Physics Laboratory Manual

PHYC 20080
Fields, Waves and Light
2018-2019

UCD DUBLIN

Name..

Partner's Name ....

Demonstrator ....

Group ....

Laboratory Time ....

Contents

Introduction

Physics is an experimental science. The theory that is presented in lectures has its origins in, and is validated by, experiment.

Laboratories are staged through the semester in parallel to the lectures. They serve a number of purposes:

- ***an opportunity, as a scientist, to test theories by conducting meaningful scientific experiments;***
- ***a means to enrich and deepen understanding of physical concepts presented in lectures;***
- ***an opportunity to develop experimental techniques, in particular skills of data analysis, the understanding of experimental uncertainty, and the development of graphical visualisation of data.***

Based on these skills, you are expected to present experimental results in a logical fashion (graphically and in calculations), to use units correctly and consistently, and to plot graphs with appropriate axis labels and scales. You will have to draw clear conclusions (as briefly as possible) from the experimental investigations, on what are the major findings of each experiment and whetever or not they are consistent with your predictions. You should also demonstrate an appreciation of the concept of experimental uncertainty and estimate its impact on the final result.

Some of the experiments in the manual may appear similar to those at school, but the emphasis and expectations are likely to be different. Do not treat this manual as a 'cooking recipe' where you follow a prescription. Instead, understand what it is you are doing, why you are asked to plot certain quantities, and how experimental uncertainties affect your results. It is more important ***to understand and show your understanding*** in the write-ups than it is to rush through each experiment ticking the boxes.

This manual includes blanks for entering most of your observations. Additional space is included at the end of each experiment for other relevant information. All data, observations and conclusions should be entered in this manual. Graphs may be produced by hand or electronically (details of a simple computer package are provided) and should be secured to this manual.

There will be six 2-hour practical laboratories in this module evaluated by continual assessment. Note that each laboratory is worth 5% so each laboratory session makes a significant contribution to your final mark for the module. Consequently, attendance and application during the laboratories are of the utmost importance. At the end of each laboratory session, your demonstrator will collect your work and mark it.

Laboratory Schedule

Students will be assigned to one of a number of groups and must attend at a specified time on Tuesday or Thursday afternoons. Check the notice-boards to find out which group you are in. In total you will perform six experiments during the semester.

Students seeking guidance on the format expected for practical reports for PHYC20080 are referred to the back of this manual where an example report for an experiment on springs, designed to introduce students to Hooke's law and graphing experimental data, is included. Reports can be typed or handwritten.

Semester Week	Week Start Date 2018	Room 143 SCIENCE EAST	Room 144 SCIENCE EAST	Room 145 SCIENCE EAST
Wk 1	10th Sep	Waves		
Wk 3	24th Sep		Interference /Diffraction	
Wk 5	8th Oct			Resistivity
Wk 7	22nd Oct	Sound		
Wk 9	5th Nov		Lenses	
Wk 11	19th Nov			Solar Cells

Lab Rules

1. No eating or drinking.

2. Bags and belongings are placed on the shelves provided in the labs.

3. Students are only permitted to start a lab where they have this school of physics manual in print. The school of physics lab manual for your module is available in print from the school of physics admin office and is also available online from the school of physics pages.

4. Students generally work in pairs in the lab, however reports are prepared individually and must comply with UCD plagiarism policy (see next page).

UCD Plagiarism Statement

(taken from http://www.ucd.ie/registry/academicsecretariat/docs/plagiarism_po.pdf)

The creation of knowledge and wider understanding in all academic disciplines depends on building from existing sources of knowledge. The University upholds the principle of academic integrity, whereby appropriate acknowledgement is given to the contributions of others in any work, through appropriate internal citations and references. Students should be aware that good referencing is integral to the study of any subject and part of good academic practice.

The University understands plagiarism to be the inclusion of another person's writings or ideas or works, in any formally presented work (including essays, theses, projects, laboratory reports, examinations, oral, poster or slide presentations) which form part of the assessment requirements for a module or programme of study, without due acknowledgement either wholly or in part of the original source of the material through appropriate citation. Plagiarism is a form of academic dishonesty, where ideas are presented falsely, either implicitly or explicitly, as being the original thought of the author's. The presentation of work, which contains the ideas, or work of others without appropriate attribution and citation, (other than information that can be generally accepted to be common knowledge which is generally known and does not require to be formally cited in a written piece of work) is an act of plagiarism. It can include the following:

1. Presenting work authored by a third party, including other students, friends, family, or work purchased through internet services;
2. Presenting work copied extensively with only minor textual changes from the internet, books, journals or any other source;
3. Improper paraphrasing, where a passage or idea is summarised without due acknowledgement of the original source;
4. Failing to include citation of all original sources;
5. Representing collaborative work as one's own;

Plagiarism is a serious academic offence. While plagiarism may be easy to commit unintentionally, it is defined by the act not the intention. All students are responsible for being familiar with the University's policy statement on plagiarism and are encouraged, if in doubt, to seek guidance from an academic member of staff. The University advocates a developmental approach to plagiarism and encourages students to adopt good academic practice by maintaining academic integrity in the presentation of all academic work.

Summary on Uncertainties

Typically, you will need to perform measurements of a given physical quantity several times to reduce the uncertainty.

For example, if you measure the brightness of pixel on a CCD camera capturing an image of a stationary scene you might find (small) differences or variations of the intensity I caused by different noise mechanisms.

You determine the mean value of N intensity measurements as follows:

$$\boxed{< I >= \frac{\sum_{n=1}^{N} I_n}{N}}$$

where I_n refers to the individual measurements.

To determine the uncertainty, you need to take multiple measurements. This allows you to also determine the sample standard deviation σ which is a good measure for the spread in the collected data.

$$\boxed{\sigma = \sqrt{\frac{\sum_{n=1}^{N} (I_n - < I >)^2}{N-1}}}$$

A small variation in the measurements I_n and many repetitions will reduce the standard deviation. The repetition of the measurements reduces the standard error SE of the determined mean value as

$$\boxed{SE = \frac{\sigma}{\sqrt{N}}}$$

If you are making repeated measurements for different settings, for example by increasing the brightness in intervals you obtain multiple measurements each with a characteristic error. It is customary to plot the mean value for each setting with error bars of +/- one standard deviation σ. An example is shown in *Figure A* below.

The best fit of the data to, for example, a linear dependence can be determined by a so-called least squares method that minimizes the root-mean-square error. However, a simpler approach is a graphical interpretation as shown in Figure A and Figure B. Here, you simply plot the data and fit a line that stays within the determined uncertainties.

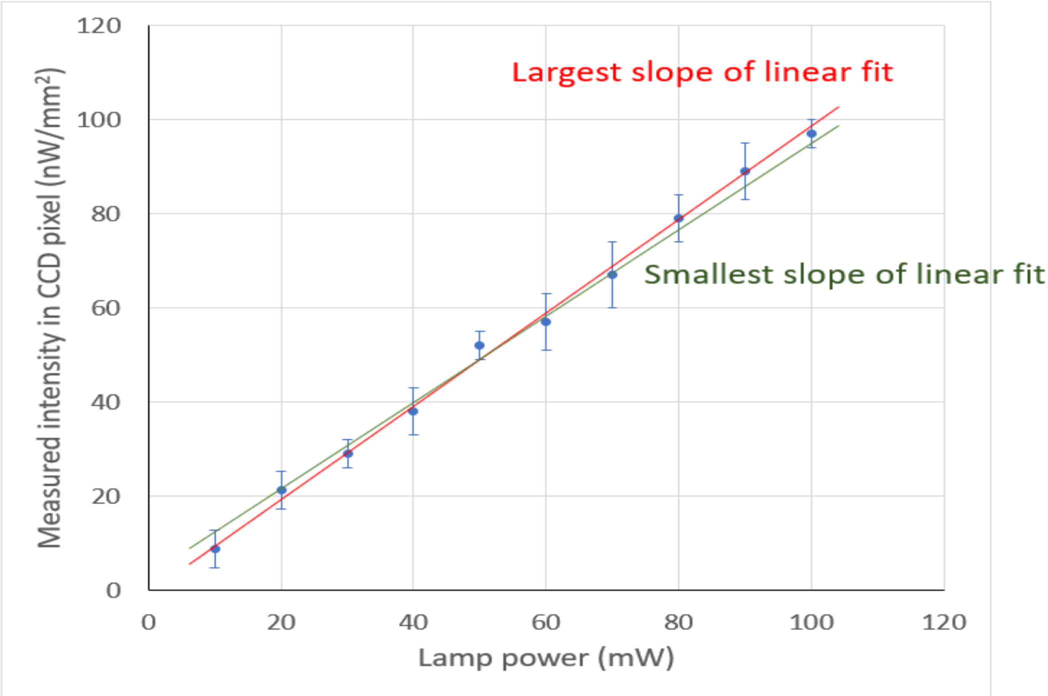


Figure A: Example of a linear fit of experimental data with average values (points) and +/- one standard deviation (error bars).

If you have multiple uncertainties such as, for example, also on the brightness settings you will have both horizontal and vertical error bars on the plot. This results in square regions of uncertainty. Yet, you can still make fits that stay confined within the limits set by the area of the errors as shown in Figure B.

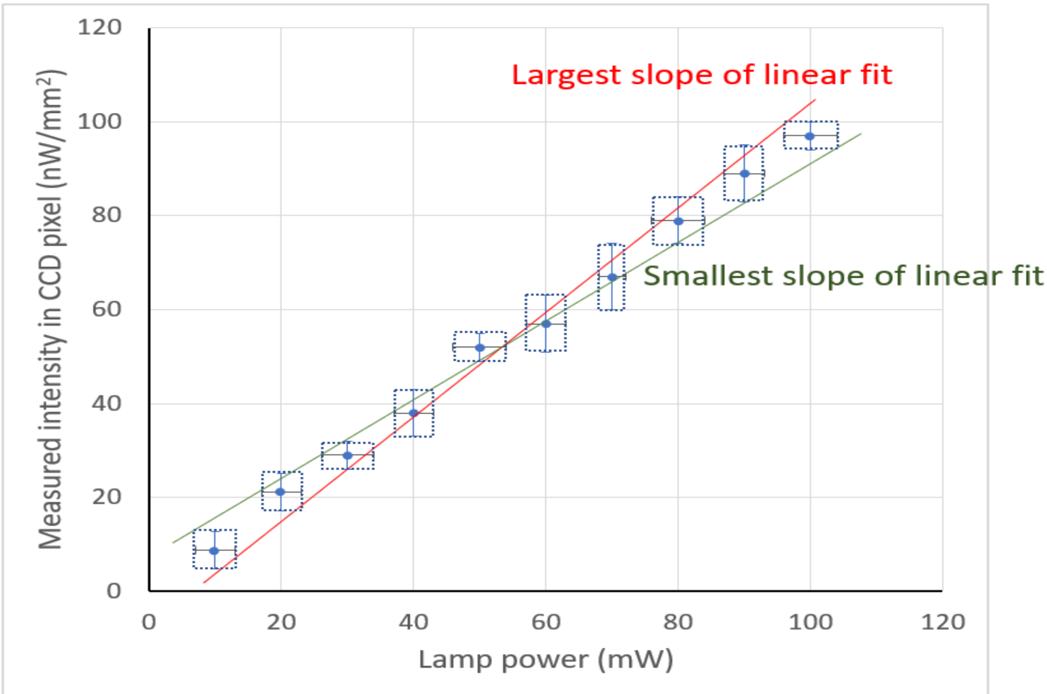


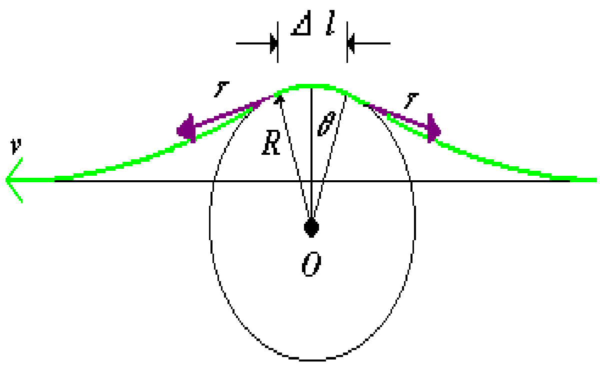
Figure B: Example of a linear fit of experimental data with average values (points) and +/- one standard deviation (error bars) on both the measured lamp power and the measured intensities.

Waves and Resonances

Introduction

This experiment produces waves in a stretched wire and looks at how the frequency of vibration is related to the tension of the wire, its length and the mass per unit length. The phenomenon of resonance is used in the investigation.

Using Newton's laws, it can be shown[1] that the velocity, v, of a symmetrical pulse on a string, as shown on the right, is related to the tension of the string, T, and the mass per unit length, μ, by



$$v = \sqrt{T/\mu} \qquad \text{(Eq. 1)}$$

Thus the velocity of a wave along a string depends only on the characteristics of the string and not on the frequency of the wave. The frequency of the wave is fixed entirely by whatever generates the wave. The wavelength of the wave is then fixed by the familiar relationship:

$$v = f\lambda \qquad \text{(Eq.2)}$$

Example: A string on a bass guitar is 1m long and held under a tension of 100N. If the string has a mass of 10g, what is the velocity of a wave on the string?
Include the velocity calculation and its value in your **report**.

If a wave with a frequency of 50Hz is sent into the string, what will its wavelength be?

Include the wavelength calculation and its value in your **report**.

A *resonant* frequency is a natural frequency of vibration determined by the physical parameters of the vibrating object. There are a number of resonant frequencies for a string which are the multiples of its length (l) that allow standing waves to be formed.

[1] The portion of the wire Δl experiences a tension on each end. The horizontal components cancel and net vertical force of $2T\sin\theta \approx 2T\theta = T\Delta l/R$ acts. Newton says this force = mass x acceleration. The mass is $\mu\Delta l$. Looking at the system from a frame where the pulse is at rest (and the wire moves with velocity *v*), the portion of wire moves along the indicated circle and the centripetal acceleration is v^2/R. Thus $T = \mu \cdot v^2$ and the result follows.

Thus $\lambda_{resonant} = 2l / n$. where n=1,2,3...

Answer the following questions:

What is the lowest resonant frequency (the fundamental) of the bass guitar string referred to above?

What happens if a wave with a frequency which is the *same* as the resonant frequency enters the string?

What happens if a wave with a frequency which is *different* to the resonant frequency enters the string?

Eq.1&2 can be combined to give $f = \frac{1}{\lambda}\sqrt{\frac{T}{\mu}}$.

When this is at the resonant frequency

$$f_{resonant} = \frac{n}{2l}\sqrt{\frac{T}{\mu}} \qquad \text{(Eq. 3)}$$

Experimental Procedure

In this experiment we will attempt to confirm *Eq.1* above by sending waves of different frequency into the wire and identifying the **resonant** frequency.

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The apparatus is shown in *Figure 1* and consists of a stretched string held under tension by a hanging known weight from predetermined slots on a tensioning lever. The resultant tension is then calculated by the formula $sMgz$ where s = the slot number on the lever, M = mass, g = gravity and z is a constant = 0.26. To get accurate results it is important to set this lever to horizontal by adjusting the string adjustment knob on the opposite end. In this configuration, the tension equals the force exerted by gravity. The wire passes over two adjustable bridges, which define nodes (points of no vibration), thus changing the length in which a wave can resonate. There is a driving coil through which an ac signal, of variable frequency, is passed. Resonances are located by observing on the oscilloscope, the amplitude of the signal from the detector coil. (information on the use of an oscilloscope can be found in this manual (Studying sound using an oscilloscope)).

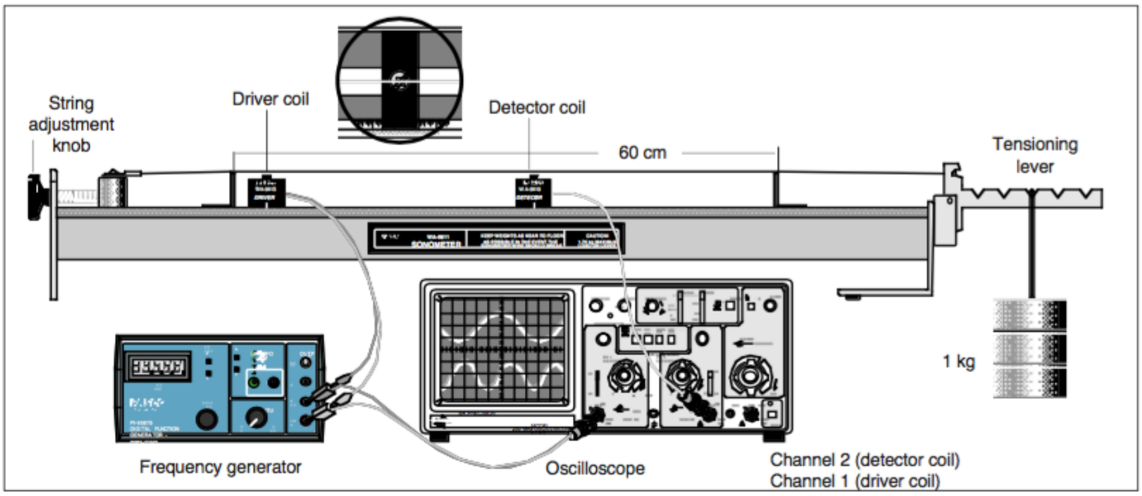

Figure 1. The apparatus

Choose eight different positions of the bridge and find the lowest frequency at which maximum vibrations (resonance) occurs.

The mass/unit length of the wire is 0.39g/m

In your notebook: create a similar table to the one below, add more rows at the bottom and tabulate your measurements.

Wire Tension (N) =	Mass/unit length μ=	
Resonant Frequency (Hz)	Length (m)	1/Length (m^{-1})

Plot the resonant frequency against 1/*l*.

What should the slope be equal to algebraically and numerically?

What is the slope of a straight line fit to your data?

Include the answers in your **report** and also comment on whether you consider that Eq.3 has been verified and whether a good agreement exists between theory and experiment.

Investigation 2:
Now place the bridges at fixed positions, 60 cm apart.
The tension that is produced by the 1kg mass depends on its position on the hanger. See the figure below, and use this fact to vary the tension in the wire and find the lowest frequency at which maximum vibrations occur. Remember that you will need to account for the factor z=0.26 mentioned above.

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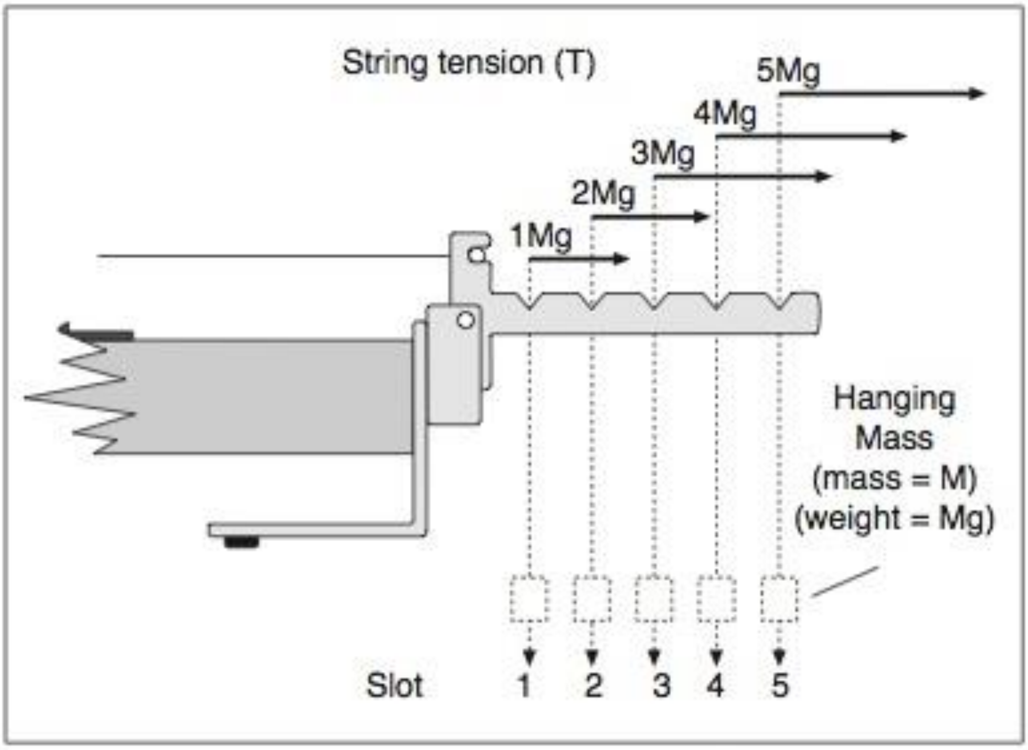


★ In your notebook: create a similar table to the one below and tabulate your measurements.

Length (m) =	Mass/unit length μ=	
Resonant Frequency (Hz)	Frequency squared (s^{-2})	Wire tension (N)

Plot the square of the resonant frequency against the tension.

What should the slope be equal to algebraically and numerically?

What is the slope of a straight line fit to your data?

Comment on whether you consider Eq.3 has been verified and whether a good agreement exists between theory and experiment.

Set up a resonant position and write down the frequency. Now increase the frequency until you see resonance again, and write down this frequency.
What do you notice? With reference to Eq.3, explain in your **report** what is happening.

Conclusion:

Describe in your report, in up to three sentences, what are the major findings of this experiment.

You should also comment on how your experimental results might be improved and also on the uncertainties that might have been introduced in these measurements.

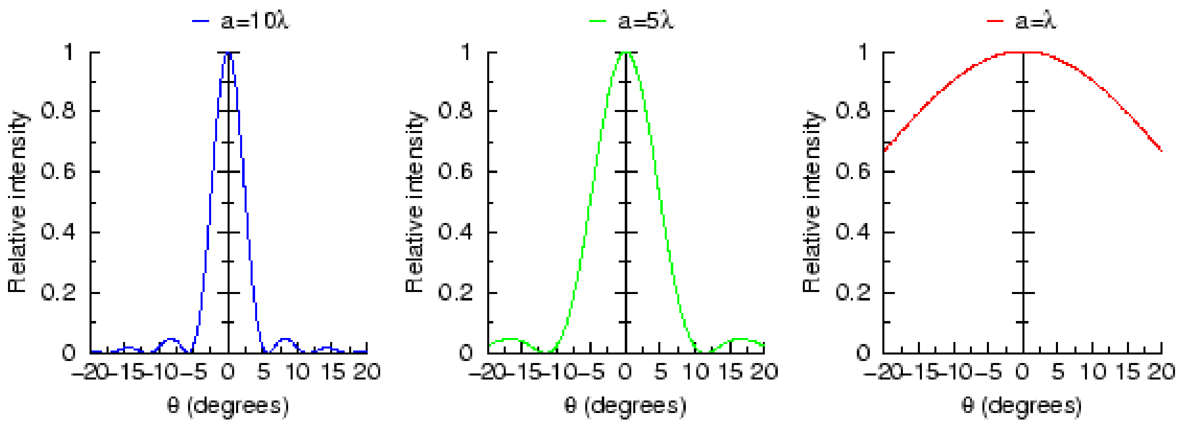
Interference and Diffraction

Introduction

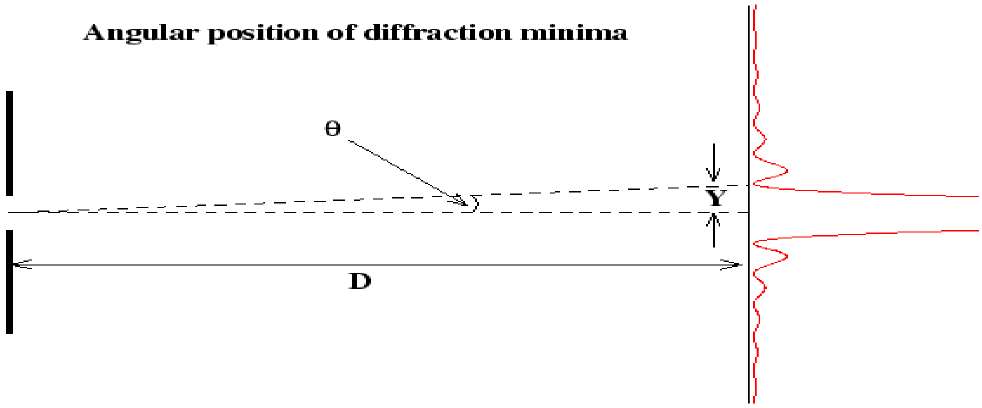
The aim of this experiment is to investigate the interference of light. Shining light through a single slit or a double slit produces characteristic diffraction patterns whose features depend on the wavelength of the light and the size of the slit.

When light passes through a slit, or around an obstacle, diffraction effects are produced if the dimensions involved are of the same order of magnitude as the wavelength of the light. If the diffraction pattern is viewed on a screen, a set of alternate bright and dark fringes will be observed. The diffraction can be of two types (a) Fresnel, - where the object to screen distance is comparable to the object size and (b) Fraunhofer, where the light is parallel and the distances involved are large. The latter is easiest to treat mathematically.

Investigation 1: Single Slit Diffraction



The figure above shows the intensity pattern as a function of angle when a single slit of width ***a*** is placed in the path of a beam of light. Three different slit widths are shown. From left to right they correspond to a size 10 times larger than the wave length (λ) of the light, 5 times larger, and the same size as the wavelength of the light respectively. The width of the pattern depends on the width of the slit; as the slit width is reduced, the pattern broadens. The wavelength of green light is about 550 nm, which is close to 0.5 microns.



A schematic of the experimental arrangement is shown above. It can be shown that the minima of the patterns satisfy:

$$\boldsymbol{a\sin\theta = m\lambda} \qquad \text{(Eq. 1)}$$

where θ is the angle the fringe makes with the beam axis and *m* is the order number.

For the 1st **minimum,** *m*=1 and since θ is small, $\sin\theta \approx \tan\theta = Y/D$ where *Y* is the distance from the central maximum to the first minimum and *D* is the distance from the pattern to the slit. Thus

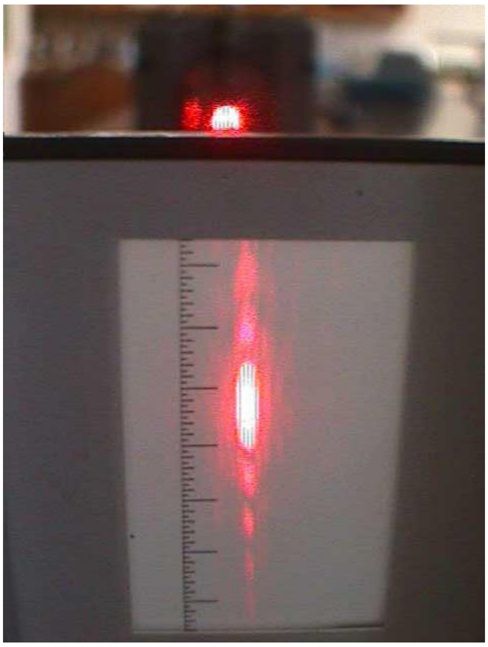
$$\mathbf{a = \lambda\ D/Y} \qquad \text{(Eq. 2)}$$

Apparatus

A laser is used as the light source since it provides a source of monochromatic, coherent light. The light passes through the slit and onto a screen as shown in the figure below.

★ In your **report**, explain why we use a **coherent** and **monochromatic** source.

Procedure



Align the laser beam so that it passes through the slit and strikes the viewing screen. Make the distance, D, from the slit to the screen as large as possible in order to maximise the size of the image and reduce your measurement uncertainty.

The diffraction pattern should look something like the figure here. Identify the central maximum and the first order minima around it. The distance between these two minima is $2Y$.

Given that the wavelength of the light is 632.8 nm, you should work out the width of the slit.

1. Record your data in your notebook and find a value (with an uncertainty) for the width of the slit.

2. Is it possible to measure the slit width using the **second order minima**? If so, what value do you get and how does it compare with your first result ?

3. If time permits, repeat these measurements for a second slit.

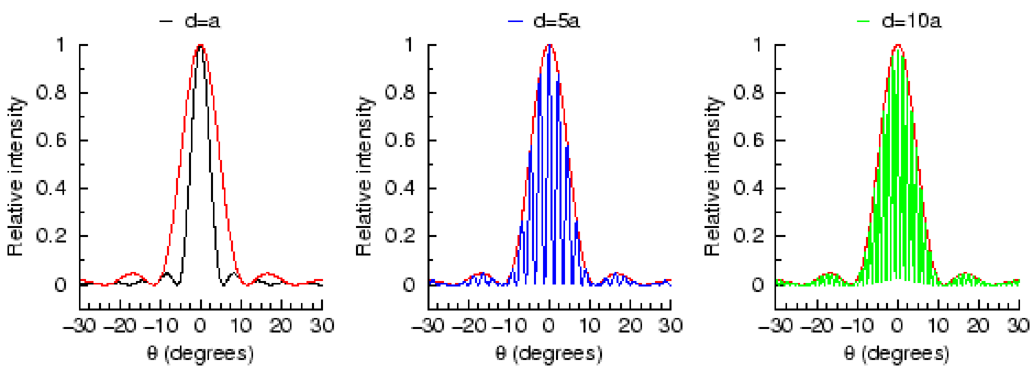
In your **report**, include the answers to points 1 – 3 above.

You can use this technique to measure very small distances with high precision.

If an object which presents a rectangular aspect to the beam (such as a wire or human hair) is placed in front of the laser, a diffraction pattern will be produced identical to that produced by a rectangular aperture of the same dimensions.

Find the width of a human hair. Record your measurement in your notebook and present them in your **report**.

Investigation 2: Double slit Diffraction (Young's slits)



If a double slit is placed in the path of the beam, a Young's slits interference pattern is obtained, which is superimposed on the single slit diffraction pattern as shown in the diagram above. If *d* is the separation of the slits, constructive interference (a bright fringe) is obtained when

$$n\lambda = d\sin\theta \qquad \text{(Eq.3)}$$

When the angle is small this can be written as

$$n\lambda \approx d\,\theta \qquad \text{(Eq. 4)}$$

Therefore the angular separation between adjacent maxima is

$$\lambda / d = y / D \qquad \text{(Eq. 5)}$$

where **y** is the linear seperation between adjacent maxima.

Procedure

Replace the single slit by the double slit. Move the slit carrier sideways until the laser light passes through one slit, when you will get a single slit diffraction pattern on the screen. As you continue to move the slit carrier, the laser light will pass through both slits and the diffraction will break up into an interference pattern.

Use Eq.5 above to estimate the slit separation. To do this, you will need to measure the separation between the adjacent maxima which are very close together. To increase your precision therefore, measure a number of bright fringes and divide by the number of separations. (Careful: 2 fringes delineate just one gap.)

Record your observations in your notebook and make an estimate of the slit separation.

Don't forget the experimental uncertainty.

Include the above measurements and observations in your report.

Conclusion:

- Describe in your **report**, in up to three sentences, what are the major findings of this experiment.

- You should also comment on how your experimental results might be improved and also on the uncertainties that might have been introduced in these measurements.

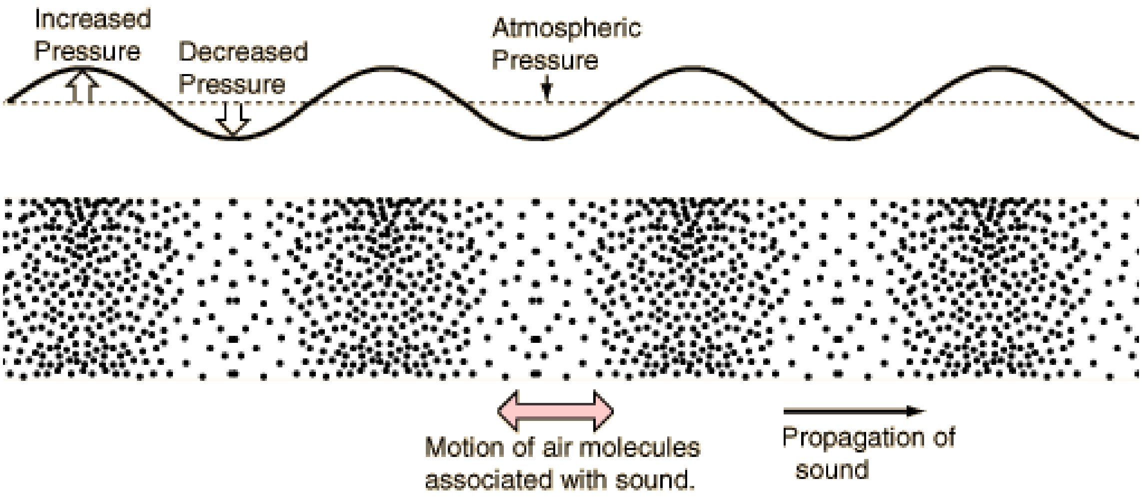
Studying Sound using an Oscilloscope

Introduction

Sound is a longitudinal wave that propagates in solids, liquids or gases. In this experiment you will measure the **speed of sound.** You will investigate resonance wave patterns in tubes of air of various lengths and determine the **wavelengths**, λ, of the sound waves. Using the known **frequency,** f, you will be able to determine the speed of sound in air, **c**, since these quantities are related by the equation:

$$c = f\lambda \qquad \text{(Eq. 1)}$$

You will also determine the speed of sound more directly, by recording the time taken for a sound pulse to travel down a closed tube and reflect off the end.
As sound passes a point in air, the pressure rises and falls in an almost periodic fashion. For this experiment we will assume that the pressure changes are periodic. The sound is generated by a speaker driven at a given frequency, the motion of the speaker compresses and rarefies the air, setting up the sound wave.

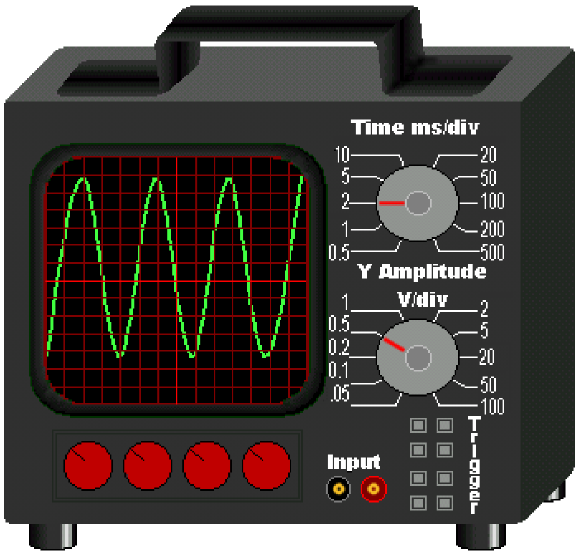


The pressure wave is picked up by the microphone which acts as a *transducer*, changing the sound signal into an electrical signal. This can be displayed on the oscilloscope.

The Oscilloscope

An oscilloscope is a device for looking at electronic signals that may change in time. It is a bit like the zoom lens on a camera: you can change the magnification on both the time and voltage axes and see the signal in more detail. But changing the magnification (or gain, to give it its proper title) does not change the signal itself. Older oscilloscopes are built around a cathode ray tube (a TV tube) and four main electronic circuits to control the screen all housed in one unit. Newer oscilloscopes are digital devices. Oscilloscopes may be triggered either externally or internally. The trigger essentially marks the time equal zero for the oscilloscope, the zero on the x-axis. The signal trigger can be derived from any signal applied to the Y-input or vertical amplifier by the 'scopes internal triggering circuitry. Alternatively, the signal trigger can be derived from some external source applied via the external trigger input.

The X-axis on the oscilloscope screen is the time axis; the Y-axis is the voltage axis. The trace that appears on the screen may be measured by counting the number of divisions between features e.g. peaks.



In this case there are 4 divisions between peaks, and the oscilloscope is set to 2 ms per div.

With reference to the oscilloscope image on the right, answer the following questions in your **report**:

What is the period (T) of the wave?

What is the peak-to-peak voltage?

From the value you have obtained for the period of the wave, you can calculate a frequency using the relationship f = 1/T.

What is the frequency of the signal displayed in the image above?
(Note: convert the period to seconds before calculating the frequency).

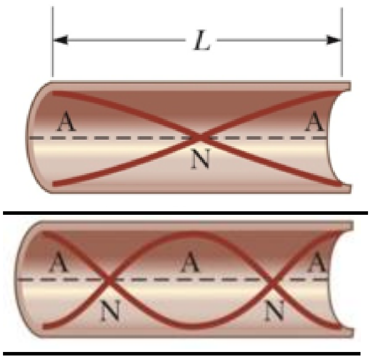
The oscilloscope can display waveforms for two signals which are input on one of two channels (CH1, CH2). You can alter what you see using the controls on the front panel.

Resonance

A standing wave occurs when a sound wave is reflected from an end of a tube so that the returning wave interferes with the original wave. A node is a point along a standing wave where the wave has minimum amplitude, in the case of sound it's a point where the air stays relatively still, and an antinode is a point where the wave has maximum amplitude.
Resonance states depend on the tube set up, there are two and they are;

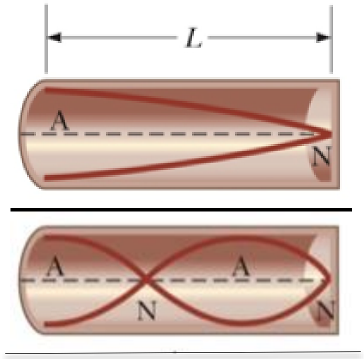
- Open tube (open at both ends)
- Closed tube (open at one end)

Open tube



An open tube is characterised by having antinodes at both open ends, and having one less node than the number of antinodes. Wavelengths at which resonance can occur in an open tube are described by the equation, $\boldsymbol{\lambda} = \boldsymbol{2L}/\boldsymbol{n}$ where $\boldsymbol{L}$ is the tube length and $\boldsymbol{n}$ an integer (n = 1,2,3,4…).

Closed tube



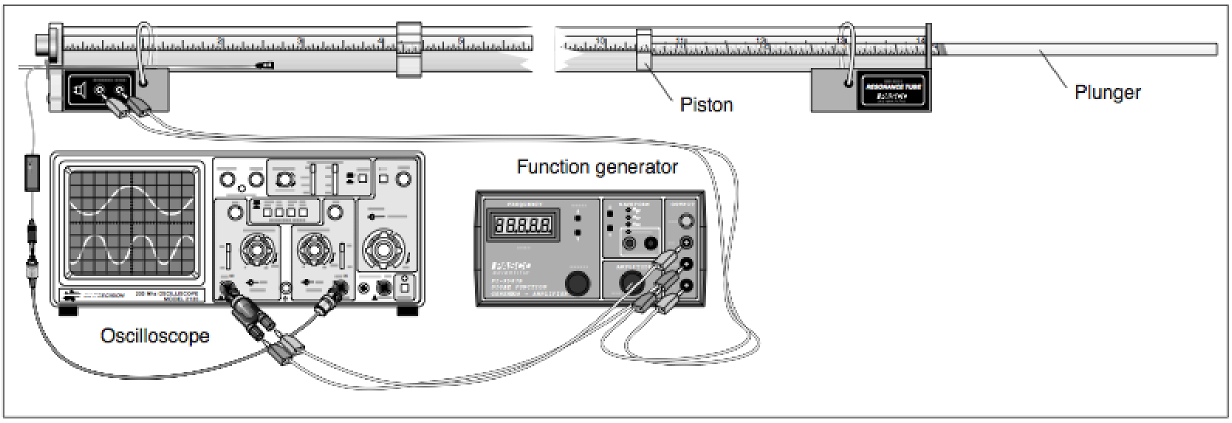
A closed tube is characterised by having a node at the closed end and an antinode at the open end. Wavelengths at which resonance occurs are described by the equation, $\boldsymbol{\lambda} = \boldsymbol{4L}/\boldsymbol{n}$ where $\boldsymbol{L}$ is the tube length and $\boldsymbol{n}$ is an odd integer (n = 1,3,5,7..).

The diagrams shown above describe the displacement of the air, this means at an antinode you have a lot of movement and at a node you have no movement. A microphone, measures the air pressure and not its displacement. At the antinodes, the air is moving the most, as a result most of it is forced into the nodes, so you have higher pressure at the nodes, so where you have a displacement node you will have a pressure antinode and, where you have a displacement antinode you will have a pressure node. A sketch of a pressure wave pattern would have the same wavelength as the displacement pattern except it would be shifted by $\lambda/4$.

★Think about the apparatus you have and how the wavelength of the sound is related to the distance between nodes or anti-nodes for a particular resonance wave pattern.

Investigation 1

For any given tube length, there are a variety of resonant frequencies. Likewise there are a variety of tube lengths for any given resonant frequency. In this experiment you will examine a series of tube lengths, which will resonate at a particular frequency. From this you will work out the speed of sound.



Procedure

- Set the apparatus up as shown above. The microphone for detecting the sound should be attached to the piston that alters the tube length.
- Move the piston to make the air column as long as possible and set the function generator to 800Hz and turn the amplitude of the signal generator down.
- ★ Record this frequency in a table similar to the one below.
- Turn the amplitude of the function generator up until the speaker is clearly heard.
  Be sure not to over drive the speaker, you should be able to hear the sound but it should not be too loud. For higher frequencies the amplitude will need to be reduced, as the function generator may be more efficient at higher frequencies.
- Trigger on the speaker output when using the oscilloscope.
- Slowly push the piston further into the tube until you find a point that produces the largest sound as well as the largest trace on the oscilloscope screen. Record this position.
- Continue moving the piston down the tube until you have found all positions where resonance will occur and record them.
- Repeat this procedure for three more different frequencies.

Frequency:	Frequency:	Frequency:	Frequency:
Piston Positions	Piston Positions	Piston Positions	Piston Positions

★ For each frequency, work out the wavelength, and then calculate the speed of sound.

★ What is your average overall value for the speed of sound and does it agree with the accepted value of 343 m/s at a temperature of 20^{o}C? Remember to include all calculations in your report

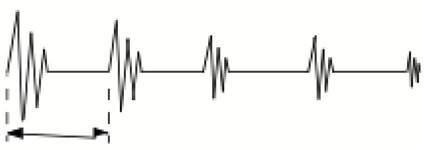
★ What could be the sources of uncertainty in this experiment?

Investigation 2

In the previous experiment you calculated the speed of sound by working out the wavelength, and then using the known frequency to obtain the speed of sound. In this experiment you will measure it more directly by timing a pulse as it propagates down the tube and reflects off the end.

Procedure

- Set the function generator to emit a 10Hz square wave, at a low amplitude.
- Turn up the amplitude until the speaker is clearly heard making a distinct clicking sound.
  Be sure not to over drive the speaker, you should be able to hear the sound but it should not be too loud. For higher frequencies the amplitude will need to be reduced, as the function generator may be more efficient at higher frequencies.
- The oscilloscope should be triggered with the output from the function generator. When viewed at a frequency similar to that of the function generator a train of pulses, similar to that on the oscilloscope shown in the diagram for investigation 1, should be visible.
- Increase the sweep speed of the oscilloscope until you are able to see more clearly the details of the pulses along one part of the square wave.
- The microphone signal should be a series of waves, as in the diagram below, which represent the returning waves echoing off the face of the piston. The time separation between these pulses will depend on the length of the tube.



Time from initial pulse until echo

- Determine how long it is from the initial pulse to the first echo. Record this result, the sweep setting (sec/cm) and also the distance from the speaker to the piston.
- Repeat this for five tube lengths.

Tabulate your data.

Determine the speed of sound in the tube and estimate the uncertainty on this result. How does it compare with the results of investigation 1.

Conclusion:

Describe in your report, in up to three sentences, what are the major findings of this experiment.
You should also comment on how your experimental results might be improved and also on the uncertainties that might have been introduced in these measurements.

Measurement of the Focal Lengths of Lenses and a Determination of Brewster's Angle

This experiment investigates the behaviour of light crossing from one medium to another. In the first part you will determine the focal lengths of concave and convex lenses. In the second part you will see how the reflected and transmitted rays depend on the polarisation of the light and determine Brewster's angle, the angle at which no light with parallel polarisation is reflected.

Part 1: Determining the focal length of Lenses and Mirrors.

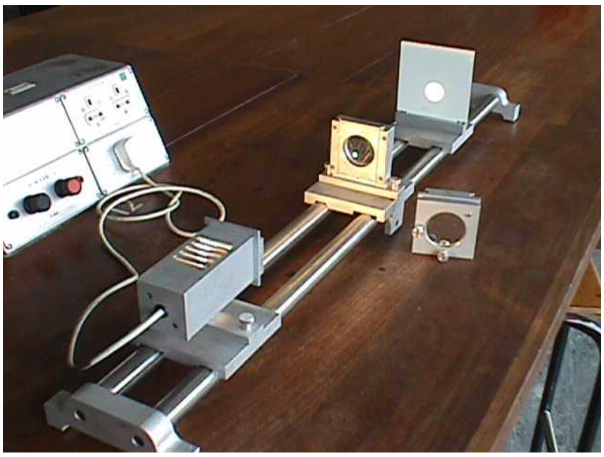
The phenomenon of refraction (or bending) of light at the interface between two materials can be used to make optical components to form images. Parallel light hitting a spherical material will either converge or diverge depending on whether the surface is convex or concave **-** to remember which shape is which, recall the entrance to a cave. Thus both a convex lens and a concave mirror are converging. For a thin spherical lens or mirror the distance of the object from the lens, u, and the distance of the image, v, are related by

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f} \qquad \text{(Eq.1)}$$

where f is a constant for a particular lens or mirror, called its **focal length**.

*(a) To determine the focal length of a **convex** lens*

Set up the apparatus as shown here with the light source passing through the lens forming an image on the screen. The object is a cross drawn on the frosted glass of the projector. Place the source 50 cm from the lens and move the screen until you obtain the sharpest image. Adjust the equipment so that the object and image are both at the same height i.e. the optical axis is horizontal and parallel to the edge of the bench.



Make at least five different measurements of source and image distances. Create in your notebook a similar table to the one below and enter the data with their associated uncertainties.

Sketch the image.

u (cm)	Δ ***u*** (cm)	***v*** (cm)	Δ ***v*** (cm)	***f*** *(cm)*
… add rows …				
Mean of the separate focal length determinations				
Standard deviation of these determinations				

For each pair of measurements, calculate the focal length and enter it in the last column. Find the mean and standard deviation of these focal lengths which are roughly equal to the best estimation and its uncertainty.

Graph *1/v* against *1/u*.

What should the slope and intercept of the graph be?

Using the graph, calculate the best value of the focal length of the lens along with its associated uncertainty.

Include the graph, the table and the values for the focal length (with uncertainty) in your **report**.

*(b) <u>To determine the focal length of a **concave** lens</u>*

Substitute the concave lens for the convex lens. Why can't you proceed as you did for the convex lens? Briefly explain your answer in the **report**.

To overcome this problem, use the concave lens together with the convex lens. This combined system will have a focal length, *f*, given by

$$\frac{1}{f} = \frac{1}{f_1} + \frac{1}{f_2} \qquad \text{(Eq. 2)}$$

where f_1 and f_2 are the focal lengths of the individual lens.

★ Proceed as before and create in your notebook a similar table to the one displayed below.

u (cm)	*Δ* ***u*** (cm)	***v*** (cm)	*Δ* ***v*** (cm)	***f*** *(cm)*
… add 5-6 rows				
Mean of the separate focal length determinations				
Standard deviation of these determinations				

★ Use Eq.2 to find the focal length of the concave lens (with its associated uncertainty).

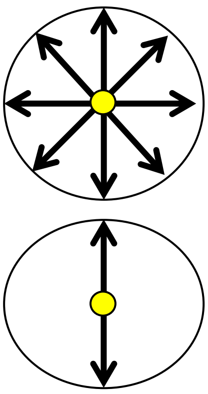
Include the value in your **report**.

Part 2: Determination of Brewster's Angle

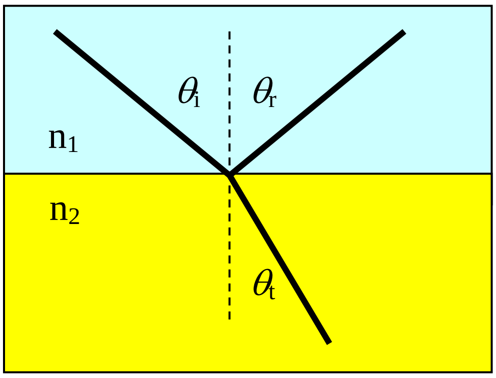
Light is an electromagnetic wave so it consists of oscillating electric and magnetic fields which have an interesting property in that the oscillations are always perpendicular to the direction in which the light is travelling.

Usually the oscillation of the electric field is orientated in many planes (each perpendicular to the direction of motion.) The light is said to be unpolarised.

However, it is possible to restrict the oscillation of the field to a single plane when the light is said to be plane polarised.



Light is coming towards you. Electric field oscillates as shown by the arrows in the plane perpendicular to you.



When light passes from one medium to another, some of the light is transmitted and some is reflected. The angles of incidence θ_i and reflection θ_r are equal while the angle of incidence and transmission are related by Snell's law:

$$\frac{n_2}{n_1} = \frac{\sin\theta_i}{\sin\theta_t} \quad \text{(Eq. 3)}$$

How much light is transmitted and how much is reflected depends on the polarisation of the light. Considering light polarised in the plane parallel to and perpendicular to the plane of incidence separately, the ratio of the intensity of the reflected to the intensity of the incident light is given by

$$R_{parallel} = \frac{\tan^2(\theta_i - \theta_t)}{\tan^2(\theta_i + \theta_t)} \quad \text{and} \quad R_{perpendicular} = \frac{\sin^2(\theta_i - \theta_t)}{\sin^2(\theta_i + \theta_t)} \qquad \text{(Eq.4)}$$

so that if R=0 no light is reflected while if R=1 all the light is reflected.
The plane of incidence is the plane which contains the surface normal and the propagation vector of the incoming radiation

The apparatus consists of a table on which the object to be measured is placed, and two arms that are free to move. One arm holds the a laser whose plane of polarisation is either known or can be set by using a polaroid, the other holds a photoresistor detector whose resistance decreases the greater the intensity of light falling on it. Thus a voltage measured across a resistor in series will increase in proportional to the intensity of light. The angles of incidence and transmission can be read from a scale on the table.
Identify the plane of incidence, it contains the incident and reflected rays. Set the plane of polarisation of the light perpendicular to the plane of incidence. Vary the angle of incidence and measure the intensity of the reflected light. To alter the plane of incidence by 90^o you will need to carefully turn the laser through 90^o.

In your notebook draw the table below and add 8-10 rows.
Record your data in the first two columns of the table and graph the results.

Light polarised ***perpendicular*** to the plane of incidence			
Angle of Incidence (degrees)	Measured Reflected Voltage (V)	Calculated angle of transmission (degrees)	Theoretical value for $R_{perpendicular}$
… add 8-10 rows …			

Repeat your measurements, in a second table like the one below, for light that is polarised **parallel** to the plane of incidence.

Light polarised ***parallel*** to the plane of incidence			
Angle of Incidence (degrees)	Measured Reflected Voltage (V)	Calculated angle of transmission (degrees)	Theoretical value for $R_{parallel}$
… add 8-10 rows …			

- Comment on the curves you have obtained and find a value for Brewster's angle θ_B, the angle of incidence at which none of the parallel polarised light is reflected: $R_{parallel} = 0$.

- Calculate also the refractive index, *n*, of the material, related to Brewster's angle by

$$n = \tan\theta_B \quad \text{(Eq. 5)}$$

- If time permits, use Eq.3 to fill in the third column of the table in your notebook (the refractive index of air can be taken to be 1). Then use Eqs. 4 to fill in the fourth column. Compare these theoretical values to your experimental values. If possible, overlay them on the same graph. Comment on the agreement.

Conclusion:

- Describe in your report, in up to three sentences, what are the major findings of this experiment.

- You should also comment on how your experimental results might be improved and also on the uncertainties that might have been introduced in these measurements.

Photoelectrical Investigations into the Properties of Solar Cells

Introduction

Solar (or photovoltaic) cells are devices that convert light into electrical energy. These devices are based on the photoelectric effect: the ability of certain materials to emit electrons when light is incident on them. By this, light energy is converted into electrical energy at the atomic level, and therefore photovoltaics can literally be translated as light-to-electricity.

The present experiment investigates: (1) the current-voltage relation known as the I-V curve of a solar cell; (2) the effect of light intensity on the solar cell's power efficiency; (3) the effect of the light frequency on the solar cell's output current.

Background Theory:

First used in about 1890, the term "photovoltaic" is composed of two parts: the word "*photo*" that is derived from the Greek word for light, and the word "*volt*" that relates to the electricity pioneer Alessandro Volta. This is what photovoltaic materials and devices do: they convert light energy into electrical energy, as French physicist Edmond Becquerel discovered as early as 1839 (he observed the photovoltaic effect via an electrode placed in a conductive solution exposed to light). But it took another century to truly understand this process. Though he is now most famous for his work on relativity, it was for his earlier studies on the photoelectric effect that got Albert Einstein the Nobel Prize in 1921 "for his work on the photoelectric effect law".

Theory:

Silicon is what is known as a *semiconductor* material, meaning that it shares some of the properties of metals and some of those of an electrical insulator, making it a key ingredient in solar cells.

Sunlight may be considered to be made up of miniscule particles called *photons*, which radiate from the Sun. As photons hit the silicon atoms within a solar cell, they get absorbed by silicon and transfer their energy to electrons, knocking them clean off the atoms.

Freeing up electrons is however only half the work of a solar cell: it then needs to herd these stray electrons into an electric current. This involves creating an electrical imbalance within the cell, which acts a bit like a slope down which the electrons will "flow". Creating this imbalance is made possible by the internal organisation of silicon. Silicon atoms are arranged together in a tightly bound structure. By squeezing (doping) small quantities of other elements into this structure, two different types of silicon are created: *n-type*, which has spare electrons, and *p-type*, which is missing electrons, leaving 'holes' in their place.

When these two materials are placed side by side inside a solar cell, the n-type silicon's spare electrons jump over to fill the gaps in the p-type silicon. This means that the n-type silicon becomes positively charged, and the p-type silicon is negatively charged, creating an electric field across the cell. Because silicon is a semiconductor, it can act like an insulator, maintaining this imbalance. As the photons remove the electrons from the silicon atoms, this field drives them along in an orderly manner, providing the electric current to power various devices.

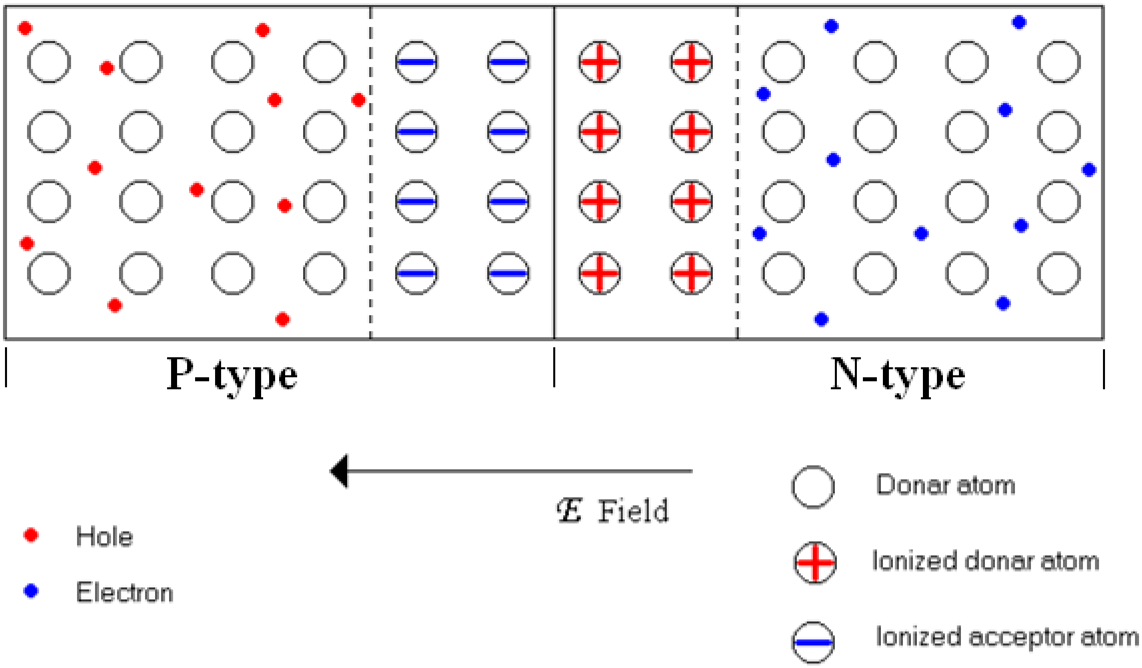


Figure 1. The pn junction within a silicon solar cell.

★ In your report, give three examples of devices that use solar cells.

Important characteristics of solar cells:

There are a few important characteristics of a solar cell: the *open circuit voltage* (**V_{OC}**), the *short circuit current* (**I_{SC}**), the *power* **(P)** *output* and the *efficiency* (**η**).

The V_{OC} is the maximum voltage from a solar cell and occurs when the current through the device is zero.

The I_{SC} is the maximum current from a solar cell and occurs when the voltage across the device is zero.

The power output of the solar cell is the product of the current and voltage. The maximum power point (MPP) is achieved for a maximum current (I_{MPP}) and voltage (V_{MPP}) product (Eq. 1).

$$P_{MAX} = V_{MPP} \cdot I_{MPP} \qquad \text{Eq. (1)}$$

The efficiency (η) of a solar cell is a measure of the maximum power (P_{max}) over the input power (P_{LIGHT}) (Eq. 3):

$$\eta = \frac{P_{MAX}}{P_{light}} = \frac{V_{MPP} \cdot I_{MPP}}{P_{light}} \qquad \text{Eq. (2)}$$

Figure 2 shows a typical IV curve from which the above solar cell characteristics can be derived. A similar IV curve graph should be achieved in the first part of the present laboratory.

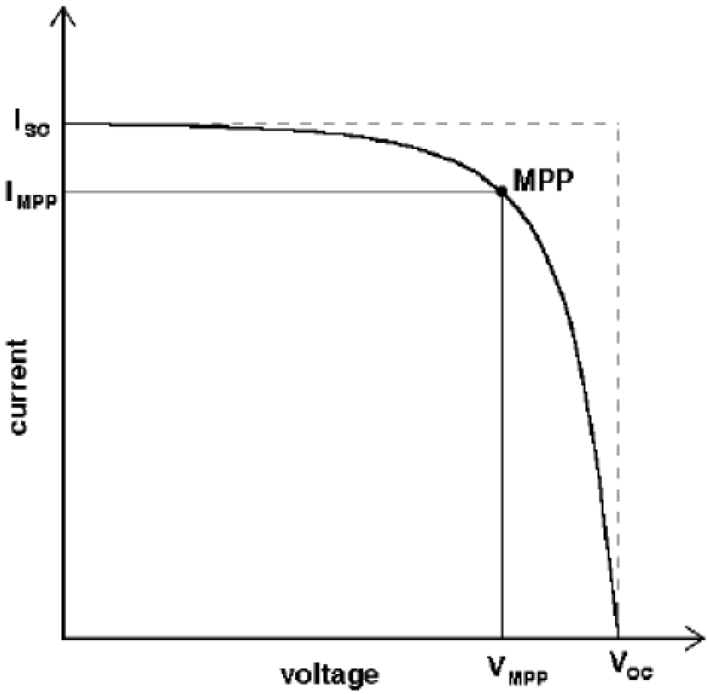


Figure 2. The IV curve of a solar cell, showing the open circuit voltage (V_{OC}), the short circuit current (I_{SC}), the maximum power point (MPP), and the current and voltage at the MPP (I_{MPP}, V_{MPP}).

Apparatus

The apparatus (*Figure 3*) consists of a silicon solar cell, one ammeter, one voltmeter, a halogen light source, filters, a variable load resistor, crocodile clips and wires.

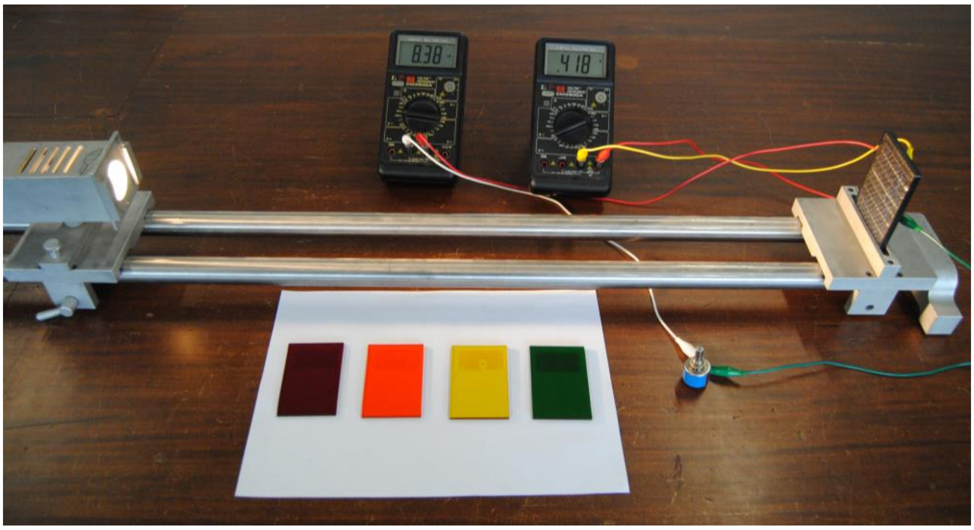


Figure 3. Apparatus for measuring the IV curve of a silicon solar cell.

<u>*Part 1. Measuring the IV curve of a silicon solar cell*</u>

The apparatus for the Part 1 consists of a solar cell, an ammeter and a variable resistor both connected in series with the solar cell, and a voltmeter connected in parallel. The electrical circuit required in this experiment is given in *Figure 4*.

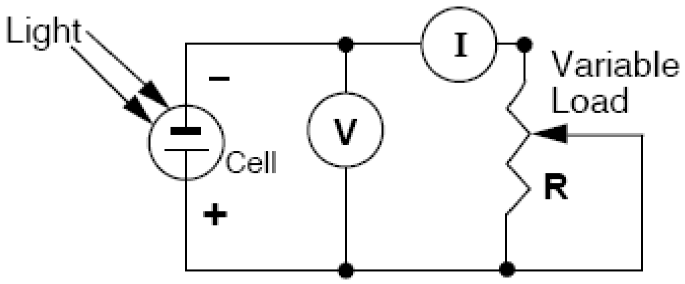


Figure 4. The solar cell's IV curve electrical circuit.

By taking current and voltage measurements of a solar cell while using a variable resistor, you determine the current-voltage relation, or what is called the solar cell IV curve. The current and voltage of each reading are multiplied together to yield the corresponding power at that operating point.

Method:

1. Use the orange meter to measure the resistance of the load resistor, work out which connection is which.
2. Use the same meter to measure the open-circuit voltage, V_{OC}, of the solar cell. You can connect the meter directly to the solar cell.
3. Include the load resistor and check that the voltage you measure varies as you would expect when you change the resistance.

4. Set the circuit diagram as shown in *Figure 4,* use the yellow meter to measure the current.
5. Fix the solar cell vertically on the aluminium rail, facing toward the halogen light source. Set the distance between the light source and the solar cell to be as large as possible.
6. Switch on the halogen light source and allow 2-3 minutes for it to stabilise
7. To quickly test your setup, measure:
   - the short circuit current (by setting the variable load resistor to 0); you should get a value of around 30 mA;
   - and the open circuit voltage (by setting the variable load resistor to maximum – rotate until the other end of the load resistor is reached); you should get around 400 mV.
   Make sure you get the values in the positive range, otherwise reverse the wire connection to get them positive (e.g. if you get - 400 mV, then interchange the wires coming into the voltmeter and similarly for the ammeter).
8. Slowly increase the resistance of the variable load resistor (from 0 towards max) until you notice a small change in current. For each step, simultaneously record both the current and the voltage. Take readings in small steps of resistance in order to get 20 – 25 measurement points.
9. Continue until reaching the maximum resistance of the variable resistor
10. Create a table in your notebook as indicated below; calculate the power in the table ($P = V * I$).

Measurement	*Voltage (mV)*	*Current (mA)*	*Power (mW)*
1	413	0	0
2	409	2.1	858.9
…	…	…	…
25	0	30.8	…

11. Plot the IV curve (current vs voltage) and indicate the V_{OC} and I_{SC} on the graph.
12. Plot the power vs voltage (the power graph); indicate the P_{max} in the power curve and find the corresponding voltage. From this graph identify V_{MPP} and I_{MPP} and show them on the previous graph too.

Don't forget to include the two graphs and the values of I_{SC}, V_{OC}, P_{max}, I_{MPP} and V_{MPP} in your **report**.

Considering that the incident power of the halogen light source (P_{LIGHT}) is 1 W, calculate from Eq.2 the efficiency of the solar cell. Include it in your **report**.

Part 2: Characterise the effect of light intensity on the solar cell efficiency

Repeat the set of measurements from Part 2 using the same experimental setup and method, only this time by (approximately) halfing the distance between the light source and the solar cell. By doing this you increase the incident light intensity on the solar cell and you have to measure the response of the solar cell to this increase.

In your notebook, create a table as indicated below and include 15-20 lines of measurements. Tabulate your measurements and discuss your results in your **report** based on the following questions.

Measurement	*Voltage (mV)*	*Current (mA)*	*Power (mW)*
1	474	0	0
2	472	4.3	2029.6
…	…	…	…
20	…	90.7	…

How does the efficiency change when the distance between the light source and the solar cell is decreased?

Comment on the I_{SC} and V_{OC} values that you have measured for the 2 distances (in part 1 and in part 2).

How do you anticipate that the output power of the solar cell will change when the lamp-cell distance decreases? What about the solar cell's efficiency? Are these values different when compared to those obtained in part 1?

What relationship between the solar cell efficiency and light intensity can you deduce from your findings?

You should also comment on how your experimental results might be improved and also on the uncertainty that might have been introduced in these measurements.

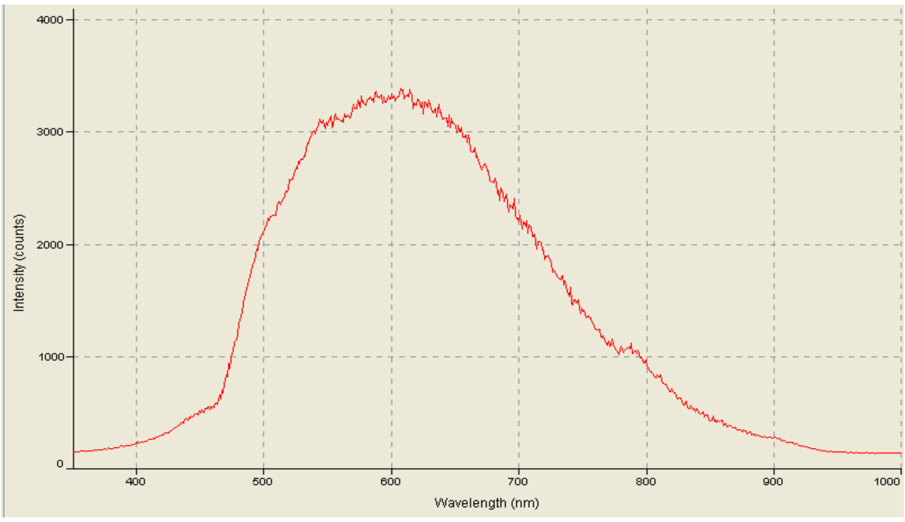
Part 3: Characterise the effect of light frequency on the solar cell efficiency

The aim of this part is to determine the relation between wavelength and the current output of a silicon solar cell (known as silicon's spectral response). The spectral responsivity is a function of the photons' wavelength; it is measured in amperes per watt (A/W) and it is a measure of how much current comes out of the device per incoming photon of a given wavelength (energy).

You will be using the conditions from part 2, with the load resistor set to zero, (half maximum distance between solar cell and light source), and you will be measuring only the solar cell current with an ammeter when using different light filters and the halogen light source.

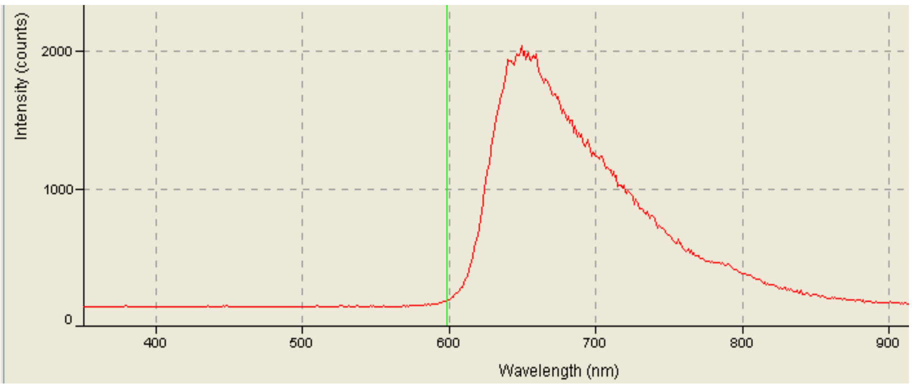
You are given 4 different filters: red, orange, yellow and green that transmit light above or between certain wavelengths.

As can be seen from the image below, when using no filters, the solar cell receives wavelengths between 400-900 nm from the halogen light.



Halogen light source spectrum

If placing the red filter between the light source and the solar cell, only wavelengths higher than 600 nm will be transmitted.

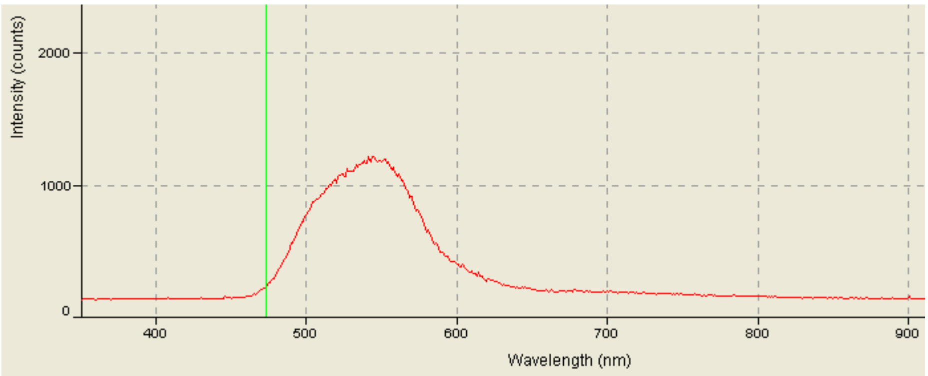


Red filter transmits above 600 nm

For the orange filter only wavelengths above 555 nm and for the yellow one only wavelengths above 475 nm will be transmitted.

The red, orange and yellow filters described above are called longpass filters as they block the wavelengths below a given value.

The green filter that you will use is slightly different to the longpass ones, as it transmits only a wavelength band (in this case 473 – 600 nm). This type of filter is called a bandpass filter and in general it can be of any desired colour.



Green bandpass filter transmits between 473 – 600 nm

Take a measurement of the current from the silicon solar cell with one filter at a time.

In the first measurement use no filters, this will be the maximum current value. In your notebook create a table similar to the one indicated below and tabulate all your results.

Filter colour	$\lambda_{transmitted}$ (nm)	$I_{measured}$ (mA)	Response factor	$I_{corrected}$ (mA)
No filter	400 - 900	80.2	1	80.2
Red	> 600	60.1	0.91	60.1 * 0.91 = 54.691
Orange	> 555	…	0.73	
Yellow	> 475	…	0.72	
Green	473 - 600	…	1	

You can calculate the $I_{corrected}$ (column 5) for each filter by using the response factor (F):

$$I_{corrected} = I_{measured} * \text{Response Factor}$$

Comparing the $I_{corrected}$ for the red, orange and yellow filters, explain which part of the light spectrum has produced the most current from the solar cell?

Plot the $I_{corrected}$ *vs* λ for red, orange and yellow filters only. For this, consider:

$$\lambda_{red} = 700 \text{ nm}, \lambda_{orange} = 605 \text{ nm}, \lambda_{yellow} = 580 \text{ nm}.$$

How does the current change with the wavelength of the incident light?

- Taking the value of $I_{corrected}$ corresponding to the full wavelength range of the halogen bulb (400-900 nm), and given that you are able to measure the $I_{corrected}$ between 600-900 nm (using the red filter) and also between 473 - 600nm (using the green filter), calculate (from your table) the value of $I_{corrected}$ between 400 - 473 nm.

Conclusion:

- Describe in your report, in up to three sentences, what are the major findings of this experiment.

- You should also comment on how your experimental results might be improved and also on the uncertainties that might have been introduced in these measurements.

Determination of the Resistivity of a Metal Alloy using a Wheatstone Bridge

Introduction

This experiment uses a simple but clever piece of apparatus, called the Wheatstone bridge, to measure an unknown resistance to high precision and accuracy. The Wheatstone bridge is a circuit set up in a delicate balance so that no current flows through a galvanometer (which is a very sensitive current measuring device). Any deviations from zero are readily detected, so when the Wheatstone bridge is balanced, you know to high precision that no current is flowing in the galvanometer and this leads to high precision in determining the resistance of an unknown substance. Wheatstone bridge circuits are often at the centre of many electronic measuring devices, remote sensing equipment and switches. The resistance, *R*, of a substance is directly proportional to its length, *L*, and inversely proportional to its cross-sectional area, *A*, as well as depending on the material it is made from. Thus,

$$R = \rho L / A \qquad \text{(Eq.1)}$$

where the resistivity, ρ, depends on the material.

In your **report**, answer the following questions:

If you double the length of a resistor what happens to its resistance?

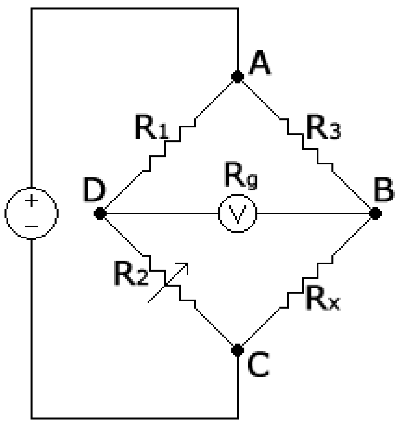
If you double the radius of a cylindrical resistor, what happens to its resistance?

Wheatstone Bridge circuit

The Wheatstone bridge is shown here and has two known resistances R_1, R_3, one variable resistor, R_2, and the unknown resistor R_X. When the meter is balanced, i.e. when the current through the galvanometer R_g is zero:

$$R_X / R_3 = R_2 / R_1 \qquad \text{(Eq. 2)}$$

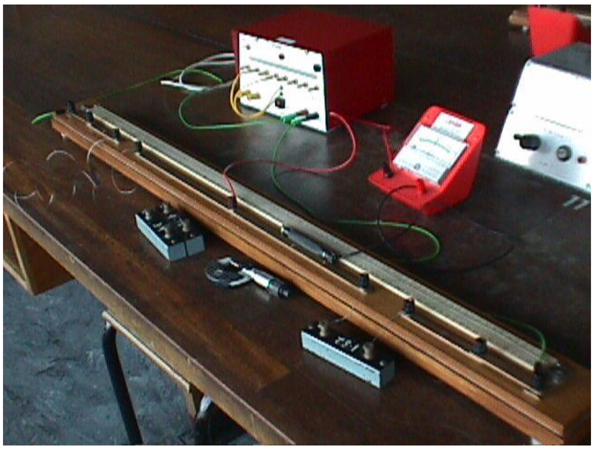
(We will prove this later).

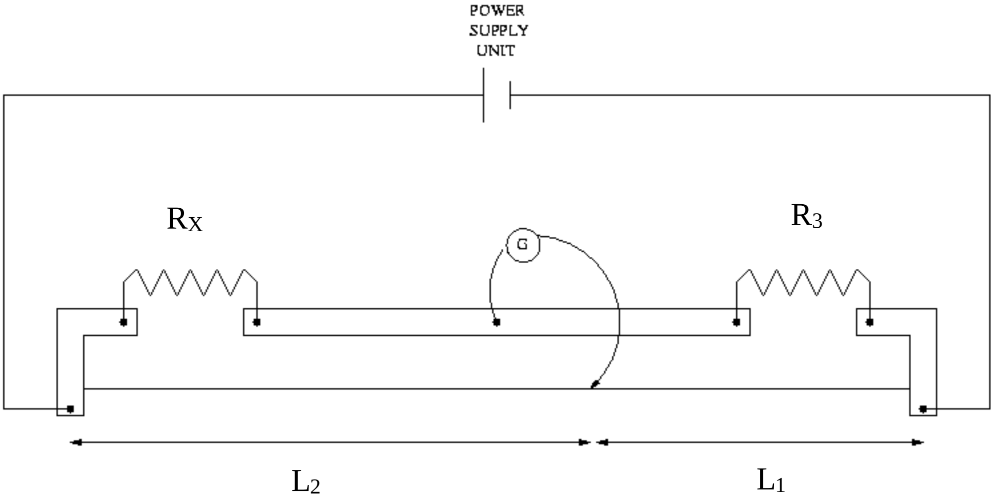


Apparatus

The apparatus used to measure the resistance of the alloy is shown on the right and schematically below. Note the similarity with the Wheatstone bridge above.
Instead of measuring R_1, R_2 however, we take advantage of the fact that the resistance of a resistor is proportional to its length and so:

$$R_2/R_1 = L_2/L_1 \quad \text{(Eq. 3)}$$





Method

Connect the apparatus as shown above.
→ take particular care that the contacts to R_3 and R_X are tight.
→ make sure that the longest length of R_X is used (i.e. make the contacts with the shortest possible lengths at each end and ensure that the wire cannot short itself).
→ use the shortest possible lengths of wire to connect the known resistors to the bridge.

Press the contact maker against the wire and find two points, which give deflections of the galvanometer in opposite directions.

Between these points locate accurately the point of contact which gives no deflection.
→ measure L_1 and L_2, noting that L_2 is the length opposite R_X and L_1 is the length opposite R_3.
→ record your values in your **notebook** by creating a table like the one below.
(Don't forget to include uncertainties).

R_3	L_1	L_2	R_X

Interchange R_3 and R_X and repeat the experiment. (Lengths L_1 and L_2 will also swap. Note that L_2 is always the length opposite R_X. If the values of L_1 and L_2 for the second balance point differ by more than 1 cm from the original ones, consult the demonstrator before proceeding. The discrepancy may be due to bad contacts on the meter bridge). Record the measurements in your notebook and present them in your **report.**

R_3	L_1	L_2	R_X

Calculate and **report** the average value for the unknown resistance of the alloy R_x.

Repeat the measurements for different values of the fixed resistor, R_3. Create a table similar to the one below and include the results in the **report**.

R_3	L_1	L_2	R_X

Combine all your above measurements to get the best value for the resistance of the alloy R_x. Include this value and the uncertainty in your **report**.

In the next steps you will calculate the resistivity of the metal alloy.

Detach the sample wire and uncoil it carefully so as not to produce any kinks.
→ measure the wire's length, making allowance for the short lengths used at each end that were not included in the resistance measurement.

Measure the diameter by means of a micrometer screw at about six different places uniformly distributed along the wire.

Record you measurements in your notebook and use Eq. 1 to calculate the resistivity of the metal alloy along with its uncertainty.

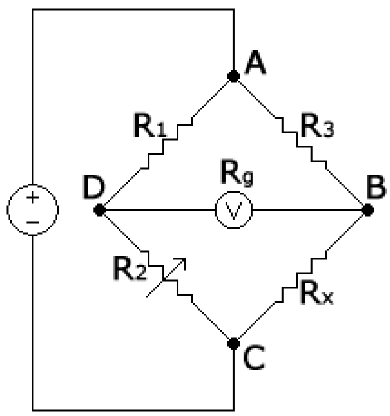
Show in your report how have you calculated the resistivity and what value you obtained, including the uncertainty.

Finally, prove what we have assumed all along, that

$$R_X / R_3 = R_2 / R_1$$

Remember, when balanced, no current flows in the leg DB.

The solution is outlined in the seven steps below.



1) What current flows along DB?
2) What can you say about V_{DB}, the voltage difference between D and B?
3) What can you say about V_{AD} compared to V_{AB}? Write an equation to express this.
4) What can you say about V_{DC} compared to V_{BC}? Write an equation to express this.
5) Let I_L be the current that flows along the left hand line A->D->C and I_R the current that flows along the right hand line A->B->C. (Remember nothing flows from D->B)
6) Express each of V_{AD} , V_{AB} ,V_{DC} , V_{BC} as a current times a resistance using Ohm's Law.
7) Substitute into the two equations in steps 3 & 4 and divide one equation by the other.

Based on these 7 steps, include the solution in your **report**.

Conclusion:

Describe in your report, in up to three sentences, what are the major findings of this experiment.

You should also comment on how your experimental results might be improved and also on the uncertainties that might have been introduced in these measurements.

Graphing

Many of the experiments in this laboratory involve the plotting of a graph. Graphs are very important in Physics as they provide a simple display of the results obtained in an experiment and of the relationship between two variables. <u>More accurate and reliable information can be obtained from a graph than from the analysis of any particular set of results</u>.

Plotting graphs by hand:

(1) *Scale:* It is important to choose the scales so as to make full use of the squared page. The scale divisions should be chosen for convenience; that is, one unit is either 1, 2 or 5 times a power of ten e.g. 0.5, 5, 100 etc., but never 3, 7, 9 etc.

(2) *Marking the points:* Readings should be indicated on the graph by a ringed dot ⊗ and drawn with <u>pencil</u>, so that it is possible to erase and correct any unsatisfactory data.

(3) *Joining the points:* In the case of a straight line which indicates a direct proportion between the variables, the ruler is positioned so that the line drawn will pass through as many points as possible. Those points which do not lie on the line should be equally distributed on both sides of the line. A point which lies away from this line can be regarded as 'doubtful' and a recheck made on the readings. In the case of a curve, the individual experimental points are <u>not</u> joined with straight lines but a smooth curve is drawn through them so that as many as possible lie on the curve.

(4) *Units:* The graph is drawn on squared page. Each graph should carry **title** at the top e.g. Time squared vs. Length. The axes should be labelled with the name and units of the quantities involved.

(5) In the case of a straight-line graph, the equation of the line representing the relationship between the quantities x and y may be expressed in the form

$$y = mx + c$$

where **m** is the slope of the line and **c** the intercept on the y-axis. The slope may be positive or negative. Many experiments require an accurate reading of the slope of a line.

Using JagFit

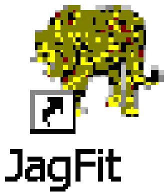
In the examples above we have somewhat causally referred to the ***'best fit'*** through the data. What we mean by this, is *the theoretical curve which comes closest to the data points having due regard for the experimental uncertainties.*

This is more or less what you tried to do by eye, but how could you tell that you indeed did have the best fit and what method did you use to work out statistical uncertainties on the slope and intercept?

The theoretical curve which comes closest to the data points having due regard for the experimental uncertainties can be defined more rigorously[2] and the mathematical definition in the footnote allows you to calculate explicitly what the best fit would be for a given data set and theoretical model. However, the mathematics is tricky and tedious, as is drawing plots by hand and for that reason....

We can use a computer to speed up the plotting of experimental data and to improve the precision of parameter estimation.

In the laboratories a plotting programme called Jagfit is installed on the computers. Jagfit is freely available for download from this address:
http://www.southalabama.edu/physics/software/software.htm



Double-click on the JagFit icon to start the program. The working of JagFit is fairly intuitive. Enter your data in the columns on the left.

- Under **Graph**, select the columns to graph, and the name for the axes.
- Under **Error Method**, you can include uncertainties on the points.
- Under **Tools**, you can fit the data using a function as defined under **Fitting_Function**. Normally you will just perform a linear fit.

[2] If you want to know more about this equation, why it works, or how to solve it, ask your demonstrator or read about 'least square fitting' in a text book on data analysis or statistics.

Example Report
Springs

James Mooney 20th July 2015

ABSTRACT
The purpose of this exercise is to explore how springs respond when different masses are suspended from them and use the data to learn about graphing scientific data.

INTRODUCTION
In many scientific disciplines data is presented in the form of plots. Typically these plots will have labeled horizontal and vertical axes with scales indicated, points with a horizontal or vertical lines to represent uncertainty or precision and a line or curve superimposed through the data points to illustrate the trend or rate of change.

★ *Why do we make such plots?*
By making these plots we can visually illustrate what the data is saying. At a glance, rates of change, trends, maximums, minimums and averages can be immediately ascertained.

★ *What features of the graphs do you think are important and why?*
Key features of the graphs are:
- Clearly labeled horizontal and vertical axes:- without this you have no context or reference for the plot and would have no way of telling what the data refers to.
- The scale of each axis:- as data is all about measurement, an appropriate scale expands the data to best illustrate the trends.
- Horizontal or vertical lines through data points:- These lines indicate how precisely the data has been measured.

★ *Preparation*
To define the length of each spring, the point at which the coils end and angle perpendicular from the coils was determined to be the two reference points for measuring. Measurements were taken between these two points and the tabletop, the latter being a fixed point.

Initial length of spring 1 3.4 cm
Initial length of spring 2 6.0 cm

Length of springs with mass hanger attached (+20 g)

	Spring 1	Spring 2
Position of the top of spring	51.2	50.8
Position of the bottom of spring	43.3	38.8
New length of spring (cm)	7.9	12.0

MEASUREMENTS FOR SPRING 1

Object Added	Total mass added to the mass hanger (g)	New reference position (cm)	New spring length (cm)
Disk 1	30	41.5	10
Disk 2	40	39.7	12
Disk 3	50	37.7	14
Disk 4	60	36.0	15.2
Disk 5	70	34.1	17
Disk 6	80	32.3	19
Disk 7	90	30.4	21

MEASUREMENTS FOR SPRING 2

Object Added	Total mass added to the mass hanger (g)	New reference position (cm)	New spring length (cm)
Disk 1	30	35.5	15
Disk 2	40	31.7	19
Disk 3	50	28.6	22
Disk 4	60	25.4	25
Disk 5	70	22.3	29
Disk 6	80	19.0	31.8
Disk 7	90	15.8	35

Allowing for the inaccuracy of the wooden meter ruler, the varying angles whilst sighting the line from spring to ruler and the ensuing fluctuations caused by this act, the uncertainty in the y-values was estimated to be ± 0.5cm.

★ **DESCRIBE THE 'STEEPNESS' OF THE SLOPES FOR SPRING 1 AND SPRING 2**
Spring 2's slope is almost twice as steep as that of spring 1 reflecting how spring 2 extends more readily when mass is applied than spring 1.

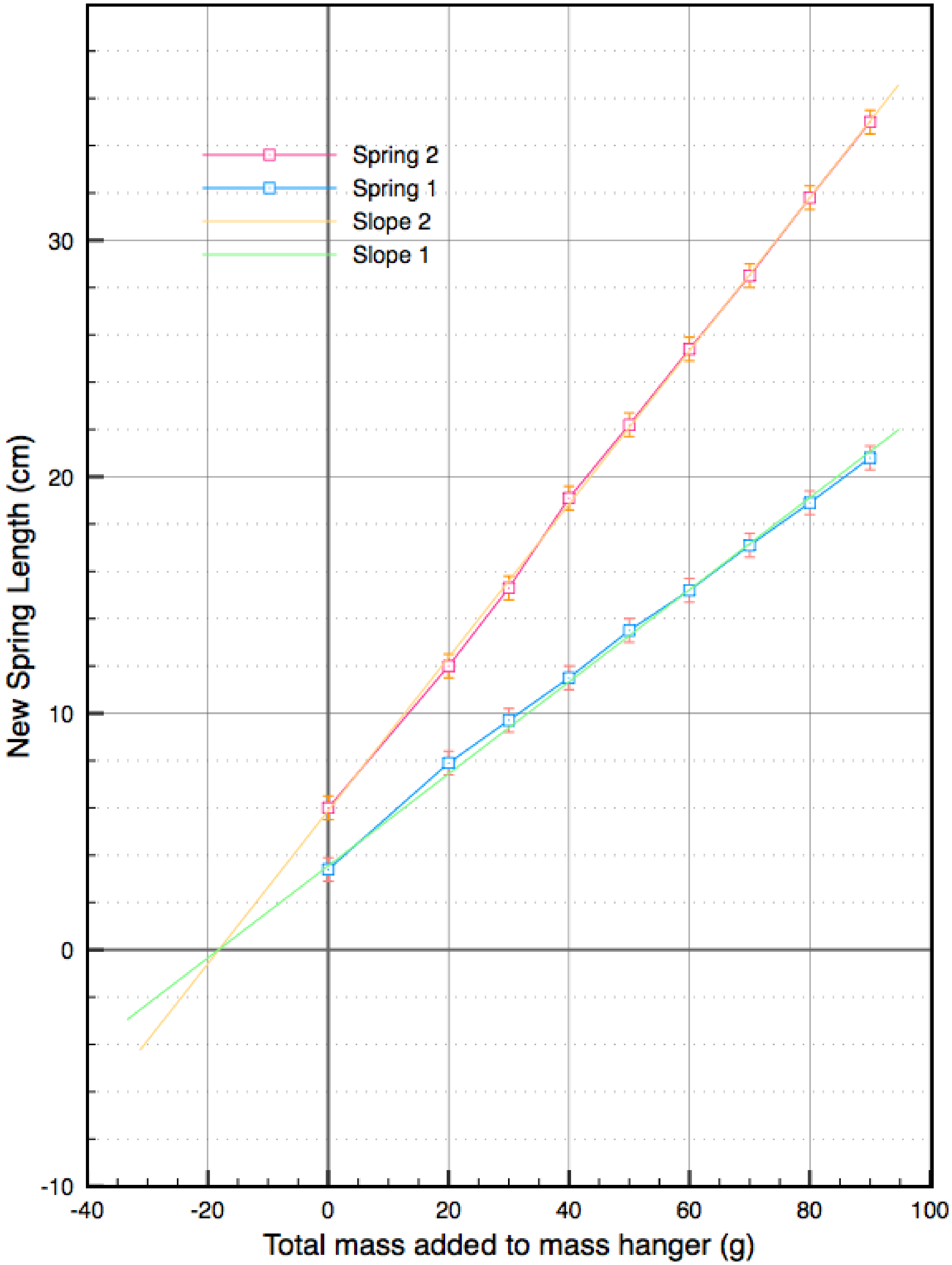
★ **SLOPE SPRING 1**
Start Point (20,7.9) End Point (90,20.8)

$$m=\frac{\Delta y}{\Delta x}=\frac{20.8-7.9}{90-20}=\frac{12.9}{70}$$

Equation of line for spring 1

$$y=\frac{12.9}{70}x+3.4$$

GRAPH OF DATA FOR SPRINGS 1 & 2



SLOPE SPRING 2
Start Point (20,12) End Point (90,35)

$$m=\frac{\Delta y}{\Delta x}=\frac{35\text{-}12}{90\text{-}20}=\frac{23}{70}$$

Equation of line for spring 2

$$y=\frac{23}{70}x+6$$

WHAT ARE THE TWO INTERCEPTS?
Spring 1: when x=0, y is 3.4.
Spring 2: when x=0, y is 6.

These are the lengths of the springs measured before adding any weights.

HOW CAN YOU USE THE SLOPES OF THE TWO LINES TO COMPARE THE STIFFNESS OF THE SPRINGS?
The slopes illustrate that spring 1 is almost twice as stiff as spring 2

CONCLUSION
The linear behaviour of springs is clearly illustrated by the graph of the data depicting the correlation between the length of each spring and the mass added. This demonstrates Hooke's law, which states that the extension produced is proportional to the force applied. In this case the force on the spring is proportional to the mass added. Within the experimental uncertainties the graphs for the two springs are consistent with this law. The graph shows that spring 1 is stiffer than spring 2.