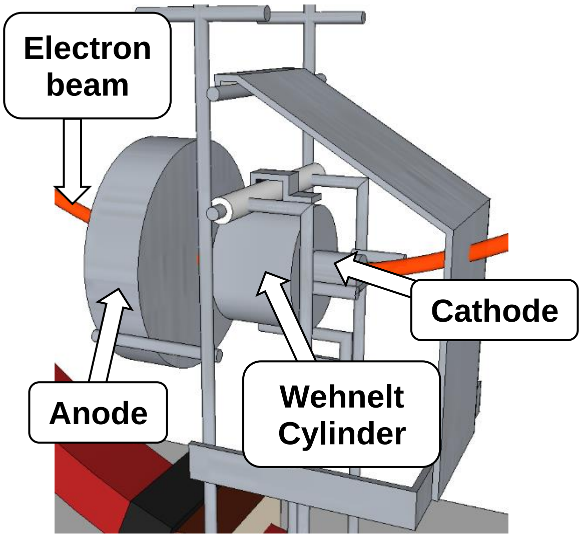
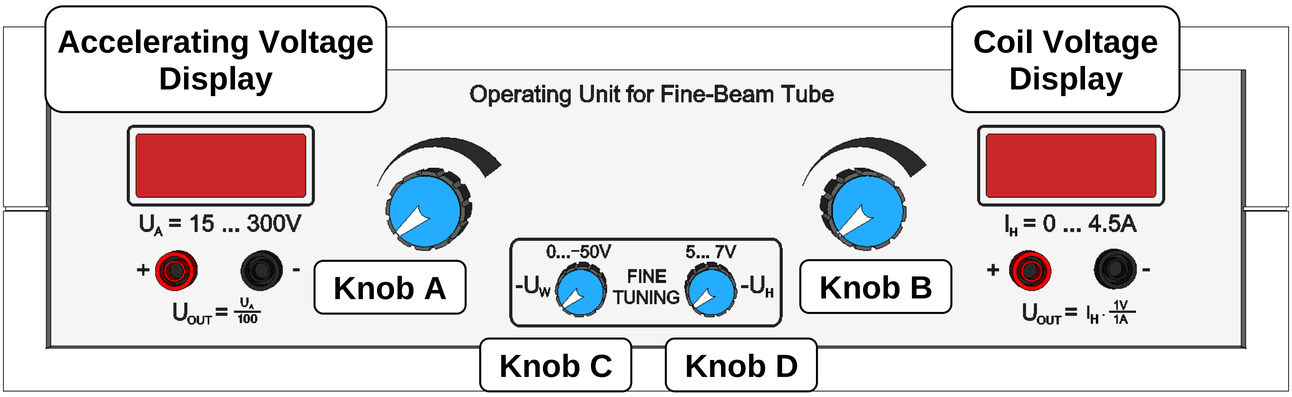


Fig 9.1b close up of electron gun



The **Fine Beam Tube Apparatus** is an evacuated glass tube containing Helium, sitting equidistant between two **Helmholtz Coils**. The Helmholtz coils are a special arrangement of coils, where they are placed the same distance apart as their radius. In this configuration the Helmholtz coils produce an even magnetic field which then surrounds the emitted electron beam which is then deflected into a circular orbit.

Fig 9.1c close up of beam Power Supply Unit



The base unit contains Power Supplies for the following:

a) Accelerating voltage to the anode contained within the Fine Beam Tube, which can be adjusted using **Knob A**, the uncertainty in the display is ± 1V.

b) DC power to the Helmholtz coils which generate the magnetic field, which can be adjusted using **Knob B**, the uncertainty in the display is ± 1V.

c) a Wehnelt cylinder which focusses the electron beam, which can be adjusted using **Knob C**.

d) Voltage to the heater (cathode) which generates the electron beam, and can be adjusted using **Knob D**

Inside the **Fine Beam Tube**, a sharply delimited electron beam is generated by a system comprising of an indirectly heated oxide cathode, a perforated anode and a Wehnelt cylinder which is used to focus the electron beam. Impact ionisation of helium atoms creates a very bright sharply delimited trace of the electron path in the tube. The electron beam is accelerated through a potential difference of V volts, emerging from the hole in the apex of the conical anode as shown in figure 9.2a.

Without an applied magnetic field in the Coils, the electron beam will be horizontal (Figure 9.2a) and with the field applied it forms a circular orbit (Figure 9.2b).

Fig 9.2a electron beam no magnetic field

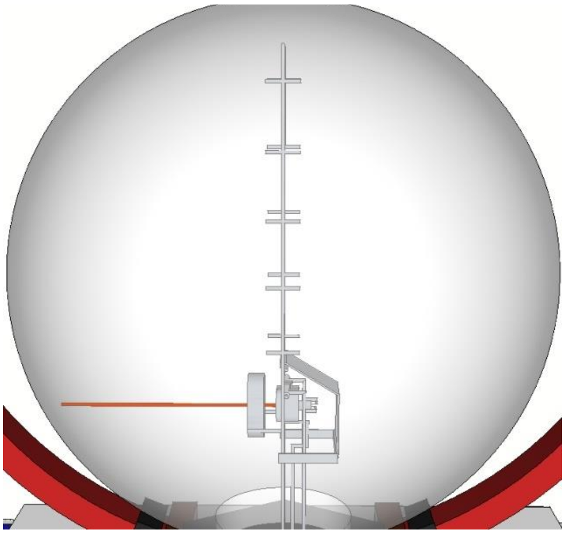
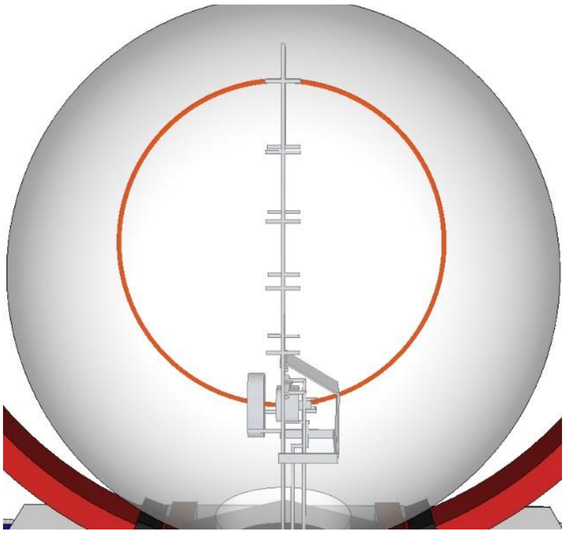
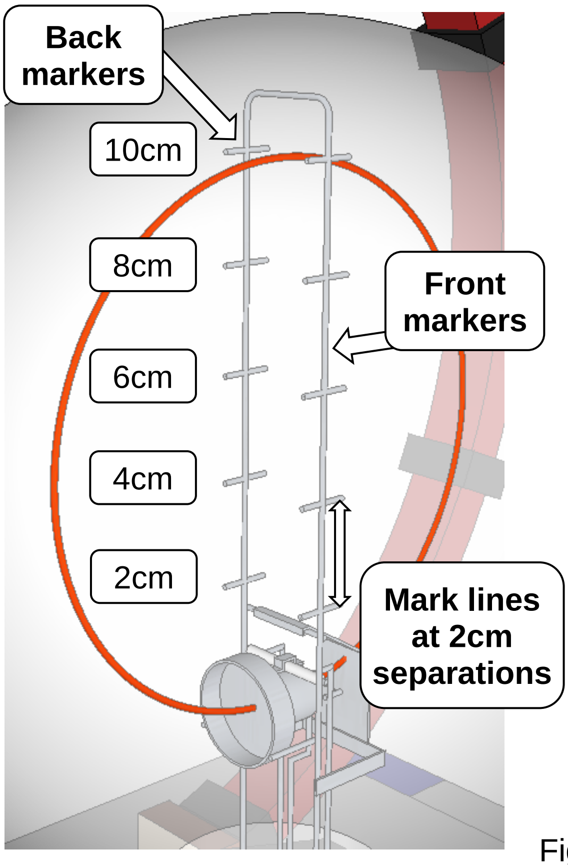


Fig 9.2b magnetic field applied





Both back and front wire measurement markers are located in the centre of the **Fine Beam Tube** as shown in Figure 9.3. The two sets of marks, one in front and one behind the beam allow both vertical and horizontal parallax to be compensated for. Indicating marks are set at 20, 40, 60, 80 and 100mm from the beam exit.

In Figure 9.2b above, the picture is located such that the back and front grids are aligned (horizontal alignment) and that the 100mm front and back marks are aligned. If using your eye, it can be better to close one eye to make this measurement more reproducible.

Fig 9.3 The measurement markers in the **Fine Beam Tube** for determining the diameter of the circular orbit of electrons.

Introduction and Background Theory

The Lorentz force describes the force on a charged particle (of charge e) moving with velocity v in a magnetic field of induction B. It is given by:

$$\boldsymbol{F} = e(\boldsymbol{v} \times \boldsymbol{B}) \qquad \text{equation (9.1)}$$

this is the vector cross product of v with B, where θ is the angle between v and B, which can be rewritten as

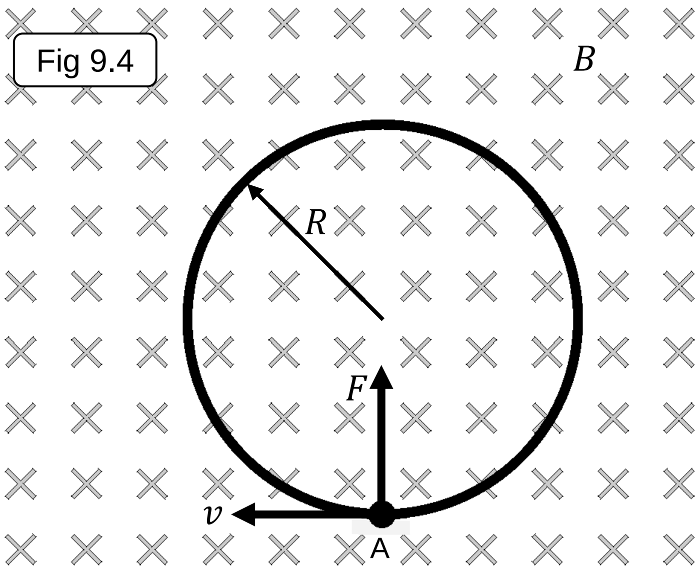
$$F = evBsin\theta \qquad \text{equation (9.2)}$$

This can be simplified even further when v and B are perpendicular to each other in which case θ = 90º (= 1) to give:

$$F = evB \qquad \text{equation (9.3)}$$

Here the force is perpendicular to both v and B causing the particles to move in a circular orbit. Therefore the Lorentz Force is equal to the Centripetal Force on the electron. Thus, as illustrated in figure 9.4, an electron at point A moving with a velocity v in a homogeneous magnetic field of strength B which is perpendicular to the plane of the paper (pointing towards you) experiences a force F in the plane of the diagram which deflects it vertically (remember that e is negative for an electron)

Fig 9.4



The force, F, remains perpendicular to the new direction and has the same magnitude, so a circular path results - the force eVB providing the necessary centripetal force $\frac{m_e v^2}{R}$ for a circular path of radius R.

So this can be described in the following equation:

$$\frac{m_e v^2}{R} = evB \qquad \text{equation (9.4)}$$

Where:

m_e = mass of an electron (in kilogrammes)
v = velocity the electron is travelling at (in metres per second)
R = radius of the circle the electron is travelling in (in metres)
e = electron charge (in coulombs)
B = strength of the magnetic field the electron is travelling in (in tesla)

This leads to

$$\frac{e}{m_e} = \frac{v}{BR} \qquad \text{equation (9.5)}$$

The velocity of the electrons is quite hard to measure but in this experiment they are accelerated by a potential difference, V, between the cathode and the anode. As a result of this we can equate the electric potential energy (eV) with the kinetic energy gained as:

$$\frac{1}{2}m_e v^2 = eV \qquad \text{equation (9.6)}$$

Combining equations (9.5) and (9.6) we can eliminate the velocity entirely and rewrite the equation as:

$$\frac{e}{m_e} = \frac{2V}{(R.B)^2} \qquad \text{equation (9.7)}$$

and then

$$V = B^2\left(\frac{e}{m_e}.\frac{R^2}{2}\right) \qquad \text{equation (9.8)}$$

So for any accelerating Voltage, V, the electron beam will travel in a circular path whose diameter ($2\,R$) is governed by the applied magnetic field B. In this experiment we will choose a fixed diameter for a set of readings, set by one pair of the markers inside the fine beam tube (Figure 9.3). The markers are set at distances of 20, 40, 60, 80 and 100mm from the anode tip. They are also placed either side of the emerging beam to allow for parallax to be removed.

So for the first chosen diameter, choose an accelerating voltage between 200 and 300V and then vary the coil current so that the electron beam has the correct diameter. The suggestion is to pick at least five voltages for each chosen diameter and take measurement for at electron beam diameters of 40, 60, 80 and 100mm.

Finally, a plot of $2\,V$ against R^2B^2 for all the data should give a straight line through the origin with a gradient of $\frac{e}{m_e}$.

Calculating the Magnetic Field:

The Helmholtz coils provide an approximately uniform magnetic field over the region of the tube. To calculate the magnetic field B from our values of current, I, in the Coil we need to use the Helmholtz equation:

$$B = kI \qquad \text{equation (9.9)}$$

where k is the theoretical value and is given by:

$$k = 0.721\mu_0\left(\frac{n}{d}\right) \qquad \text{equation (9.10)}$$

where:

B = strength of the magnetic field (in Tesla's)
n = number of turns in one coil = 124
I = current in the coil (in Amps)
d = the separation of the coils = 0.1475 metres
μ_0 = permeability of free space (vacuum) = 4π x 10^{-7}Hm^{-1} (Henry's per metre), as the electrons are in a vacuum tube in this experiment.

Note that for this experiment the uncertainty equations are given in the appendix.

Experimental Procedure

Task 1: Set up and preliminary observations.

The e/m apparatus will be setup in the darkroom. You are welcome to experiment with the lighting to give your best results for measuring results from the electron beam diameter. A large **Black Foam Board Shield** is also supplied to help with alignment.

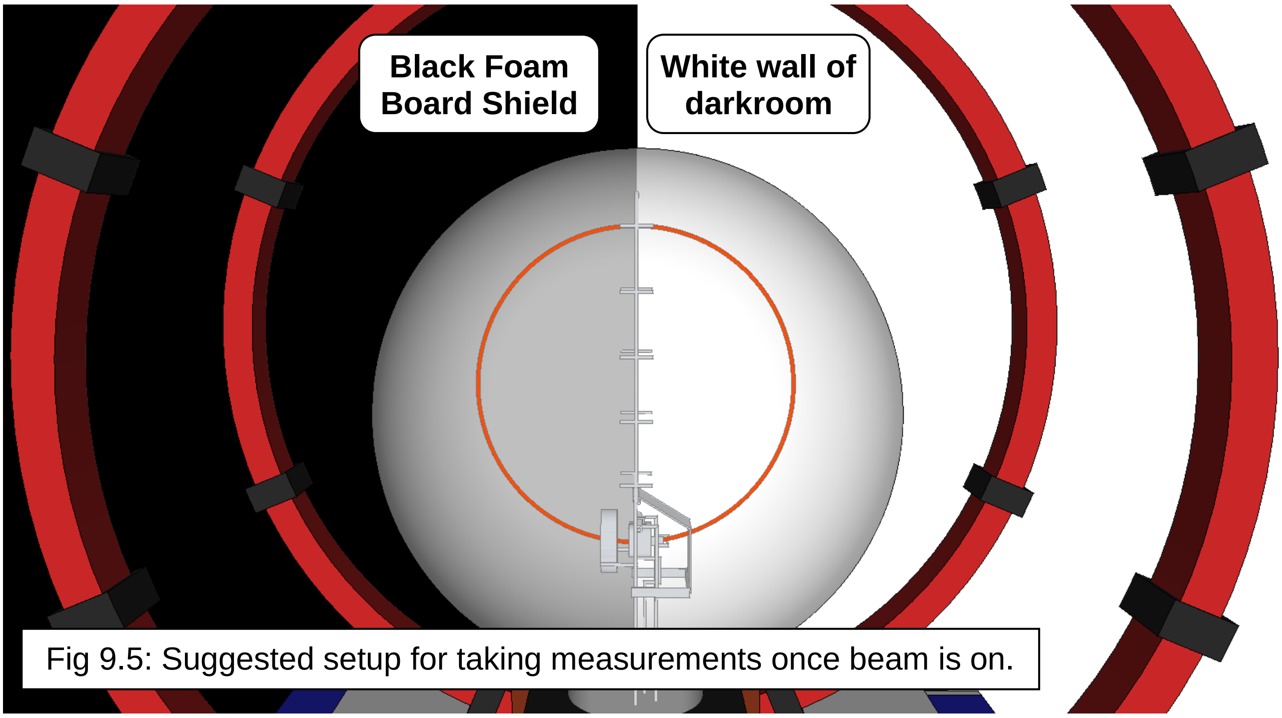


Fig 9.5: Suggested setup for taking measurements once beam is on.

1.1) Place the black foam board shield at the back of the unit so that it aligns with the vertical line of the marker grids inside the Fine Beam Tube as shown in Figure 9.5. When the room is darkened the circular electron beam can then be seen on the left-hand side against the black background, while the markers can be seen against the white wall of the darkroom as illustrated in Figure 9.5 above. You could also experiment with the table lamp to illuminate the wall/markers to get the best contrast.

1.2) Switch the unit on at the back and adjust the heater voltage using **Knob D** to the middle position, which will provide ~6 Volts. The anode/cathode assembly should start to glow.

1.3) Set **Knob B** for the coil current to zero. Wait for a minute for the heater temperature to stabilise.

1.4) Turn **Knob A** for the anode Voltage and set it to ~300V. The electron beam will be horizontal (Figure 9.2a).

1.5) Turn **Knob C** to adjust the Wehnelt voltage to focus the beam so that a very clear and narrow electron beam is visible.

1.6) Turn **Knob B** to increase the current passing through the Helmholtz coils and check that the electron beam curves upwards.

1.7) Further increase the current in the coils, this will increase the magnetic field. What happens? does the electron beam diameter get bigger or smaller? And why?

1.8) Increase the accelerating Voltage V using **Knob A**. What happens? Does the electron beam diameter get bigger or smaller? And why?

Record the above observations to your lab notebook.

Task 2: Data collection and analysis.

2.1) Start with an electron beam diameter of 100mm (the top set of markers). Choose a starting Accelerating Voltage (e.g. 200V) and vary the Coil Current such that the electron beam aligns with the 100mm markers. Use the horizontal makers at the front and back to reduce parallax for setting this diameter.

- What do you think the uncertainty of this measurement is?
- If you increase the current to make the electron beam smaller and then come back again do you get the same current?
- What is the thickness of the horizontal grid markers and does this affect your accuracy? Is this an uncertainty in the diameter or the current or both?

2.2) Create a table in your Lab Notebook or an MS Excel spreadsheet similar to the one shown below to record your readings along with their uncertainties for setting the electron beam diameter to 100mm. If you need help using MS Excel, please ask the Demonstrator.

Electron Beam diameter:	$\boldsymbol{2R}$ = 100 ± $\Delta\boldsymbol{R}$? (mm)							
Accelerating Voltage $\boldsymbol{V}$ $\Delta\boldsymbol{V}$ = ?	Current, $\boldsymbol{I}$	$\Delta\boldsymbol{I}$	Calculated Field $\boldsymbol{B}$	$\Delta\boldsymbol{B}$	$\boldsymbol{B^2}$	$\Delta\boldsymbol{B^2}$	$\boldsymbol{R^2B^2}$	$\Delta\boldsymbol{R^2B^2}$
Units: Volts	Amps		Tesla		Tesla^2		m^{2}Tesla^2	Tesla^2
200								
220								
240								
260								
280								
300								

2.3) Repeat for other accelerating Voltages, ranging from 220, 240, 260, 280 and 300V (300V is the maximum you should use for all the experiments) and record your results along with their associated uncertainties.

2.4) Calculate the magnetic field strength along with its uncertainty B ± ΔB using equation (9.7), and then the field squared B^2 ± ΔB^2.

2.5) Calculate the product squared R^2B^2 ± ΔR^2B^2. For this of measurements for 2R = 100mm.

2.6) Repeat Tasks 2.2 to 2.5 and measure (and create a Table for each) for setting the electron beam diameter to 80mm, 60mm and 40mm. For each electron beam diameter you can vary the chosen accelerating Voltages (for example odd values of 210, 230, 250, 270 and 290V). You could also do one set of measurements where you approach the set diameter from a larger value and another set where you approach the set diameter from below. Do you bias the current depending on which direction you approach from?

2.7) Plot a graph of $2V$ vs R^2B^2 and calculate the gradient and its uncertainty. You should include error bars for both $2V$ and R^2B^2 on to your graph.

Use the LINEST function in MS Excel to determine the gradient and its uncertainty of this graph. This will be the prediction of the value of the charge to mass ratio for an electron $\frac{e}{m_e}$ along with its uncertainty.

What to include in your Lab Notebook

1) A short Introduction describing the Experimental Aims including the expected target value with a reference.
2) A short method section explaining what you did, also include labelled schematic diagrams of the apparatus.
3) You may also want to develop the key physics equations as a reminder of what you will measure and how you will do the analysis including the uncertainty analysis.
4) A table of the measurements and calculations for the various parameters and their uncertainties.
5) A graph of graph of $2V$ vs R^2B^2 including uncertainty bars.
6) In your Conclusion state your final calculated value of $\frac{e}{m_e}$ along with its uncertainty and compare and comment on comparison to the expected value.

Also answer the following questions:
- Did your points, together with their uncertainties touch the best fit line? If not, what could be an additional source of an uncertainty that is not included?
- Was the expected value within your calculated uncertainty or not?
- Any random or systematic uncertainties that should be considered?
- Any suggested improvements to the apparatus or experimental method?

Appendix 9.1: Uncertainty equations

$\frac{\Delta B}{B} = \sqrt{\left(\frac{\Delta k}{k}\right)^2 + \left(\frac{\Delta I}{I}\right)^2}$ where $\frac{\Delta k}{k} = \frac{\Delta d}{d}$
$\Delta(B^2) = 2B.\Delta B$
$\Delta\left(\frac{e}{m}\right) = \sqrt{\left(\frac{\Delta\text{gradient}}{\text{gradient}}\right)^2 + \left(\frac{2\Delta R}{R}\right)^2} \cdot \left(\frac{e}{m}\right)$

Experiment 10

Measurement of Stefan's Constant

Experimental Aims:
- To obtain an accurate value for Stefan's constant.
- To demonstrate the validity of Stefan's Law and the practical limitations of this model.

Learning Objectives:
- To learn how to use data loggers and computer data collection software.
- To gain experience using MS Excel to analyse large data sets and plot graphs for selected regions of data to minimise the uncertainty in the final value.
- To practice complex data analysis skills to determine the final value and the uncertainty in this value.
- To be able to critically evaluate the results of an experiment; to compare measured results with expected values and comment on the agreement within uncertainties.
- To be able to suggest plausible explanations for any differences between the measured and expected results.

VITALs

E1 b: Keep a detailed laboratory notebook
E1 c: Perform appropriate calculations

Preparation:
You are expected to have done these things before you turn up to the lab session:
- **Watch the Online Supporting Video** (link is on Minerva) and become familiar with the experimental method and data analysis.
- Read this manuscript and become familiar with the physics behind these experiments.
- Read the section on 'The Transfer of Heat' in Tipler and find out what emissivity means.
- Fill in the online Health & Safety form as described below.

Risk Assessment and Safety:
Read the Health and Safety information on the next page and fill in the online H&S form. The technician will check online that you have filled this in before you start. It can be reached either via this QR code, via the link on MINERVA or this weblink here: https://forms.office.com/e/x93B4yazhU

WARNING: The Steam Generator, Radiator, Tubing & Condenser apparatus will get very hot during use, please be careful and use the safety equipment when the experiment is underway. When the water level light on the Steam Generator turns on, ask the demonstrator or technician of staff to refill it for you.

WARNING: Water sometime collects in the Radiator. If you hearing bubbling noises coming from the Radiator, please notify a member of the lab staff so it can be safely emptied.

WARNING: The Condenser will become hot during use (as it's doing its job by extracting heat from the steam to cool it into water), please be careful when working near the trough of water.

Appendices at the end of this script:
Appendix 10.1: Uncertainty Equations (page 163)

School of Physics & Astronomy	**RISK ASSESSMENT RECORD**
BUILDING:	Bragg Building, Room 4.08, 1st Year Physics Undergraduate Lab
DESCRIPTION OF ACTIVITY:	**EXPERIMENT 10: Stefan’s Constant**

SIGNIFICANT HAZARDS	**EXISTING CONTROL MEASURES**	SEVERITY 1=minor/2=serious/ 3=major	LIKELIHOOD 1=low/2=medium/ 3=high	RISK RATING
Radiator	Take care with the radiators as they can become hot.	2	2	4
	Can fill with water during the experiment. If they need emptying then ask the lab Technician.	1	2	1
Steam Generator	Take care with the Steam Generators as they become hot with use.	2	2	4
	Keep an eye on the water level indicator. If it lights up ask your Demonstrator or the Technician to refill it.	1	1	2
Electrical equipment	All equipment to have an up to date PAT test sticker. Some of the instruments used are powered by mains electricity. No such instrument should be tampered with or have its plug or fuse replaced.	1	1	1

PEOPLE AT RISK	**ADVERSE EFFECTS**	**ACTIONS TO BE TAKEN & TIMESCALES**
All students, demonstrators and staff members	Electrical shock Burns Steam burns	If an electrical item appears to be faulty, consult the laboratory technician. Apparatus will become hot with prolonged use so take care when handling.

	Name	**Signature**	**Date**
ASSESSED BY:	Angela Beddows (Technician)	Angela Beddows	27/07/2023
GROUP HEAD:	Dr Peter Hine (Laboratory Convener)	P.J. Hine	27/07/2023
SAFETY SUPERVISOR:	Stuart Weston (Department Safety Officer)	[illegible]	27/07/2023

Experimental Apparatus

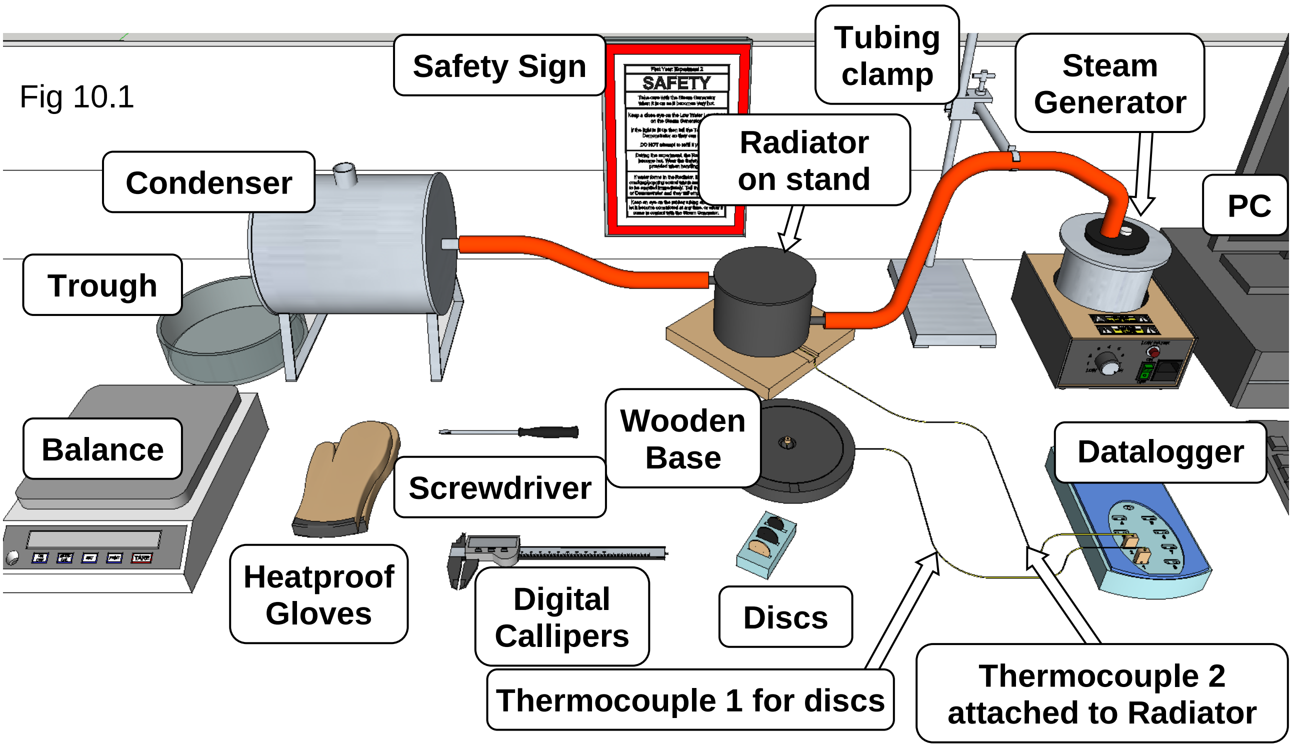


Fig 10.1

The apparatus consists of a **Steam Generator** which is two thirds full of water. When hot enough this generates steam which is carried through rubber tubing to the **Radiator** (painted black) which sits on its own stand. This has a light to indicate if the water level is too low. A **Tubing Clamp** prevents the tube from coming into contact with the surface of the Steam Generator. Steam passes through the tubing into the bottom of the **Radiator** where it rises, heats the Radiator and then passes through the **Condenser** to cool (and drains into a **Trough**). During the experiment the Radiator and Steam Generator bung must be handled with a pair of **Heatproof Gloves** as they become very hot. Two Thermocouples are connected to a **Datalogger** which is connected to a laptop so temperature readings can be recorded. The **Wooden Base** contains **Thermocouple 1** to attach to the **Copper Discs** in turn and **Thermocouple 2** is soldered to the underside of the Radiator as shown in figure 10.2 below.

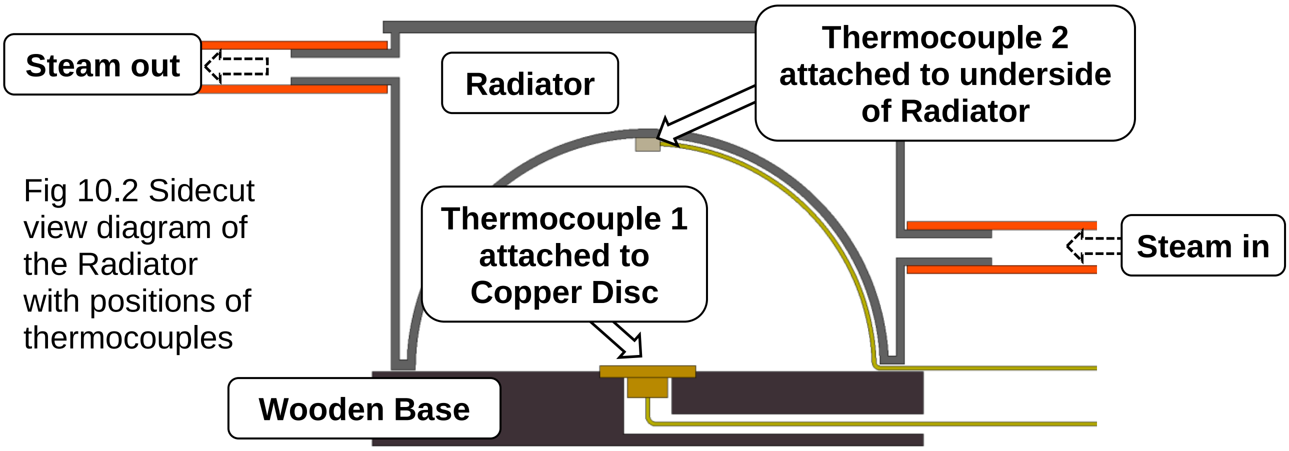


Fig 10.2 Sidecut view diagram of the Radiator with positions of thermocouples

Three **Copper Discs**, two blackened discs of different sizes and one shiny disc are used during the experiment being placed in turn on top of Thermocouple 1 using the **Screwdriver**. **Digital Callipers** and a **Balance** are used to measure the diameters and masses of the three discs. When the experiment is underway and the Radiator is at a constant temperature, the measurement proceeds by putting the disc under investigation onto the Wooden Base and using the Heatproof Gloves to place the Radiator onto this base. The heating rate for the disc is then measured until it reaches a temperature of ~30°C.

Introduction and Background Theory

According to Stefan's Law the total energy, U, in Joules per second, emitted each second from 1m^2 of a black body at temperature T (in Kelvin) is given by

$$U = \sigma T^4 \text{ Js}^{-1} \qquad \text{equation (10.1)}$$

where σ is known as **Stefan's Constant**. At **equilibrium** this must also be the rate at which energy is absorbed by the surface of a black body. The object of the experiment is to determine σ by placing a Radiator (a blackened hemisphere) at ~100°C above a small copper disc. The *net rate* at which energy is absorbed by the disc is then simply proportional to the rate of increase of its temperature.

To measure the radiant energy absorbed by the copper disc care must be taken in designing the apparatus to reduce to a minimum the heat transfer by the processes of conduction and convection. Here convection is minimised by having the radiant source (a blackened hemisphere maintained as close to 100°C as possible) above the copper disc while the use of a black wooden base provides thermal insulation against conduction. Thermocouples monitor the temperature of the copper disc and the Radiator. Temperature readings can be recorded at pre-selected time intervals using the Temperature Data logger. Stefan's constant can be found from measuring **the *initial* linear of rise of temperature** of the disc **immediately after** the hot Radiator is placed over it.

Assuming that before the Radiator is put in position, **the disc is in thermal equilibrium with the wooden base at a laboratory temperature, T_0** (in Kelvin) then the disc will be radiating and absorbing energy at

$$U = A\sigma T_0^4 \text{ Js}^{-1} \qquad \text{equation (10.2)}$$

where A is area of the disc. When the Radiator at temperature T_i is introduced, the disc will absorb energy at a rate of $A\sigma T_i^4$ Js^{-1}. Thus its initial gain of energy is $A\sigma(T_i^4 - T_0^4)$ Js^{-1} and this will cause its starting temperature T_0 to rise at a rate given by:

$$\text{Power} = \frac{\Delta Q}{\Delta t} \quad \text{and} \quad \Delta Q = mc\Delta T$$

$$\frac{\Delta Q}{\Delta t} = mc\frac{dT}{dt} = A\sigma(T_r^4 - T_0^4) \qquad \text{equation (10.3)}$$

where Q is heat flow, m is the mass of the disc and c the specific heat of the material (value for Copper is 385 JKg^{-1}). Note that this equation will only apply to the **initial** rate of rise of temperature (clearly as the disc temperature rises the rate at which it radiates energy also rises). Here we are also assuming negligible conductive transfer of heat to the base and along the wires of the thermocouple. If the disc under investigation is not a perfect blackbody (perfect energy absorber) then we can introduce a parameter, ε, called the emissivity so that equation 10.2 becomes:

$$U = \varepsilon A\sigma T^4 \qquad \text{equation (10.4)}$$

If the experiment is felt to be a success, then the ratio of the experimentally measured Stefan's Constant, to the true value, will give a measure of the emissivity 'ε' where:

$$\varepsilon = \frac{\sigma_{measured}}{\sigma_{true}}$$

It is possible that this parameter also mediates for any energy loses due to conduction/ radiation and other such effects.

Experimental Procedure

Task 1: Heating the Radiator and preparation for Task 2

1.1) Login to the computer and start up the PicoLog Recorder programme (its icon will either be on the Desktop or in the Start Menu). Also open an MS Excel spreadsheet and save this to your login home directory as you will need to use it to store and analyse your data. On the PicoLog programme you should see the TC-08 as a device along with a live readout of the current temperature of the thermocouples from Channels 1 and 2 (see datalogger). If the two channels are not active, then click on the channel number on the device to bring up the menu as shown in figure 10.3 below, where you can activate the channel, name it and set the sample interval (1 second).

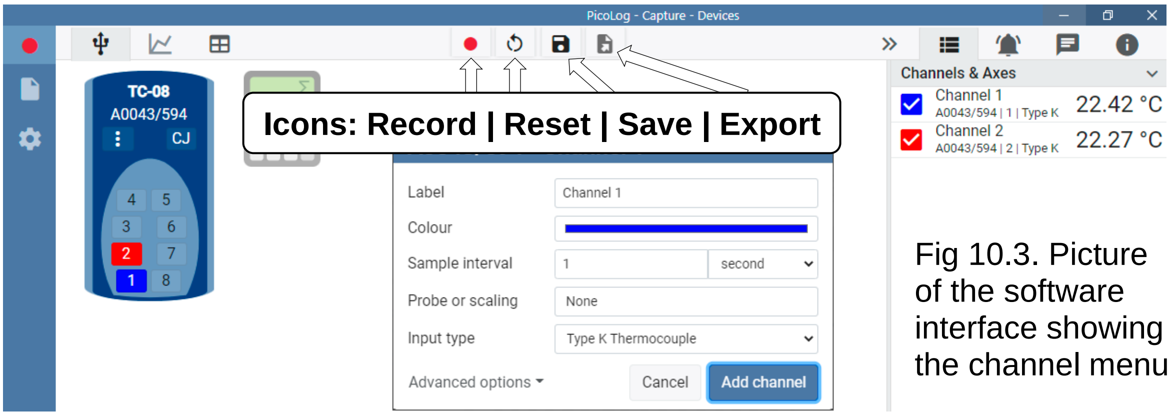


Fig 10.3. Picture of the software interface showing the channel menu

1.2) Click on the Reset Icon to clear any previous data, then click on Record Icon as shown in figure 10.3 and select Local Capture and then Continuous Capture for on the next 2 menus that appear as show in figure 10.4 below:

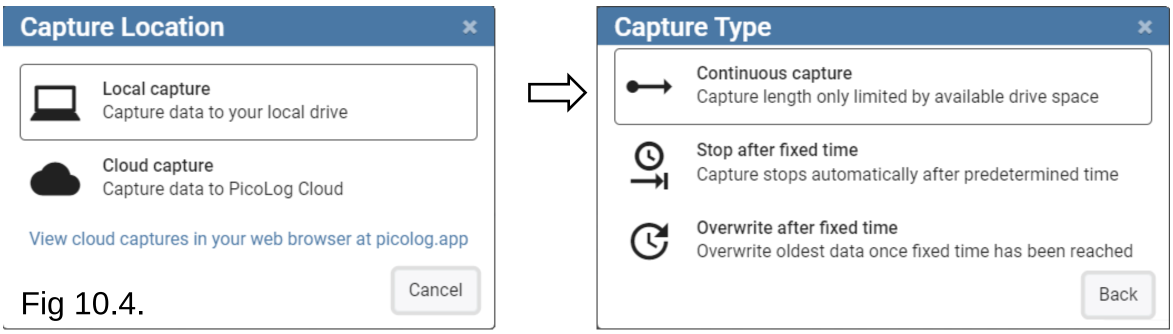


Fig 10.4.

1.3) Now the logger is recording the data, you need to heat the radiator using the Steam Generator. Before switching it on, remove the large black bung and check the Steam Generator is full to the black line which you can see inside the cylinder. If it is not then fill it up to the black line and replace the bung firmly. Do **not** fill it above the black line because if you overfill the Generator it will cause safety issues.

1.4) Once you have checked there is sufficient water, switch on the Steam Generator. It will take at least 10 minutes from when it is first switched on to generate steam and a further 5 minutes for the Radiator to start heating up to its operating temperature. Click on the Graph Icon to show a live recording of the data, and graph options Icon to select how to follow the data.

1.5) Whilst you are waiting for it to get up to steam, measure the size and mass of three Copper Discs you are going to use.
For each disc:
- Measure the diameter using the Digital Vernier Calliper.
- Check that the disc has a small screw inserted in the underside before you weigh it, if it is missing then ask the Technician to insert one. You will need to weigh it with the screw in to get its total mass using the balance provided.
- The mass of the Copper Collar, shown in figure 10.5 below, is **1.392g ± 0.001g**. For each Task add this to the mass of the Disc you measured to give you the total mass of copper attached, m.
- Record these diameters and masses in the spreadsheet along with their uncertainties.

1.6) Attach the Large Blackened Copper Disc to the Copper Collar using the screwdriver provided as shown in figure 10.5. Do NOT remove this collar. If the collar becomes detached then ask the Technician or Demonstrator to replace it for you. Keep the black Wooden Base away from the Radiator whilst that heats up.

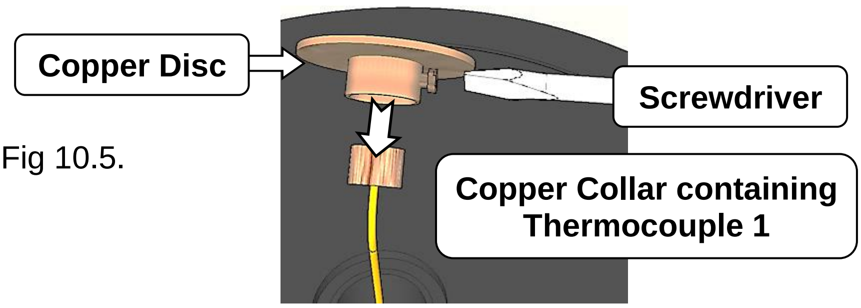
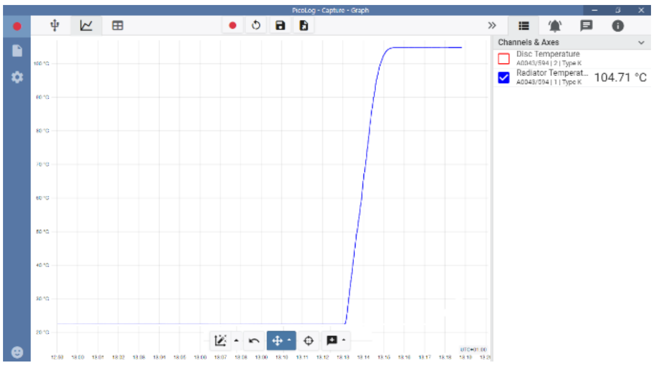


Fig 10.5.

1.7) Keep an eye on the temperature of the radiator. Once the radiator has heated up to a constant temperature as shown in below in figure 10.5 below, click on the Record button to STOP the data recording and click on the Save Data icon (as shown on figure 10.3). The first time you do this you may have to configure the data table. It is good practise to save the data in the format of the programme, but also save it as a ‘.csv’ file, using the Export Icon, so you can load it directly into MS Excel for the analysis. For your write up in this case only, you are allowed to take a full screenshot of each run, and you can do this by clicking the button to the right of the Save Icon.

Fig 10.5.

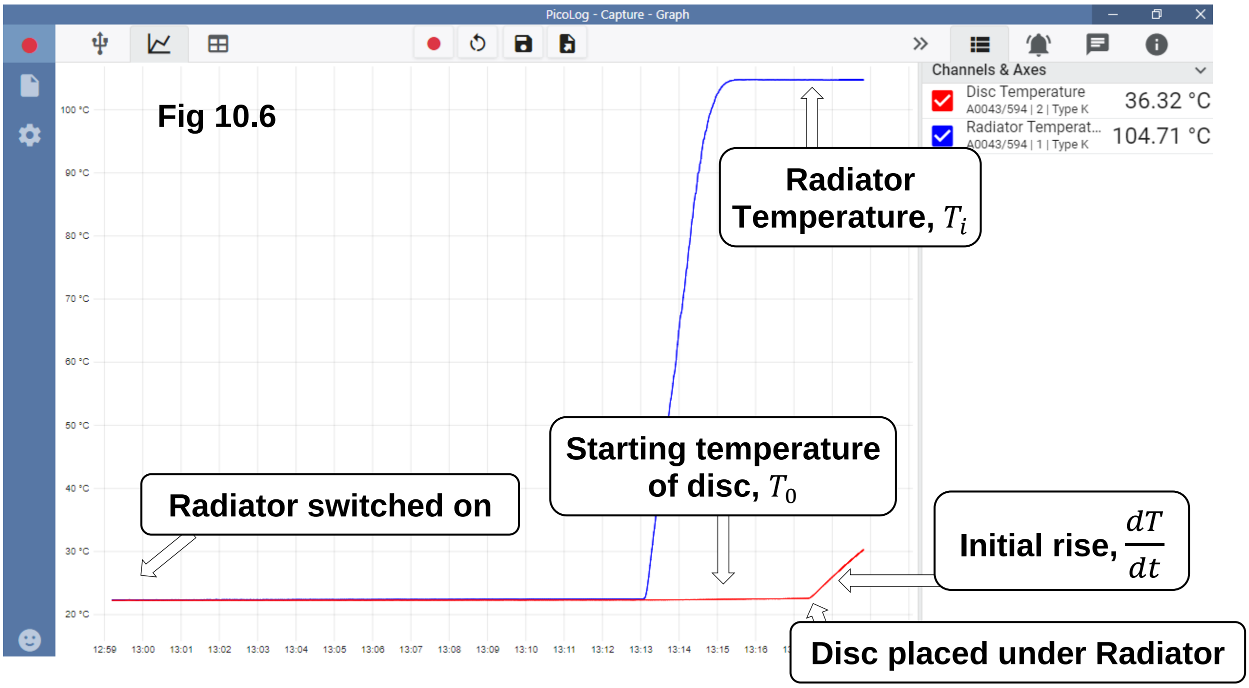


Task 2: Collecting data for the large Blackened Disc.

It is important to arrange the apparatus so that you are able to place the Radiator underneath the Wooden Base in a simple deft movement using the **Heatproof Gloves** provided (watch the video to check how this is done). Keep the Wooden Base with the Disc attached away from the Radiator until it needs to be used.

2.1) Click on **Record** icon again and set up a new recording file as explained in Task 1.2. Then click on the Graph Icon and set it so it shows both channels.

Once the Disc has reached a stable starting temperature, **using the Heatproof Gloves** pick up the Radiator and slide the black Wooden Base underneath it so it is covered. Watch the temperature of the disc rise to 30°C then stop recording and save your data as a.csv file with a different name to the previously saved file. The graph should look similar to figure 10.6 below:



2.2) Using the **Heatproof Gloves** remove the black Wooden Base from under the Radiator and place the Radiator back on its stand. Leave the Radiator switched on.

The region just before the disc is placed under the radiator and starts to heat up can be averaged to find the start temperature, T_0. See Task 5 for how to handle your data and calculate Stefan's Constant for this Disc.

Task 3: Collecting data for the small blackened copper disc.

For this task you will investigate the heating rate and calculate Stefan's Constant of the smaller blackened disc as the heat absorbed depends on the discs area (equations 10.2 and 10.4). You can also investigate whether the smaller disc gives a value of Stefan's constant closer to the true value.

3.1) Remove the large blackened Copper Disc from the Collar, fit the wooden washer over the Collar and attach the **smaller** blackened Copper Disc (the washer will stop the smaller disc falling through) once fitted gently pull the wire through the Base so that the copper disc rests on the rim in the hole in the Wooden Base. If the Collar becomes detached then ask the Technician or Demonstrator to replace it for you.

3.2) Having saved the data from Task 2, start a new recording and data file. As you handle the disc, it warms up from the heat in your hand and so you should monitor the disc temperature and wait until its returns to a constant temperature (close to room temperature) which will take 10 minutes or so, an example is show in figure 10.7 below. This is an excellent experimental detail that you should add to your Lab Notebook (stop the recording and then save the file after you are happy the temperature has returned to room temperature).

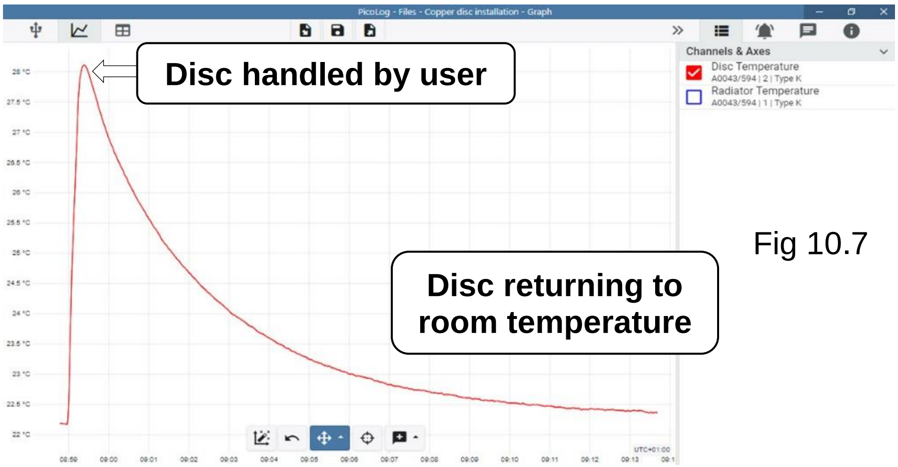


Fig 10.7

3.3) While you wait for the smaller blackened disc to return to room temperature, this is an excellent time to start your analysis of the large blackened disc and do at least one pilot calculation whilst in the Lab, so you can ask the Lab Staff or your demonstrator if you have any issues.

3.4) Once the Disc has returned to a steady temperature, stop recording and start a new recording. As described in Task 2 **use the Heatproof Gloves** to lift the Radiator and slide the Wooden Base containing the Disc under it. Again, wait for its temperature to rise to 30 and stop recording, **save the data** in a new file. Using the **Heatproof Gloves** remove the Wooden Base from under the Radiator and remove the Disc using the screwdriver. Also remove the wooden washer.

Task 4: Measuring Stefan’s Constant for the Shiny Copper Disc.

Repeat Task 3 using the large shiny disc, first removing the Wooden Washer before attaching the Disc. Remember to let the disc return to room temperature before recoding the data in a new file.

Data Analysis

You should now have 4 sets of data, one for the Radiator coming up to operating temperature and a set of data for each Disc including the diameter and mass of each Disc & Collar.

For each set of Disc data, plot a graph of Temperature (*y* axis) versus Time (*x* axis) in either MS Excel or Origin and measure the gradient of the linear section using the LINEST function (in $°Cs^{-1}$).

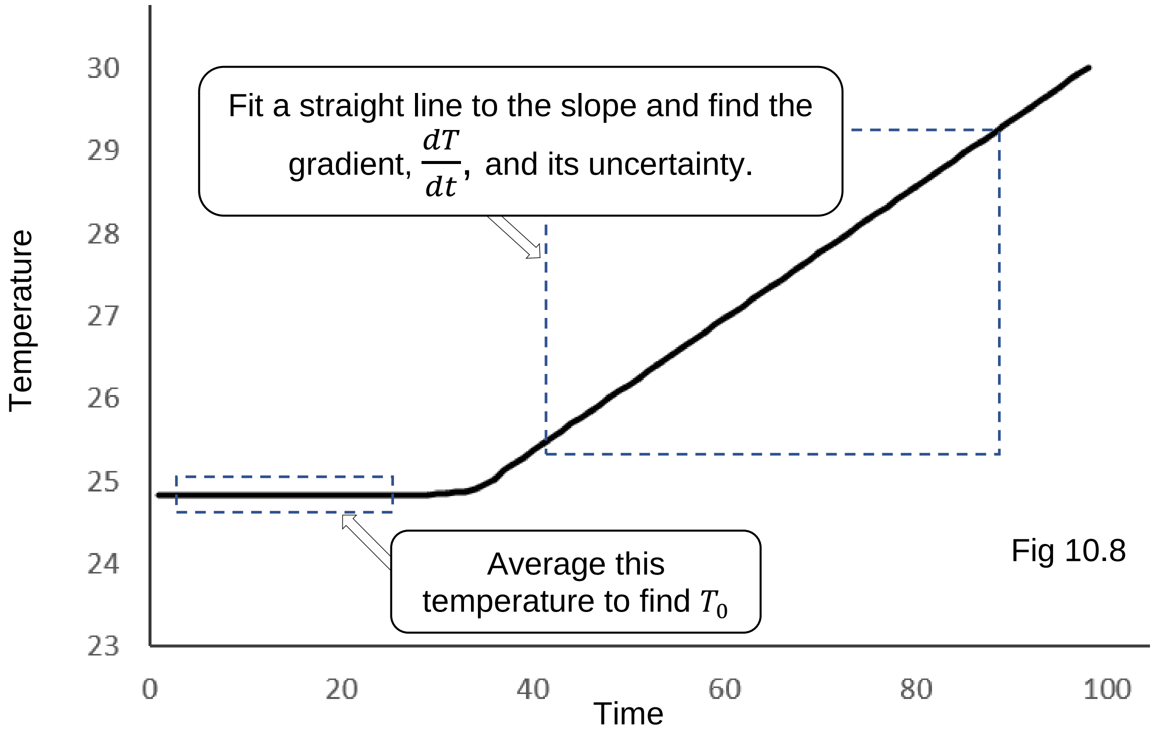


Fig 10.8

Using this gradient and the other data you collected determine Stefan’s Constant, σ, for each Disc along with its uncertainty using equation (10.3). Remember that T_i and T_0 should be in degrees Kelvin. It doesn’t matter for the gradient, as this is the same when using either (°Cs^{-1}) or (Ks^{-1}).

What to include in your Lab Notebook

1) A short Introduction describing the Experimental Aims including the expected target value with a reference.
2) A short method section explaining what you did, also include labelled schematic diagrams of the apparatus.
3) You may also want to develop the key physics equations as a reminder of what you will measure and how you will do the analysis including the uncertainty analysis.
4) Add a summary Table of your three measured values of Stefan’s Constant (and associated uncertainties) in comparison to the true value
5) In your Conclusion state your final calculated value of Stefan’s Constant along with its uncertainty and compare and comment on comparison to the expected value.
6) Also answer the following questions:
   - Did the disc area affect the results? If so any suggestions?
   - Did the surface appearance (black or shiny) of the large disc affect the measured Stefan’s constant? If so any suggestions?
   - Suggestions for improvements to the experimental procedure of the background physics.

Appendix 10.1: Uncertainty Equations.

$$\frac{\Delta\sigma_m}{\sigma_m} = \sqrt{\left(\frac{\Delta m}{m}\right)^2 + \left(\frac{\Delta grad}{grad}\right)^2 + \left(\frac{\Delta A}{A}\right)^2 + \frac{\left(4T_i^{\,3}\Delta T_i\right)^2 + \left(4T_0^{\,3}.\Delta T_0\right)^2}{\left(T_i^{\,4} - T_0^{\,4}\right)}}$$

$$\frac{\Delta A}{A} = \frac{2\Delta d}{d} \qquad \therefore \Delta A = \frac{2\Delta d}{d}.A^{-\frac{\pi}{4}d^2} \qquad \Delta A = 2\frac{\pi}{4}.\frac{d^2}{d}.\Delta d = \frac{\pi}{2}d.\Delta d \qquad \Delta\varepsilon = \frac{\Delta\sigma_m}{\sigma_m}.\varepsilon$$