

# A Level Practical Skills Matches

(first teaching 2015)

## A level Practical Skills matches and data logging

Data Harvest has a large archive of worksheets, practical experience and support documentation. In this book we have attempted to provide materials that use data loggers to support the practical skills assessments of the current A and AS level examination. We notice that use of data logging, data loggers and sensor technology is an integral part of the Ofqual and government orders and this has been reflected in the new specifications created by the examination boards in England. The worksheets have been tailored to make them useable for assessment, they have reduced instructions and guidance. Data Harvest has available 5 volumes of A level standard teaching worksheets that contain more detailed instruction and student guidance.

The book contains:

### Section A: Biology

Teacher's notes and student worksheets for 15 practical ideas

### Section B: Chemistry

Teacher's notes and student worksheets for 13 practical ideas

### Section C: Physics

Teacher's notes and student worksheets for 19 practical ideas

### Section D: Maths modelling and functions

Support for mathematical and general skills

The role of mathematics in Advanced level science has been formalised into a common set of skills that should be used in each of the sciences. The software that Data Harvest produces contains a lot of mathematical functionality that can be applied directly to experimentally derived data. The help given in the section includes:

1. **Mathematical modelling** - Comparison of experimental data to theoretical data is a fundamental skill of science. Three case studies of how to model the theoretical solution from experimental data are provided as exemplar materials.
  - **Decay and exponents.** Use the half-life data to produce the theoretical decay curve and overlay it on the curve derived from protactinium decay.
  - **Oscillations and SHM.** An analysis of the sine wave form produced by oscillations. Creation of the model sine curve from period, frequency and angular change data.
  - **Capacitor charge and discharge.** Comparison of the experimental charge / discharge curve to the curve created from the time constant. Using tools in the EasySense software to create a Log linear plot for  $-1/CR$ .
2. **The Function Wizard guide.** Gives assistance and advice on use of formula to construct, modify and abstract data. These are powerful mathematical tools that can be used directly on the experimentally collected data, making the maths relevant to the students learning.

# BIOLOGY

## CONTENTS

Teacher's notes: 1. The effect of temperature on membrane permeability in beetroot .....	4
1. The effect of temperature on membrane permeability in beetroot.....	7
Teacher's notes: 2. Protease and casein (milk powder) reaction .....	11
2. Protease and casein (milk powder) reaction .....	15
Teacher's notes: 3. How does enzyme activity (protease) change with temperature? .....	17
3. How does enzyme activity (protease) change with temperature? .....	19
Teacher's notes: 4. How does enzyme (protease) activity change with pH? .....	21
4. How does enzyme (protease) activity change with pH? .....	24
Teacher's notes: 5. The effect of lipase on milk .....	27
5. The effect of lipase on milk .....	30
Teacher's notes: 6. Cobalt as an inhibitor of enzyme activity (protease) .....	33
6. Cobalt as an inhibitor of enzyme activity (protease).....	35
Teacher's notes: 7. Amylase and starch reaction.....	37
7. Amylase and starch reaction .....	39
Teacher's notes: 8 How does enzyme activity (amylase) change with temperature? .....	41
8. How does enzyme activity (amylase) change with temperature? .....	43
Teacher's notes: 9. How does enzyme (amylase) activity change with pH? .....	45
9. How does enzyme (amylase) activity change with pH? .....	48
Teacher's notes: 10. The breakdown of starch by the enzyme amylase (diastase) using a Light level sensor.....	50
10. The breakdown of starch by the enzyme amylase (diastase) using a Light level sensor .....	52
Teacher's notes: 11. Colorimetric determination of glucose concentration .....	55
11. Colorimetric determination of glucose concentration .....	57
Teacher's notes: 12. Quantitative Benedict's test for glucose measurement .....	60
12. Quantitative Benedict's test for glucose measurement.....	63
Teacher's notes: 13 (a – b). Titration of amino acid (alanine).....	66
13a. Titration of amino acid (alanine) .....	70
13b. Titration of amino acid (alanine) using a burette.....	75
Teacher's notes: 14. A Margaria Kalamen power test .....	78
14. A Margaria Kalamen power test.....	80
Teacher's notes: 15 (a – d). Photosynthesis and CO <sub>2</sub> .....	82
Teacher's notes: 15a. Effect of CO <sub>2</sub> on the rate of photosynthesis .....	86
15a. Effect of CO <sub>2</sub> on the rate of photosynthesis.....	89
Teacher's notes: 15b. Effect of colour of light on the rate of photosynthesis.....	92
15c. Effect of light intensity on the rate of photosynthesis .....	102
Teacher's notes: 15d. Respiration and CO <sub>2</sub> .....	105
15d. Respiration and CO <sub>2</sub> .....	109

## Biology

The table below lists the practical worksheets (in order) in the biology section. For each practical there is a student worksheet and a teachers' guidance. Practical skills are indicated from the guidance given by the examination boards

Practical name	Sensors	Practical skills
1. The effect of temperature on membrane permeability in beetroot	Colorimeter	a, b, c, j, l
2. Protease and casein (milk powder) reaction	Colorimeter	a, b, c, l
3. How does enzyme activity (protease) change with temperature?	Colorimeter	a, b, c, l
4. How does enzyme (protease) activity change with pH?	Colorimeter	a, b, c, l
5. Effect of lipase on milk	pH	a, b, c, l
6. Cobalt as an inhibitor of enzyme activity (protease)	Colorimeter	a, b, c, l
7. Amylase and starch reaction	Colorimeter	a, b, c, l
8. How does enzyme activity (amylase) change with temperature?	Colorimeter	a, b, c, l
9. How does enzyme (amylase) activity change with pH?	Colorimeter	a, b, c, l
10. The breakdown of starch by the enzyme amylase (diastase) using a Light level sensor	Light level (set to transmission range)	a, b, c, l
11. Colorimetric determination of glucose concentration	Colorimeter	a, b, c, f, l
12. Quantitative Benedict's test for glucose measurement	Colorimeter	a, b, c, f, l
13. Titration of an amino acid (alanine)	pH	a, b, c, f, l
13a. Titration of an amino acid (alanine) using a burette	pH	a, b, c, f, l
14. A Magaria Kalamen power test	Pressure mats	a, b, h, l
15a. Effect of CO <sub>2</sub> on the rate of photosynthesis	Carbon dioxide	a, b, h, l
15b. Effect of colour of light on the rate of photosynthesis	Carbon dioxide	a, b, h, l
15c. Effect of light intensity on the rate of photosynthesis	Carbon dioxide, Light level	a, b, h, l
15d. Respiration and CO <sub>2</sub>	Carbon dioxide	a, b, h, l

**Apparatus and Techniques:** Skills identified in biology where data logging, data loggers or sensors should be considered.

- AT a - Use appropriate apparatus to record a range of quantitative measurements.
- AT b - Use appropriate instrumentation to record quantitative measurements, such as a colorimeter or potometer
- AT c - Use laboratory glassware apparatus for a variety of experimental techniques to include serial dilutions

- AT f – Use qualitative reagents to identify biological molecules
- AT h – Safely and ethically use organisms to measure: plant or animal responses, physiological functions
- AT i - Use ICT such as computer modelling, or data logger to collect data, or use software to process data
- AT j – Safely use instruments for dissection of an animal organ, or plant organ
- AT l – Use ICT such as computer modelling , or data logger to collect data , or use software to process data

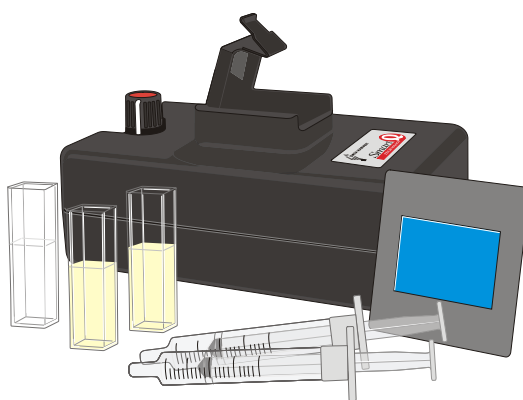
## Teacher's notes

### 1. The effect of temperature on membrane permeability in beetroot

#### Practical skills AT a, b, c, j, l

The colour of beetroot is due to the presence of a red pigment, anthocyanin, in the cell sap. The experiment investigates the effect of temperature on the selectively permeable membranes of beetroot. The membrane of a cell "keeps the insides in and the outsides out". Anthocyanins are large molecules produced in the cell and are unable in normal circumstances to cross the membrane. If the pigment is released from the cell then something must be happening to damage the cell membrane and affect its' permeability.

This is a variation of the classic beetroot membrane experiment that uses heat to change the permeability of the membrane. There is no reason why your own version cannot be used.



#### Apparatus

1. Colorimeter set to the Transmittance range
2. Blue filter and Cuvettes
3. 7 test tubes and test tube rack
4. Cork borer
5. Tile
6. Scalpel
7. Small beaker
8. Graduated pipette
9. Mounted needle
10. Large beaker
11. Thermometer
12. Large beetroot(s)

#### Set up

Recording method		Display
Meters	Numeric section window	Full Size

If you are using a logger with an LCD screen the readings from the Colorimeter can be read directly from it.

## Practical notes

It is probably better to have the beetroot cylinders pre-prepared from a number of roots, the students then take several cylinders from the stock which will randomise the beetroot tissue.

The method describes the use of a mounted needle to place the discs into the hot water; a variation has the discs placed into a tube of water and the whole tube placed into a water bath for 5 minutes. The water bath will heat the water around the discs. The advantage of this method is that the discs do not need transferring; the disadvantage is that the temperature may not be as well controlled.

Students should be encouraged to refine the "denaturing" point of the membrane by filling in data with more temperature points around the sudden change in transmission.

Students should also be encouraged to record the actual temperature of the water bath and not the "indicated".

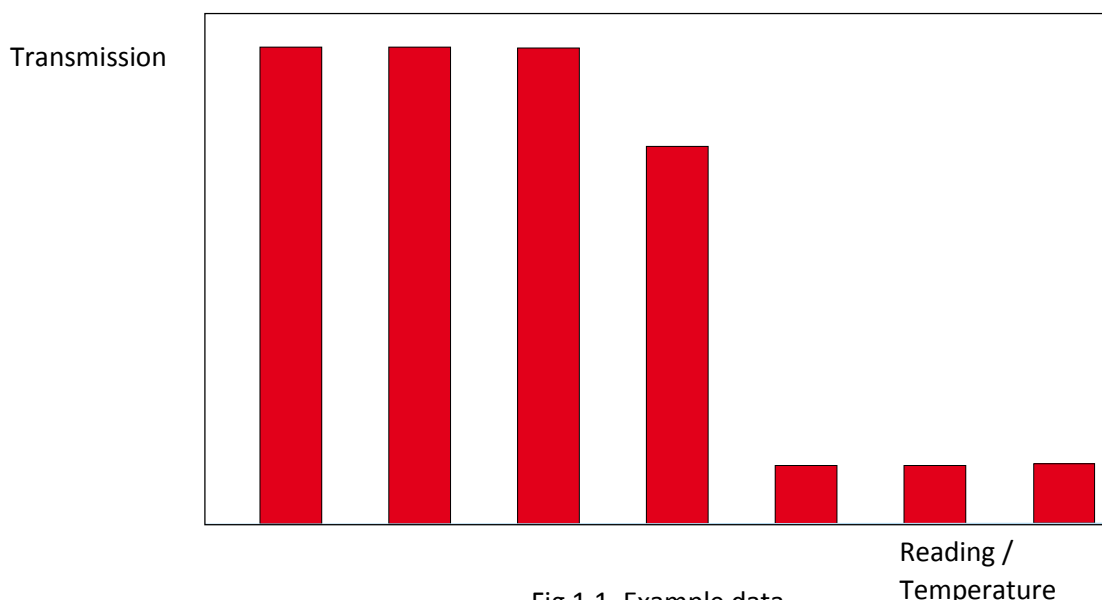


Fig 1.1. Example data

## Relationship between Transmittance (T%) and Absorbance (A)

It is normal, when doing concentration based work to use Absorbance not transmittance. Absorbance has a direct link to concentration. Transmittance has a link to concentration, but it is non-linear. The Colorimeter is unable to relay the full Absorbance range back to the logger so we collect the data in Transmittance and convert outside of the software if required.

The amount of light that penetrates a solution is known as the Transmittance. It is a ratio of intensity of the light transmitted ( $I_t$ ) to the intensity of the original light beam ( $I_o$ ).

$$T = \frac{I_t}{I_o}$$

The transmittance of a solution varies to Logbase(10) with 3 factors,

1. The molar absorptivity of the solution  $\epsilon$
2. The cell or cuvette dimension  $b$
3. The molar concentration  $C$

This is expressed as

$$\text{Log}\left(\frac{I}{T}\right) = EbC$$

Absorbance would appear to have an inverse relationship to Transmittance. In reality the light transmitted by a solution as the concentration increases does not show linearity. The true relationship is inverse and logarithmic.

$$A = -\text{Log}\left(\frac{I}{T}\right) \text{ or } A = EbC$$

Absorbance therefore gives a direct link between the intensity of the measured light in the Colorimeter and the molar concentration. The logarithmic nature of the relationship means that at one end small changes create massive change in values and at the other very large changes create very small changes in values. Experiments should be designed therefore to keep absorbance values between 0.05 and 0.7 wherever possible. If values fall outside this range then dilution should be used to bring the recorded values back into range and the dilution value used to produce the correct concentration values.

If the data is collected using the Transmission range, and you want to convert to Absorbance, use a spreadsheet or calculator to calculate absorbance.

Absorbance is defined as  $\text{Log}(I/T)$  where I = the intensity of the transmitted light (100%) and T = the value of the received light (%T value).

Conversion using a spreadsheet is best completed as a two stage process. The formulae below assume row 1 has been used for titles and the numeric data starts at row 2 in each column.

Column A - the original data	Column B - %T divided by 100	Column C - The Log of Column B (Absorbance)
A2	=A2/100	=-LOG10(B2)

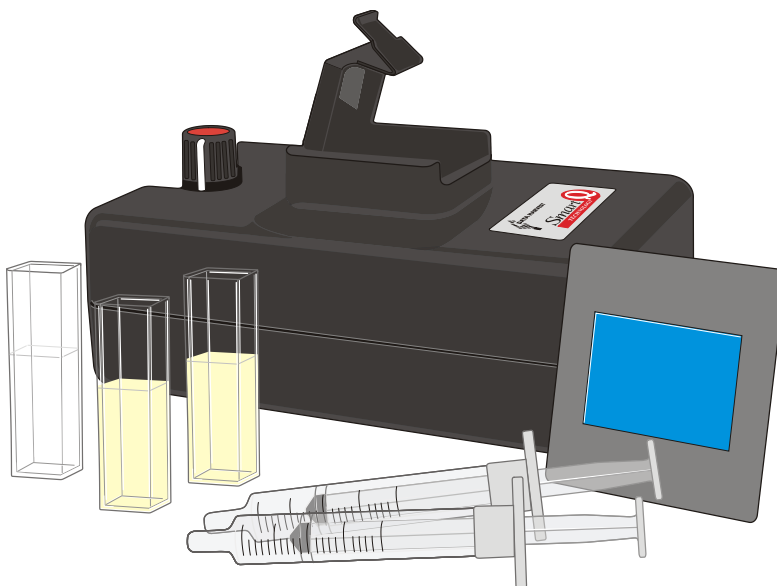
There is no need for the calculation to be broken down into steps; experience in the class however shows that being able to see clearly the stages enables the teacher to correct mistakes and follow the student's progress.



## 1. The effect of temperature on membrane permeability in beetroot

### Practical skills AT a, b, c, j, l

The colour of beetroot is due to the presence of a red pigment, anthocyanin, in the cell sap. You are going to investigate the effect of temperature or ethanol on the selectively permeable membranes of beetroot. The membrane of a cell "keeps the insides in and the outsides out". If the pigment is released from the cell then something must be happening to the permeability of the cell membrane. By plotting the intensity of the colour in the solution surrounding the treated beetroot against the value of the change around the beetroot (temperature, % ethanol) you will reveal the point at which the membrane becomes denatured and unable to prevent migration of the anthocyanin to the outside of the cell.



### Apparatus

1. Colorimeter set to the Transmittance range
2. Blue filter and Cuvettes
3. 7 test tubes and test tube rack
4. Cork borer
5. Tile
6. Scalpel
7. Small beaker
8. Graduated pipette
9. Mounted needle
10. Large beaker
11. Thermometer
12. Large beetroot or prepared beetroot cylinders

### Risk assessment

TAKE CARE WITH CORK BORER AND MOUNTED NEEDLE – MIND YOUR FINGERS.

## Method

### Stage 1

1. Use a cork borer to cut cylinders of fresh beetroot tissue. Place on a tile and cut into 42 x 3 mm wide discs. Place all the discs in a small beaker and wash under a running tap for at least 5 minutes.
2. Label the test tubes 30°C, 40°C, 50°C, 60°C, 70°C, 80°C and 100°C. Use a graduated pipette to add 6 cm<sup>3</sup> of cold water to each.
3. Prepare a water bath using a large beaker, tripod, gauze and bunsen burner. Heat gently to 30°C and remove the bunsen burner. Make a note of the exact temperature.
4. Impale 6 beetroot discs on a mounted needle with space between each disc.
5. Place the 6 beetroot discs on the needle into the water bath for exactly 1 minute. Remove the discs from the water and push off the discs into the test tube labelled 30°C. The discs will need to be left for the same length of time e.g. 20 minutes.
6. Heat the water bath gently to 40°C and repeat with the next set of 6 discs.
7. Repeat the procedure for the other tubes, raising the temperature of the water bath by 10°C each time, remove the discs and leave for the same length of time e.g. 20 minutes.
8. Shake the tubes, hold to the light and compare the colour of the liquids in each.

### Stage 2 - comparing the colour intensity

1. Connect the Colorimeter to the data logger. Place the blue filter in the front slot of the Colorimeter.
2. Select Meters on the logger or within the software. If you are using the software the label at the top of the section should read Transmittance (%T), if it is not change the range of the Colorimeter.
3. Select the tube that appears to have the darkest coloured solution. Fill a cuvette with this solution. Place this cuvette in the Colorimeter (make sure the ribbed faces of the cuvette are to the sides of the Colorimeter) and close the lid.
4. Use the control knob on the Colorimeter to give a transmittance reading of 10%. Remove the cuvette and keep to check the colorimeter drift.
5. Fill a cuvette with the contents of each test tube in turn, place in the Colorimeter, close the lid and measure the transmission reading. Record the reading into a table.

Temperature of water (°C)	Actual temperature of water (°C)	Transmission reading (%T)
30		
40		
50		
60		
70		
80		
90		

Note: If you find it impossible to get a reading with the darkest solution, dilute it down until you can get a reading. Remember to correct for this.

## Results and analysis

- Plot a graph of Transmission (%T) on the y-axis vs. Temperature on the x-axis.
- Look at the graph, and decide if you need to collect some data over a narrower range of temperatures. If you decide to do this, the same method should be employed and the new data can be plotted onto the same graph.
- If required transfer the results to a spreadsheet and calculate the Absorbance using the information on the next page. Absorbance gives a more linear relationship with change in concentration.

## Questions

1. Explain your findings, using your knowledge of cell membranes.
2. Assess the reliability of the results you have obtained and evaluate the methods and techniques used in the experiment.
3. Suggest any modifications you could make to improve the experiment.

### Relationship between Transmittance (T%) and Absorbance (A)

It is normal, when doing concentration based work to use Absorbance not transmission. Absorbance has a direct link to concentration. Transmittance has a link to concentration, but it is non-linear. The colorimeter is unable to relay the full Absorbance range back to the logger so we collect the data in Transmission and convert outside of the software if required.

The amount of light that penetrates a solution is known as the Transmittance. It is a ratio of intensity of the light transmitted ( $I_t$ ) to the intensity of the original light beam ( $I_o$ ).

$$T = \frac{I_t}{I_o}$$

The transmittance of a solution varies to  $\text{Log}_{(10)}$  with 3 factors,

1. The molar absorptivity of the solution  $E$
2. The cell or cuvette dimension  $b$
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This is expressed as

$$\text{Log}\left(\frac{I}{T}\right) = EbC$$

Absorbance would appear to have an inverse relationship to Transmittance. In reality the light transmitted by a solution as the concentration increases does not show any obvious linearity. The true relationship is inverse and logarithmic.

$$A = \text{Log}\left(\frac{I}{T}\right) \text{ or } A = EbC$$

Absorbance therefore gives a direct link between the intensity of the measured light in the colorimeter and the molar concentration.

Conversion from Transmission to Absorbance is possible and is best completed as a two stage process. The formula below, for use in a spreadsheet, assumes row 1 has been used for titles and the numeric data starts at row 2 in each column.

Column A - the original data	Column B - %T divided by 100	Column C - The Log of Column B (Absorbance)
A2	=A2/100	=LOG10(B2)

There is no need for the calculation to be broken down into steps; experience however shows that being able to see clearly the stages enables you to correct mistakes more easily. A good scientific calculator should let you calculate in one step.

## Teacher's notes

### 2. Protease and casein (milk powder) reaction

#### Practical skills AT a, b, c, l

The liquid protease enzyme system offers several advantages over the traditional amylase system.

The enzyme is very stable and can be kept in simple conditions without losing activity.

The digestion of milk powder suspension offers a simple reaction that is very reproducible.

The enzyme uses a digestion that is easy to relate to the students experiences. Most students have not (knowingly) eaten liquid starch but nearly all will have consumed a milk based drink.

A powdered protease enzyme such as trypsin can be used as an alternative. Timings and concentrations of the enzyme will need to be changed.

Milk powder suspension (milk made from dried milk powder) has a milky opaque appearance. A non-specific protease enzyme will digest the casein present and create a transparent colourless solution of amino acid particles. The rate at which the opacity of the solution clears is proportional to the rate of the reaction.

The experiment provides the basis for several investigations into enzyme activity. The simplicity of the experiment makes it very adaptable for the study of temperature, pH, Group 1 and 2 metals, inhibitors, etc.

#### Apparatus

1. Colorimeter set to the Transmittance range
2. Blue filter and two cuvettes
3. Protease enzyme solution 1%
4. Milk powder suspension 1%
5. Two syringes or graduated pipettes (one for the protease and one for the milk powder suspension)
6. Milk powder (casein) substrate

#### Set up

Recording method	Time	Intersample	Overlay
Graph	5 minutes	500 ms	On

It is advised to run a test before using the enzyme in class to get a measure of the time span needed. Ideally you need a five minute recording time for the slowest rate. The milk powder solution and enzymes will produce variation that needs to be accounted for.

#### Practical notes

##### The casein substrate

- Add 1 g of fat free dried milk powder to 100 cm<sup>3</sup> of water (1% w/v casein to water). Scaling up the volume does not present any problems. This stock is stable and can be kept for at least 24 hours if chilled (after this time decomposition will start to take place). If dried milk powder containing fat is

used there is no significant difference to the experiment timings but the digested solution will not be as clear.

### Protease enzyme solution

- The experiments described used bacterial liquid protease purchased from NCBE\*. Its trade name is NEUTRASE. It is a stable form of the enzyme and its activity is not greatly affected by storage (in stock) or in overnight preparations. Refrigeration at 4°C is adequate for storage.

\*NCBE: The National Centre for Biotechnology Education at the University of Reading ([www.ncbe.reading.ac.uk](http://www.ncbe.reading.ac.uk)).

- The enzyme was made up as a 0.5% v/v solution with distilled water and allowed to reach room temp (21°C). The stability of this product means that a buffer is not required, neither is an acid activator. The colour of the enzyme does have an effect on the final values shown in the Colorimeter if its concentration is varied in the experiment. Other proteases can be used but the best concentration will need to be fine-tuned by pre-testing. Experience has shown that a 0.1 ml to 100 cm<sup>3</sup> stock is a good starting reference. The activity of the enzyme needs to be modified to give a completed digestion at room temperature in 3 minutes at pH 7.

The experiment can be conducted without the coloured filter. In this experiment the wavelength of the light is not critical.

Milk powder suspension (milk made from dried milk powder) contains mainly a casein protein, which is poorly soluble in water. The suspension has a milky opaque appearance. A non-specific protease enzyme will digest the casein present and create a transparent solution of colourless amino acid particles. The rate at which the opacity of the solution clears is proportional to the rate of the reaction.

If care is taken solutions can be added to the cuvette while it is placed in the Colorimeter, this will help to reduce errors in timing.

Adding the casein substrate to the enzyme gives a clear start point to the experiment and also helps mix the reagents in the cuvette.

The cuvettes have nominal capacity of 4.0 cm<sup>3</sup>, some are made to have a volume of 4.5 cm<sup>3</sup>. All instructions provide a final volume of 4.0 cm<sup>3</sup>. A smaller volume in a larger cuvette has no effect as the Colorimeter uses a light path through the cuvette about  $\frac{1}{3}$ <sup>rd</sup> of the distance up from the base of the cuvette.

The reaction should be complete within 3 minutes assuming a temperature of the solutions is at 20 to 22°C.

Make a control cuvette up of milk suspension and enzyme, let this clear and use it to set the colorimeter to 100%.

## Sample result

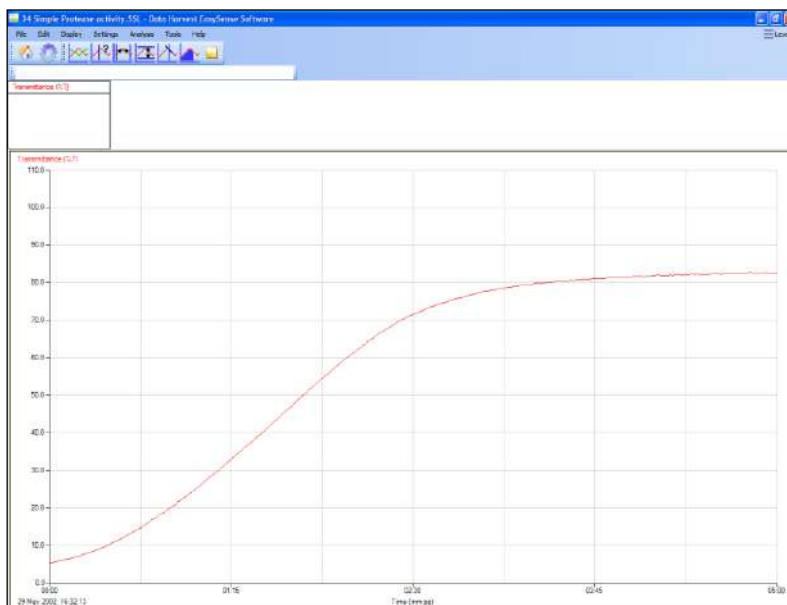


Fig 2.1 A simple protease digestion of a milk protein suspension.

Note the transmission may not reach 100%; the protease enzyme has a dark brown colour which gives some colouring to the solution even when diluted. Additionally not all the opacity of the milk powder solution is due to the suspended protein. In this experiment the powdered milk contained fatty material to improve the flavour of the reconstituted milk

### Relationship between Transmittance (T%) and Absorbance (A)

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$$T = \frac{I_t}{I_o}$$

The transmittance of a solution varies to Log(10) with 3 factors,

4. The molar absorptivity of the solution  $E$
5. The cell or cuvette dimension  $b$
6. The molar concentration  $C$

This is expressed as

$$\text{Log}\left(\frac{I}{T}\right) = EbC$$

Absorbance would appear to have an inverse relationship to Transmittance. In reality the light transmitted by a solution as the concentration increases does not show any obvious linearity. The true relationship is inverse and logarithmic.

$$A = \text{Log}\left(\frac{I}{T}\right) \text{ or } A = \epsilon bC$$

Absorbance therefore gives a direct link between the intensity of the measured light in the Colorimeter and the molar concentration. The logarithmic nature of the relationship means that for absorbances that have an equivalent transmission value of greater than 90% and less than 20% can become prone to large variances. Where absorbance is to be used experiments should be designed therefore to keep values between 0.05 and 0.7 absorbance wherever possible. If values fall outside this range then dilution should be used to bring the recorded values back into range and the dilution value used to produce the correct concentration values.

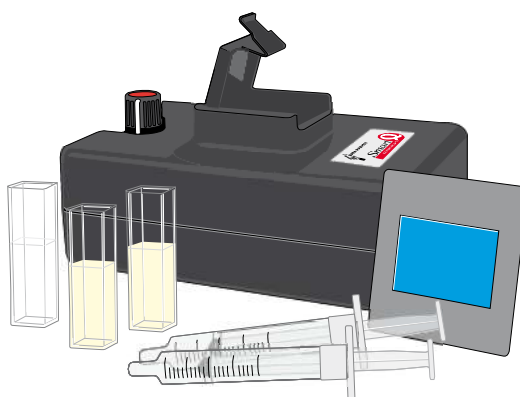


## 2. Protease and casein (milk powder) reaction

### Practical skills AT a, b, c, l

Enzymes break down large molecules into smaller molecules by a process called digestion. In this experiment the large molecule being digested is a protein and the product is a smaller amino acid molecule.

Milk powder, dissolved in water, is going to be the source of the protein. The milk solution is opaque white (milky). The enzyme (protease) will digest the milk protein producing the small amino acids, which are colourless and transparent. As the milk is digested the solution will become more and more transparent and colourless. The amount of light transmitted by the solution is therefore a measure of milk protein present.



### Apparatus

1. Colorimeter set to the Transmittance range
2. Blue filter and two cuvettes
3. Protease enzyme solution 1%
4. Milk powder suspension 1%
5. Syringes or graduated pipettes, one for the protease and one for the milk powder suspension

### Hazard information

- Do not let liquid enzymes dry up.
- Avoid direct contact of enzyme to skin and eyes.

### Method

1. Connect the Colorimeter to a data logger. Place the blue filter supplied in the front slot of the Colorimeter.
2. Create a 'control' cuvette for calibrating the Colorimeter by adding 1.0 cm<sup>3</sup> of water, 1.0 cm<sup>3</sup> of enzyme and 2.0 cm<sup>3</sup> of milk powder solution into a cuvette, mix and leave it to clear.

3. Set the recording time:

Recording method	Time	Intersample	Overlay
Graph	5 minutes	500 ms	On

4. Select Test Mode (Tools menu). Place the control cuvette into the Colorimeter and use the control knob on the Colorimeter to give a transmittance reading of 100%. Remove the cuvette.
5. Place 1.0 cm<sup>3</sup> of water and 1.0 cm<sup>3</sup> of enzyme into a clean cuvette (do not add the milk suspension yet).
6. Place the cuvette in the Colorimeter.
7. Add the milk suspension and immediately click on Start to begin logging. Close the lid.
8. Add a Title to the graph and then Save the results.

## Results and analysis

You will have a trace of the increase in light transmittance against time.

## Questions

The change in transmittance takes place because the enzyme is digesting the protein in the milk powder solution.

1. What happened to transmittance as the experiment progressed? Describe the shape of the graph.
2. Look at the beginning middle and end sections of the graph, when was the reaction fastest? Use Gradient to calculate the average gradient of the graph.
3. What would happen if whole milk was used in place of the milk powder solution?

## Teacher's notes

### 3. How does enzyme activity (protease) change with temperature?

#### Practical skills AT a, b, c, l

Milk powder suspension (milk made from dried milk powder) contains mainly casein which is poorly soluble in water. The suspension has a milky opaque appearance. A non-specific protease enzyme will digest the casein present and create transparent, colourless amino acid particles. The rate at which the opacity of the solution clears is proportional to the rate of the reaction.

The experiment described uses liquid protease enzyme but a powdered protease such as trypsin would work.

The experiment can be used,

1. To show how temperature changes in an enzyme catalysed reaction
2. To introduce and illustrate the concept of denaturing of proteins

#### Apparatus

1. Colorimeter set to Transmittance range
2. Blue filter and cuvettes
3. Casein solution (milk powder suspension)
4. Protease solution
5. Syringes or measuring pipettes
6. Water baths at 20, 30, 40, 50 and 60°C

#### Set up

Recording method	Time	Intersample	Overlay
Graph	5 minutes	500 ms	On

It is advised to run a test before using the enzyme in class to get a measure of the time span needed. The set up uses a 5 minute time span. The milk and enzyme solutions will provide variation that will need accounting for.

#### Practical notes

##### Milk powder (casein) substrate

- The casein substrate is made by adding 1 g of fat free dried milk powder to 100 cm<sup>3</sup> of distilled water (1% w/v casein to water). Scaling up of the volume does not present any problems. This stock is stable and can be kept for at least 24 hours if kept chilled (after this time decomposition will start to take place). If dried milk powder containing fat is used there is no significant difference to the experiment timings, but the digested solution will not be as clear.

## Enzyme

- The experiments described in these notes used bacterial liquid protease purchased from NCBE\*. Its trade name is NEUTRASE. It is a stable form of the enzyme and its activity not greatly affected by storage (in stock) or in overnight preparations. Refrigeration at 4°C is adequate for storage.

\*NCBE: The National Centre for Biotechnology Education at the University of Reading ([www.ncbe.reading.ac.uk](http://www.ncbe.reading.ac.uk)).

- The enzyme was made up as a 0.5% v/v solution with distilled water and allowed to reach room temperature (21°C). The stability of this product means that a buffer is not required, neither is an acid activator. The colour of the enzyme does have an effect on the final values shown in the Colorimeter if its concentration is varied in the experiment. Other proteases can be used but the best concentration will need to be fine-tuned by advanced testing. Experience has shown that a 0.1 cm<sup>3</sup> to 100 cm<sup>3</sup> stock is a good starting reference. The activity of the enzyme needs to be modified to give a completed digestion at room temperature in 3 minutes at pH 7.

If using a powdered protease, care (regarding allergies) needs to be taken when handling the powder.

## Changing temperature

Syringes were found to be the best way of measuring the small volumes needed for the cuvettes. If temperature was being studied the syringes could be placed in water baths for 3 - 5 minutes to bring the solutions up to the desired temperature. Using the temperature of the water bath as the temperature of the reaction produces convincing results.

Alternately the stock casein solutions can be kept in water baths at the required temperature. The cooling of the solution while transferring to the cuvette will produce an error; this can give an opportunity for students to explore improvements and sources of error in the analysis of the experiment.

## Controlling pH

If 0.5 cm<sup>3</sup> of buffer solution is used in the cuvette the pH will be controlled to the pH of the buffer solution. Use commercial buffer solutions with no dilution or change from the stock bottle.

## General notes

If care is taken the cuvette can be placed in the Colorimeter and the solutions added while it is in the Colorimeter, this will help reduce errors in timing.

Adding the casein substrate to the enzyme gives a clear start point to the experiment and also provided mixing of the reagents in the cuvette.

The cuvettes have nominal capacity of 4.0 cm<sup>3</sup> some are made to have a volume of 4.5 cm<sup>3</sup>. All instructions provide a final volume of 4.0 cm<sup>3</sup>. A smaller volume in the larger cuvette has no effect as the Colorimeter uses a light path through the cuvette about  $\frac{1}{3}$ <sup>rd</sup> of the distance up from the base.

### 3. How does enzyme activity (protease) change with temperature?

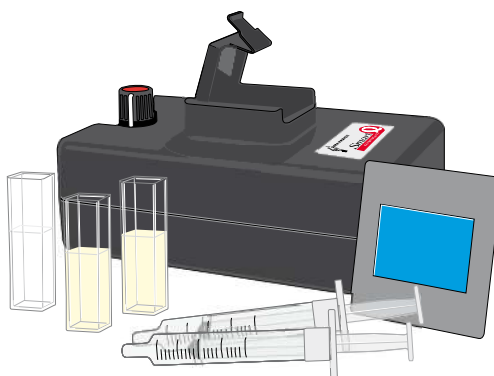
#### Practical skills AT a, b, c, I

Enzymes break down large molecules into smaller molecules by a process called digestion. The large molecule being digested in this experiment is casein (a protein) and the product is small amino acid fragments. Enzyme reactions, like all chemical reactions are effected by heat. This investigation will see if heat effects an enzyme reaction in the same way as a normal chemical reaction.

Casein (milk powder suspension) is a white opaque solution. Protease enzyme digests the casein and creates colourless, transparent amino acid fragments; as a result the solution becomes less white and less opaque. This colour / transparency change is going to be monitored.

The experiment will

3. Show how temperature changes in an enzyme catalysed reaction
4. Introduce the concept of denaturing of proteins



#### Apparatus

1. Colorimeter set to Transmittance range
2. Blue filter and cuvettes
3. Casein solution
4. Protease solution
5. Syringes or measuring pipettes
6. Water bath

#### Hazard information

- Do not let liquid enzymes dry up
- Avoid direct contact of enzyme to skin and eyes

#### Method

1. Connect the Colorimeter to the data logger. Place the blue filter in the front slot of the Colorimeter.
2. Create a 'control' cuvette for calibrating the Colorimeter by adding 3.0 cm<sup>3</sup> of the milk powder solution and 1.0 cm<sup>3</sup> of protease into a cuvette, mix and leave it to clear.
3. When the control cuvette has become clear place it into the Colorimeter. Make sure the ribbed faces of the cuvette are to the sides of the Colorimeter and close the lid.

4. Set the recording time:

Recording method	Time	Intersample	Overlay
Graph	5 minutes	500 ms	On

5. Select Test Mode (Tools menu). Use the control knob on the Colorimeter to give a transmittance reading of 100%. Remove the cuvette. Keep the cuvette to one side in case you need to check the transmittance value again.
6. Add 1.0 cm<sup>3</sup> of protease to a clean cuvette (do not add the milk powder solution yet) and place into the Colorimeter.
7. Collect 3.0 cm<sup>3</sup> of milk powder solution in a pipette or syringe from a stock of known temperature.
8. Add the milk powder solution to the cuvette and immediately click on the Start icon to begin logging. Close the lid.
9. Use Add Text to label the graph line with the temperature of the milk powder solution used. Remove the cuvette and wash it out. Save the data.
10. Check that Overlay is selected.
11. Repeat stages 6 -9 until you have used milk powder solutions at all the temperatures provided.
12. Add a Title to the graph and Save the data.

## Results and analysis

You will have traces of the increase in light transmittance against time.

## Questions

Remember the change in transmission takes place because the enzyme is digesting the milk powder solution (casein) and producing amino acids.

1. What happened to the shape of each curve as the temperature of the milk powder solution was altered?
2. What is the relationship between temperature and the rate of the reaction?
3. Plot a graph of time taken to reach 40% transmission vs. temperature. What does this show about the relationship between temperature and the protease activity?
4. Find out what denatured means, explain the graph created in question 3 using the information about denaturing.
5. How does the effect of heat on 'chemical reaction' differ from how an enzyme reacts to temperature?

## Teacher's notes

### 4. How does enzyme (protease) activity change with pH?

#### Practical skills AT a, b, c, l

Enzyme activity depends upon several factors; in this experiment the effect of pH as one of these factors will be studied.

Protease enzymes digest proteins to produce amino acids. In this experiment dried milk powder suspension is going to be the source of the protein. The protease will digest the milky white, opaque suspension producing amino acids, which are colourless and transparent. The amount of light transmitted through the solution will be proportional to the milk protein present.

Commercial enzymes such as the Neutrase enzyme suggested may work best in conditions that are not normally quoted for enzymes. The commercial developer will have searched over a very large range of organisms to harvest the enzyme, not all organisms follow the reliable model of 'blood heat' 'neutral pH'. Think of organisms living in thermal vents in deep ocean trenches or hot volcanic springs, they obviously must use enzymes and the conditions around and in these organisms fall outside the narrow range quoted in texts.

The experiment can be used to,

1. Show the effect of pH on the enzymes rate of reaction.
2. Consider the idea of a set of conditions that create an optimal rate for the enzyme.

#### Apparatus

1. Colorimeter set to Transmittance range
2. Blue filter and 2 cuvettes
3. Protease enzyme solution 1%
4. Milk powder suspension 1%
5. Buffer solutions at pH 4.0, 7.0 and 10.0
6. Distilled water
7. Syringes or graduated pipettes

#### Set up

Recording method	Time	Intersample	Overlay
Graph	5 minutes	500 ms	On

It is advised to run a test before using the enzyme to get a measure of the time span needed. The setup uses a 5 minute time span.

#### Practical notes

##### Milk powder (casein) substrate

The casein substrate is made by adding 1 g of fat free dried milk powder to 100 cm<sup>3</sup> of distilled water (1% w/v casein to water). Scaling up of the volume does not present any problems. This stock is stable and can be kept for at least 24 hours if kept chilled (after this time decomposition will start to take place). If dried

milk powder containing fat is used there is no significant difference to the experiment timings, but the digested solution will not be as clear.

### Enzyme

The experiments described in these notes used bacterial liquid protease purchased from NCBE\*. Its trade name is NEUTRASE. It is a stable form of the enzyme and its activity not greatly affected by storage (in stock) or in overnight preparations. Refrigeration at 4°C is adequate for storage.

\*NCBE: The National Centre for Biotechnology Education at the University of Reading ([www.ncbe.reading.ac.uk](http://www.ncbe.reading.ac.uk)).

The enzyme was made up as a 0.5% v/v solution with distilled water and allowed to reach room temperature (21°C). The stability of this product means that a buffer is not required, neither is an acid activator. The colour of the enzyme does have an effect on the final values shown in the Colorimeter if its concentration is varied in the experiment. Other proteases can be used but the best concentration will need to be fine-tuned by advanced testing. Experience has shown that a 0.1 cm<sup>3</sup> to 100 cm<sup>3</sup> stock is a good starting reference. The activity of the enzyme needs to be modified to give a completed digestion at room temperature in 3 minutes at pH 7

If using a powdered protease, care (regarding allergies) needs to be taken when handling the powder.

### General notes

The experiment describes the use of 3 buffer solutions and water, you may wish to extend the range of pH buffer solutions e.g. to include pH 2 and 8.

Or alternatively supply 0.1 mol dm<sup>-3</sup> hydrochloric acid and 0.1 mol dm<sup>-3</sup> sodium hydroxide. The students can add drops of the acid or alkali to the reaction mix before starting the experiment. The molarity of the solutions is kept low to prevent over dosing with the low volume of the cuvette.

The experiment can be conducted without the coloured filter. In this experiment the wavelength of the light is not critical.

Milk powder suspension (milk made from dried milk powder) contains mainly casein. The suspension has a milky opaque appearance. A non-specific protease enzyme will digest the casein present and create a solution of colourless, transparent amino acid particles. The rate at which the opacity of the solution clears is proportional to the rate of the reaction.

If care is taken the cuvette can be placed into the Colorimeter and the solutions added to it while it is in the Colorimeter, this will help reduce errors in timing.

Adding the casein substrate to the enzyme gives a clear start point to the experiment and also provides mixing of the reagents in the cuvette.

### Controlling pH

If 0.5 cm<sup>3</sup> of buffer solution is used in the cuvette, the pH will be controlled to the pH of the buffer solution. Use commercial buffer solutions with no dilution or change from the stock. Use a selection of buffers to cover two pH values either side of pH 7 e.g. 10, 8, 4 or 2. In between values could be provided to allow extension of the experiment for more able or quicker working students. They would then be able to produce a much more precise optimal pH value for the enzyme.

The cuvettes have nominal capacity of 4.0 cm<sup>3</sup> some are made to have a volume of 4.5 cm<sup>3</sup>. All instructions provide a final volume of 4.0 cm<sup>3</sup>. A smaller volume in the larger cuvette has no effect as the Colorimeter uses a light path through the cuvette about  $\frac{1}{3}$ <sup>rd</sup> of the distance up from the base of the cuvette.



If precise values for the pH are not required the experiment can be simplified to adding drops of acid or alkali to the protease/casein incubate. If this is the preferred experiment then the acid or alkali should be introduced as part of the water.

Note: High and low values of pH may cause the opacity of the milk suspension to be altered due to a non-enzyme controlled chemical reaction.

### Sample result

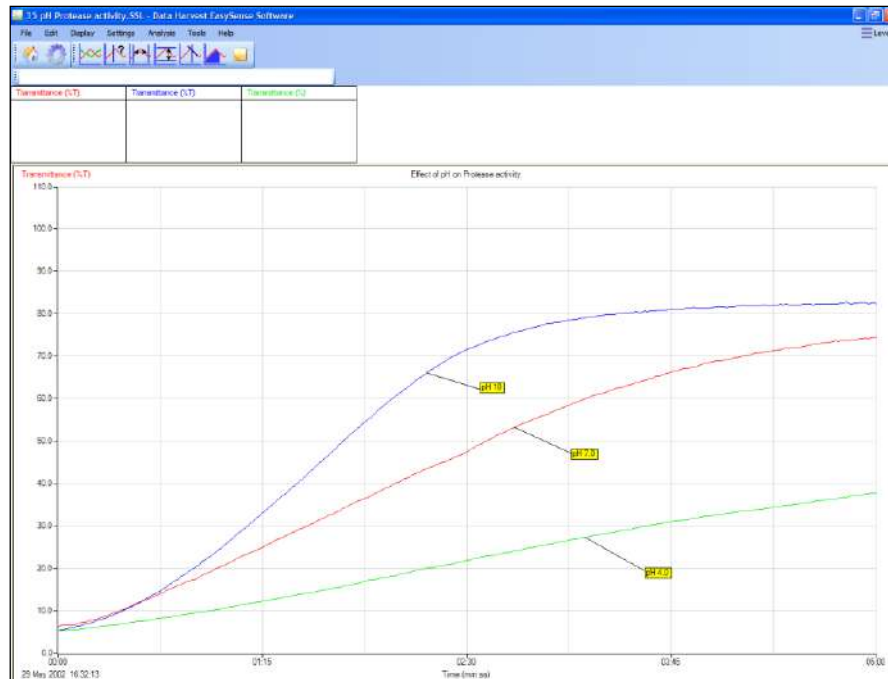


Fig 4.1 Three different pHs on the rate of casein digestion by protease.

You could create a rate function by timing how long it took to reach (for example) 30% transmission

## Extension work

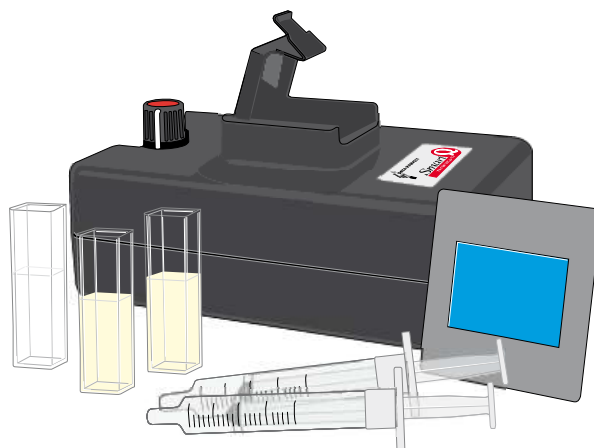
1. Does the concentration of substrate have any effect?
2. Does the source of enzyme have any effect e.g. bacterial, fungal, mammalian?
3. Does the type of substrate change the results?
4. How do metal ions (transition metal ions are inhibitors of proteases) influence the reaction?

## 4. How does enzyme (protease) activity change with pH?

### Practical skills AT a, b, c, l

Enzyme activity depends upon several factors; in this experiment the effect of pH as one of these factors will be studied. The large molecule being digested is a protein and the product is a smaller amino acid fragment.

Protease enzymes digest proteins to produce amino acids. In this experiment dried milk powder suspension is going to be the source of the protein. The suspension is opaque white (milky). The protease will digest the milk protein producing amino acids, which are colourless and transparent. The amount of light transmitted through the solution will be proportional to the milk protein present.



### Apparatus

1. Colorimeter set to the Transmittance range
2. Blue filter and two cuvettes
3. Protease enzyme solution 1%
4. Milk powder suspension 1%
5. Buffer solutions at pH 4.0, 7.0 and 10.0
6. Distilled water
7. Syringes or graduated pipettes

### Hazard information

Do not let liquid enzymes dry up.

Avoid direct contact of enzyme to skin and eyes.

### Method

1. Connect the Colorimeter to the data logger. Place the blue filter in the front slot of the Colorimeter
2. Create a 'control' cuvette for calibrating the Colorimeter by adding 3.0 cm<sup>3</sup> of the milk powder solution and 1.0 cm<sup>3</sup> of protease into a cuvette, mix and leave it to clear.
3. Set up the recording time:

Recording method	Time	Intersample	Overlay
Graph	5 minutes	500 ms	On

4. The label at the top of the y-axis should read Transmittance (%T), if not change the range of the Colorimeter.
5. When the control cuvette has become clear place it into the Colorimeter. Make sure the ribbed faces of the cuvette are to the sides of the Colorimeter and close the lid.
6. Select Test Mode (Tools menu) and use the control knob on the Colorimeter to give a transmittance reading of 100%. Remove the cuvette. Keep the cuvette to one side in case you need to check the transmission levels.
7. Add the pH buffer 10 and protease solution as listed in the table below to a clean cuvette (do not add the milk solution yet) and place into the Colorimeter.
8. Add the milk powder solution and immediately click on the Start icon to begin logging. Close the lid.
9. Use Add Text to label the graph line with the pH of the mix used. Remove the cuvette and wash it out. Save the data.
10. Make sure Overlay is selected.
11. Repeat stages 7 - 8 using each pH buffer and protease mix.
12. Add a Title to the graph and then Save the data.

Buffer volume/pH	Milk powder solution cm <sup>3</sup>	1% protease cm <sup>3</sup>	Total volume cm <sup>3</sup>
1.0 cm <sup>3</sup> of pH buffer 10	2.0	1.0	4
1.0 cm <sup>3</sup> of pH buffer 7	2.0	1.0	4
1.0 cm <sup>3</sup> of pH buffer 4	2.0	1.0	4

## Results and analysis

You will have a trace of the increase in light transmittance against time. As you repeat the experiment for different pH values the start point may not always be exactly the same. This is not a problem as the shape of the trace is more important.

## Questions

The change in transmittance takes place because the enzyme is digesting the protein in the milk powder solution.

1. What happened to transmittance as the experiment progressed? Explain the shape of the graph.
2. How does the graph change as the pH of the experiment is increased?
3. Look at the beginning middle and end sections of the graph, when was the reaction fastest? Calculate the average gradient of the graph. (Hint: use the Gradient function).
4. Pick a time on the trace and read of the transmittance value at that point. Plot this on graph paper against pH on the horizontal axis. What does this graph tell you about how an enzyme reacts to pH?
5. What would happen if whole milk were used in place of the milk powder solution?
6. Where in the organisms would you find conditions of very low and very high pH?

7. Protease digests proteins, how is its relationship to pH matched to where it is found and what it does?

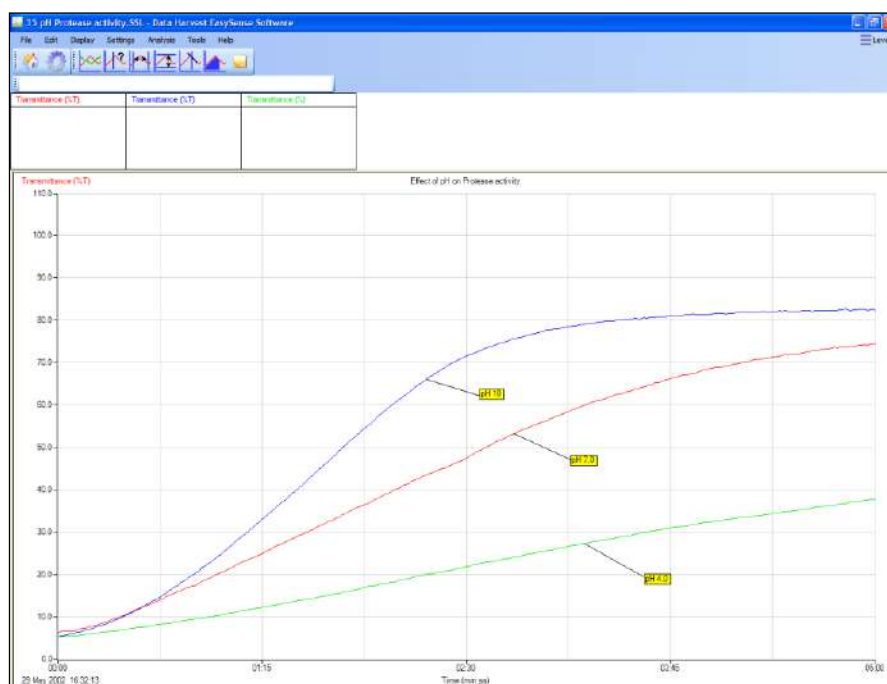


Fig 4.1 Example graph with 3 different pH values and effect on rate

You could create a rate function by timing how long it took to reach (for example) 30% transmission. With enough pH points a graph of pH vs. rate could then be plotted.

## Teacher's notes

### 5. The effect of lipase on milk

#### Practical skills AT a, b, c, l

This is an adaption of a Nuffield biology practical. The experiment, as described in the Nuffield materials, used an indicator (universal indicator) to follow the digestion of milk fat in various types of milk by pancreatic lipase.

This adaption still measures the change in pH, but uses a pH electrode to record the changes to replace the subtle colour changes of the indicator. The use of the electrode opens the opportunity to follow the whole course of the digestion using a data logger.

The combined use of the pH electrode and data logging allows the reaction to be followed in detail and so provide the students with a stimulus to extend their knowledge and understanding of enzyme activity.

A further enhancement, since the original practical, is the modern lipases that are available. The commercial interest in lipase as an additive to cleaning products (biological washing powders) has driven the development of less storage labile enzymes than the original pancreatic extract. The commercial products are more tolerant of long storage and have a more consistent activity, all of which allows the practical to be considered as a reliable alternative to amylase and starch or protease and milk protein practical.

#### Apparatus

1. pH sensor (adapter and electrode)
2. Push-button Reaction switch (optional)
3. Lipase enzyme\*
4. Selection of milks (skimmed, semi skimmed, jersey, full fat, etc.)
5. Beaker to act as a water bath for the experiment (250 or 500 ml capacity)
6. Boiling tube for the reaction
7. 1 ml capacity syringe or Pasteur pipette

\*The enzyme is a non-specific lipase. See notes for details on enzyme type, suppliers, etc.

The Reaction switch is to allow students to mark the point on the graph at which the enzyme was added (pressing the switch will create a sharp peak on the graph).

#### Set up

Recording method	Expected time	Overlay
EasyLog	5 minutes	On

If you are using a commercial lipase it should be possible to define times for the experiment run and use Graph to set up timed comparative experiments. For this set of instructions the EasyLog function is used as the activity of the user's lipase is unknown. EasyLog will record data until the user intervenes and stops the logging process, it is therefore open ended.

If you use Overlay to produce multiple graphs on a common axis, the time of the original recording will be used as the time base for all subsequent recordings.

## Practical notes

### Enzyme

Small quantities of commercial grade enzyme can be purchased from the NCBE which is based at Reading University (do a web search for latest address and products and price list).

The enzyme used for the sample results was an enzyme from a fungal source trade named Lipolase. A bacterial derived product called Lipex is also available. While they need attention to storage they are much more stable than pancreatic lipases. The Lipolase used to produce the test results was over 5 years old and had been kept in domestic quality fridge.

Make the enzyme, initially to a 1% w/v solution (i.e. 1 g in 100 cm<sup>3</sup> distilled water). If the activity is high then serial dilutions can be made to produce a typical run time of 5 minutes at room temperature (21°C).

### Risk assessment

Take care with enzyme preparation, especially from a powdered form. Mild and severe allergy symptoms can affect individuals – in some case it may be from the source (e.g. fungal but not bacterial).

### Care of the pH electrode

Fatty materials are not the best friends of pH electrodes, the interconnecting salt bridges (junctions) and the porous glass membrane can be severely affected by a build-up of fats. It is recommended that after use,

1. The electrode is soaked in lipase solution (1% w/v) for at least 2 x the duration of the practical to digest as much of any residual fat away from the glass as possible.
2. A soak in Decon 90 for 10 minutes will remove any remaining fatty acids and residual biological material.
3. A quick swirl in concentrated hydrochloric acid followed by a rinse in some KCl (4 molar) before returning to the storage solution.

The electrodes supplied by Data Harvest have replaceable salt bridge / junctions. The electrode pack should have come with a short length of the junction material and a cocktail stick. Follow the instructions in the electrode manual (or the insert packed with the electrode) for details of replacement.

### General

The practical relies on the breakdown (digestion) of fats in the milk to fatty acids and glycerol. The production of the fatty acids will increase pH; this change in pH is monitored by the pH sensor. There is no reason why an indicator cannot be added to the experiment. It can be useful to have the indicator present to show why a pH electrode is used; the ability to reliably differentiate between colours makes qualitative work very difficult.

As we are measuring pH changes this is not a good candidate to show effect of pH on the speed of the reaction. Temperature, substrate concentration, enzyme concentration, co factors can all be studied.

Bile salts have traditionally been used to help emulsify the fats in the milk, increase the surface area, and speed up the reaction. Two to three drops of detergent in the milk sample are supposed to have the same effect.

## Sample results

Semi skimmed milk. Lipase enzyme 1% w/v. 1.0 cm<sup>3</sup> and 2.0 cm<sup>3</sup> enzyme.

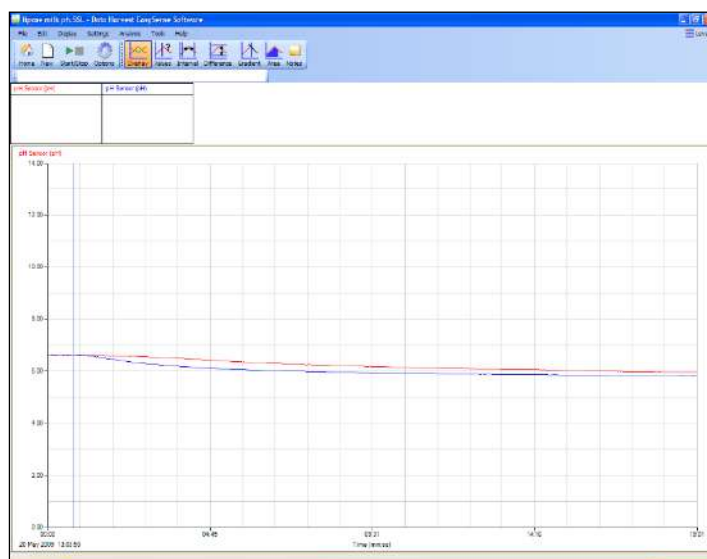


Fig 5.1 Data as collected, no scale adjustments made. Overlay was used to get both runs on the same axis set.

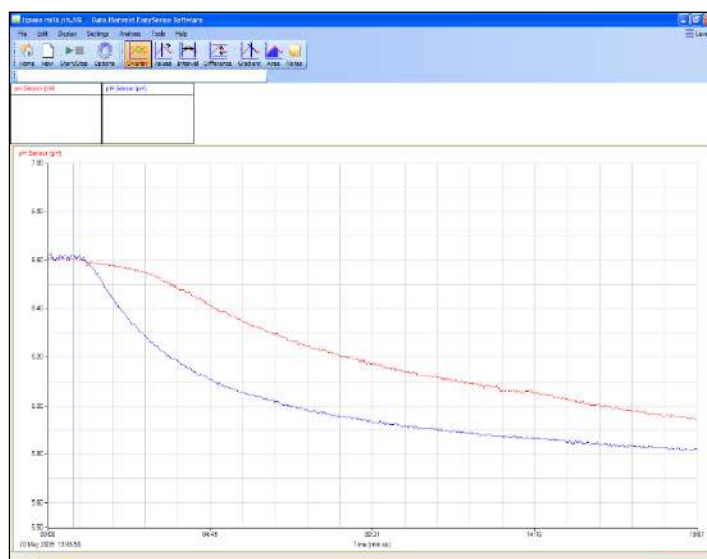


Fig 5.2 Sensor Settings (Options) has been used to reduce the y-axis scale (from 0 - 14 to 5.5 – 7.0).

Doubling the enzyme quantity has increased the rate of digestion.

The final pH is not altered by much. The quantities of digestible fats in the milk sample were obviously low. This highlights one of the reasons for this reaction – as an analysis of fat content of the milk. Milk producers are paid by quantity of milk and the quality (as fat content).

The change in pH per unit time was very small; the Gradient tool does not have the resolution to show gradients with less than 2 decimals. If the gradient is required use a Post-log Function to multiply the original data by 100. A gradient can then be calculated and shown.

Note the time for this experiment took just over 20 minutes. The lipase enzyme should be used at a much higher concentration; the target for maximum change in pH should be under 5 minutes if the practical is to be of use in standard teaching period.

## 5. The effect of lipase on milk

### Practical skills AT a, b, c, l

This investigation measures the change in pH in a sample of milk that is being digested by Lipase.

Milk contains a variety of fats (lipids); the lipase digests the fats (breaks the fats down into smaller molecules). One of the products of the digestion is acidic; the increase in acidity is therefore related to the digestion of fatty materials in the milk sample.

### Apparatus

1. pH sensor
2. Push button reaction switch (optional)
3. Lipase enzyme\*
4. Selection of milks (skimmed, semi skimmed, jersey, full fat, etc.)
5. Beaker to act as a water bath for the experiment (250 or 500 ml capacity)
6. Boiling tube for the reaction
7. 1 ml capacity syringe or Pasteur pipette

### Method

Note: As with all enzyme based reactions and investigations you must take extra care to not let anything that has come into contact with enzyme come into contact with the substrate.

1. You will need to use the large beaker as a water bath. The pH sensor simply rests inside the boiling tube and reaction mixture; there should be no need to support the electrode.
2. Measure 25 cm<sup>3</sup> of milk into the boiling tube. Place the boiling tube into a beaker of warm water (water bath) and leave for about 3 minutes to reach the temperature of the water bath.
3. Pour about 3 cm<sup>3</sup> of Lipase into a small beaker or test tube. Use a pipette to draw up 1 cm<sup>3</sup> of the lipase and leave ready for use.
4. Place the pH electrode into the milk.
5. Select EasyLog.
6. Click on Start and immediately add the Lipase (ideally the adding and starting should be at the exact same time).

If you have a Reaction switch connected, press the button just as the lipase is added to mark the graph and show the start of the reaction.

7. Allow the reaction to continue until the rate of change of pH has slowed significantly (this will be about 10 minutes).
8. Stop the recording and display the detail of the graph by right clicking in the graph area and selecting Autoscale.

To compare different milk samples.

1. Dispose of the sample of milk that has been treated with lipase; wash the boiling tube and the pH electrode to remove the milk residues.



2. After step 8, select Overlay and prepare a new sample of milk and enzyme as described (for comparison the only thing that should change in the experiment is the type of milk being tested).
3. Add the lipase; the recording will last for as long as the first recording was allowed to run.
4. Save the data, use a new name to keep the data from previous runs safe.
5. Label the graph line using the Add Text tool (right click graph menu).
6. Repeat for as many milk samples as you can.

## Results

You will record a graph that looks something like the example below. This was of a milk sample and lipase at two different temperatures. Note how the lines do not show much detail immediately after the collection of data.

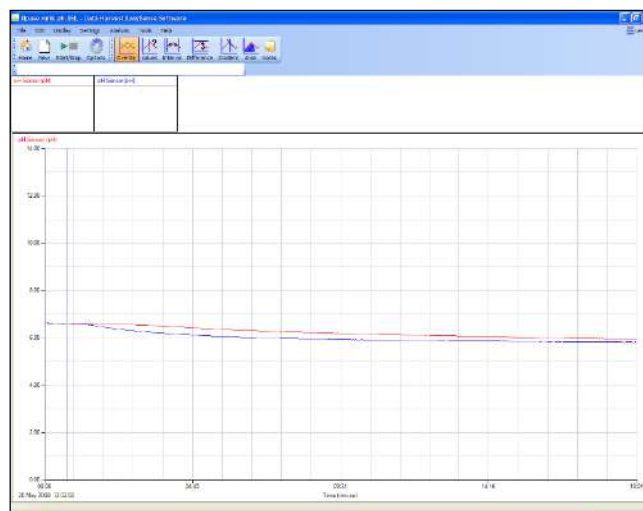


Fig 5.1 Example of how data will appear

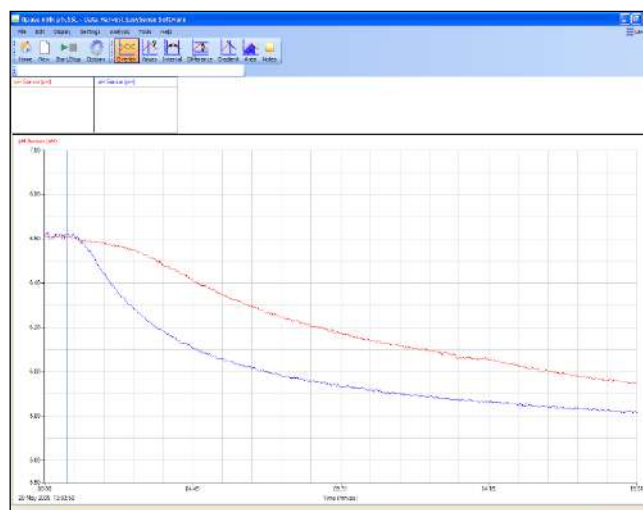


Fig 5.2 Use Autoscale or Sensor settings (Options) to adjust the scale to reveal the detail of the recording

## Questions

1. Describe the shape of the graph.
2. Explain the shape of the graph. For example, why is it not a straight line?

3. What do you notice about the rate of change of pH over the first 1 to 2 minutes?
4. If you have access to data for different milk types, compare the rate of change and the amount of change using the Values and Difference tools.
5. When lipase digests the fats in milk it produces what products?
6. What changes the pH of the milk when lipase is added to it?
7. Why would the rate of change of pH and the amount of change of pH be of use to a dairy farmer or a purchaser of milk from a farmer?

## Teacher's notes

### 6. Cobalt as an inhibitor of enzyme activity (protease)

#### Practical skills AT a, b, c, l

Many of the transition metals act as inhibitors of enzyme systems; in part this explains the toxicity of these metals. The experiment uses cobalt as an inhibitor as it is a readily available metal salt in most schools in the form of cobalt chloride. Sodium is an inhibitor of amylase activity and the comparison of action could be used to reinforce the idea of enzyme specificity.

The explanation of the mechanism behind inhibition needs preparation. There are several good sites offering animations of enzyme activity and the role of active sites. Most Advanced level texts also offer good explanations.

Enzyme inhibition can be used within the organism to help regulate the biochemistry of the organism. Some enzyme reactions use the product of the reaction to quench the reaction, producing simple feedback control. Inhibition can also explain the toxicity of some materials and why some substances can have a profound effect on the organism.

Inhibitors have a key role in therapeutics, for example in treatment of depression or Parkinsonism. In a similar way inhibition (or stimulation) of nerve impulses has the potential to alter behaviour and damage the organism.

The experiment will help to:

1. Show that enzyme activity can be controlled by agents not involved in the reaction.
2. Show that enzyme activity can be affected by simple substances.
3. Encourage students to consider a mechanism to explain why some substances can cause harm to living systems.

#### Apparatus

1. Colorimeter set to Transmittance range
2. Blue filter and 2 cuvettes
3. Protease enzyme solution 1%
4. Milk powder suspension 1%
5. Syringes or graduated pipettes
6. Buffer solution pH 6 (optional)
7. Cobalt chloride solution  $0.05 \text{ mol dm}^{-3}$

#### Set up

Recording method	Time	Intersample	Overlay
Graph	5 minutes	500 ms	On

It is advised to run a test before using the enzyme in class to get a measure of the time span needed. The set up uses a 5 minute time span. The milk and enzyme solutions will provide variation that will need accounting for.

## Risk assessment

- Cobalt has been identified as a potential carcinogen. Refer to local advice on the handling and preparation of cobalt salts.
- Care should be taken with cobalt chloride solution. Direct contact with all cobalt compounds should be avoided. Check with your local health and safety documentation for the risk assessment for cobalt compounds.

## Practical notes

### Milk powder (casein) substrate

The casein substrate is made by adding 1 g of fat free dried milk powder to 100 cm<sup>3</sup> of distilled water (1% w/v casein to water). Scaling up of the volume does not present any problems. This stock is stable and can be kept for at least 24 hours if kept chilled (after this time decomposition will start to take place). If dried milk powder containing fat is used there is no significant difference to the experiment timings, but the digested solution will not be as clear.

### Enzyme

The experiments described in these notes used bacterial liquid protease purchased from NCBE\*. Its trade name is NEUTRASE. It is a stable form of the enzyme and its activity not greatly affected by storage (in stock) or in overnight preparations. Refrigeration at 4°C is adequate for storage.

\*NCBE: The National Centre for Biotechnology Education at the University of Reading ([www.ncbe.reading.ac.uk](http://www.ncbe.reading.ac.uk)).

The enzyme was made up as a 0.5% v/v solution with distilled water and allowed to reach room temperature (21°C). The stability of this product means that a buffer is not required, neither is an acid activator. The colour of the enzyme does have an effect on the final values shown in the Colorimeter if its concentration is varied in the experiment. Other proteases can be used but the best concentration will need to be fine-tuned by advanced testing. Experience has shown that a 0.1 cm<sup>3</sup> to 100 cm<sup>3</sup> stock is a good starting reference. The activity of the enzyme needs to be modified to give a completed digestion at room temperature in 3 minutes at pH 7.

If using a powdered protease, care (regarding allergies) needs to be taken when handing the powder.

## General notes

If care is taken the cuvette can be placed into the Colorimeter and the solutions added to it while it is in the Colorimeter, this will help reduce errors in timing.

Adding the casein substrate to the enzyme gives a clear start point to the experiment and also provides mixing of the reagents in the cuvette.

The cuvettes have nominal capacity of 4.0 cm<sup>3</sup> some are made to have a volume of 4.5 cm<sup>3</sup>. All instructions provide a final volume of 4.0 cm<sup>3</sup>. A smaller volume in the larger cuvette has no effect as the Colorimeter uses a light path through the cuvette about  $\frac{1}{3}$ <sup>rd</sup> of the distance up from the base of the cuvette.

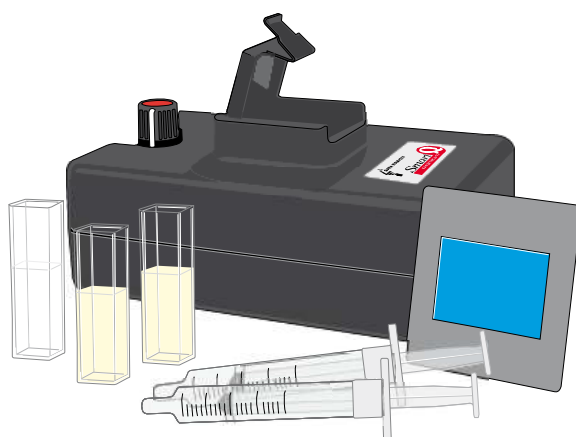
## Extension work

1. Do any other transition metals show inhibition? Try chloride salts of copper, zinc and iron.
2. Is the chloride the inhibitor? Use the same metal as a nitrate or sulphate.
3. Or do they show synergism (e.g. do they cause an increase in the rate?)

## 6. Cobalt as an inhibitor of enzyme activity (protease)

### Practical skills AT a, b, c, l

Protease enzymes digest proteins to produce amino acids. In this experiment dried milk powder suspension is going to be the source of the protein. The suspension is opaque white (milky). The protease will digest the milk protein producing amino acids, which are colourless and transparent. The amount of light transmitted through the solution will be proportional to the milk protein present. Sometimes other chemicals will interfere with the reaction and slow it down, such chemicals are called inhibitors.



### Apparatus

1. Colorimeter set to Transmittance range
2. Blue filter and two cuvettes
3. Protease enzyme solution 1%
4. Milk powder suspension 1%
5. Syringes or graduated pipettes
6. Buffer solution pH 6 (optional)
7. Cobalt chloride solution  $0.05 \text{ mol dm}^{-3}$

### Risk assessment

Do not let liquid enzymes dry up.

Avoid direct contact of enzyme to skin and eyes.

### Method

1. Connect the Colorimeter to the data logger. Place the blue filter supplied in the front slot of the Colorimeter.
2. Create a 'control' cuvette for calibrating the Colorimeter by adding  $3.0 \text{ cm}^3$  of the milk powder solution and  $1.0 \text{ cm}^3$  of protease into a cuvette, mix and leave it to clear.
3. Set the recording time:

Recording method	Time	Intersample	Overlay
Graph	5 minutes	500 ms	On

- When the control cuvette has become clear place it into the Colorimeter. Make sure the ribbed faces of the cuvette are to the sides of the Colorimeter and close the lid.
- Select Test Mode (Tools menu) and use the control knob on the Colorimeter to give a transmittance reading of 100%. Remove the cuvette. Keep the cuvette to one side in case you need to re-check the transmission level.
- Make up the first of the solutions as listed in the table below to a clean cuvette (do not add the milk solution yet) and place into the Colorimeter.
- Add the milk powder solution and immediately click on the Start icon to begin logging. Close the lid.
- Use Add Text to label the graph line with the substrate concentration used. Remove the cuvette and rinse it clean. Save the data.
- Make sure Overlay is selected.
- Repeat stages 6 -8 using the different concentrations of cobalt chloride.

Volume of 0.1% v/v enzyme cm <sup>3</sup>	Volume of milk suspension cm <sup>3</sup>	Volume of water cm <sup>3</sup>	Volume Cobalt Chloride (concentration) cm <sup>3</sup>	Total volume cm <sup>3</sup>
1.0	2.5	0.0	0.5 (0.05 mol dm <sup>-3</sup> )	4.0
1.0	2.5	0.0	0.5 (0.025 mol dm <sup>-3</sup> )	4.0
1.0	2.5	0.0	0.5 (0.0125 mol dm <sup>-3</sup> )	4.0
1.0	2.5	0.5	0.0	4.0

## Questions

- How does the graph change as the cobalt chloride concentration is increased?
- Does the reaction go to completion, or look as if it will get to completion?
- If the reaction looks as if it will finish but is taking longer with the cobalt chloride, what does this tell us about how the cobalt chloride is acting in this reaction?
- Enzyme inhibitors are described as competitive or non-competitive. Which describes the inhibition shown by cobalt chloride?

## Teacher's notes

### 7. Amylase and starch reaction

#### Practical skills AT a, b, c, l

The activity of any enzyme is affected by many factors including temperature, pH and concentration of the reactants. Amylase is a convenient model enzyme to study the effect of these factors on enzymes. The activity is studied by monitoring the removal of the starch molecule over time during the digestion. The indicator for starch, iodine, is used to colour the starch.

#### Apparatus

1. Colorimeter set to Transmittance range
2. Red filter and 2 cuvettes
3. 0.1% Amylase solution
4. Starch substrate (boiled soluble starch solution pre- treated with Iodine)
5. Graduated pipettes or syringes with a 2.5 cm<sup>3</sup> capacity

Note: It is important that the two solutions cannot become mixed, even cross contamination from syringes and glassware can adversely affect results. The solutions should be geographically separated and provided with their own glassware.

#### Set up

Recording method	Time	Intersample
Graph	5 minutes	500 ms

It is advised to run a test before using the enzyme in class to get a measure of the time span needed. The set up uses a 5 minute time span. The starch and enzyme solutions will provide variation that will need accounting for.

#### Practical notes

Studying the reaction between amylase and starch by a Colorimeter needs care to be taken in preparing for the practical. The reaction between amylase and starch depends on the number of bonds on the starch molecule available for the amylase to attack. As you add iodine to the starch many of the attack sites become occupied and you start to get a competitive inhibition of the amylase digestion. The skill for making this experiment successful is in getting enough iodine blue-black colour without slowing down the amylase digestion. The balance between the getting the colour required and loss of activity means it is easier to prepare an iodine treated starch solution from which further dilutions can be made.

If care is taken the cuvette can be placed into the Colorimeter and the solutions added to it while it is in the Colorimeter, this will help reduce errors in timing. Adding the starch iodine solution to the enzyme gives a clear start point and gives good mixing in the cuvette without the need for shaking the cuvette.

The cuvettes have nominal capacity of 4.0 cm<sup>3</sup>, some are made to have a volume of 4.5 cm<sup>3</sup>. All instructions provide a final volume of 4.0 cm<sup>3</sup>. A smaller volume in the larger cuvette has no effect as the Colorimeter uses a light path through the cuvette about  $\frac{1}{3}$ <sup>rd</sup> of the distance up from the base of the cuvette.

**Iodine solution**

A 1% (w/v) iodine in potassium iodide (aqueous) purchased from a chemical supplier was used as the stock iodine solution. This was further diluted to 0.1% by diluting the 1% stock 1:10 with distilled water.

**Soluble starch**

1% w/v provides a good substrate. The starch needs to be boiled to make a clear solution.

**Starch substrate**

The stock starch / iodine combined substrate was made using 1% w/v soluble starch and 0.1% iodine solution.

Treatment of 100 cm<sup>3</sup> starch with 4 cm<sup>3</sup> of the 0.1% iodine solution gives a deep blue - black mixture that gave good light transmission values in the experiments. The reaction, with the enzyme concentrations described, completes inside 2 - 3 minutes at the optimal conditions (i.e. pH 7.0, 32°C).

**Enzyme**

The experiments described in these notes used bacterial liquid amylase purchased from NCBE\*. Trade name is TERMAMYL. It is a stable form of the enzyme and its activity is not greatly affected by storage (in stock) or in overnight preparations. Refrigeration at 4°C is adequate for storage.

\* NCBE: The National Centre for Biotechnology Education at the University of Reading  
([www.ncbe.reading.ac.uk](http://www.ncbe.reading.ac.uk))

The enzyme was made up as a 0.1% v/v solution with distilled water and allowed to reach room temp (21°C). The high colour of the enzyme does have an effect on the final values shown in the Colorimeter. At this dilution a compromise has been reached between activity and colour.

Powdered amylase will work. Make up to the same concentration (use w/v) and test carefully to adjust the activity. Care regarding allergies needs to be taken.

It is advised to run a test before use in class to get a measure of the time span needed, from the work sheet. The starch and enzyme solutions will provide variation that will need accounting for.

**Extension work**

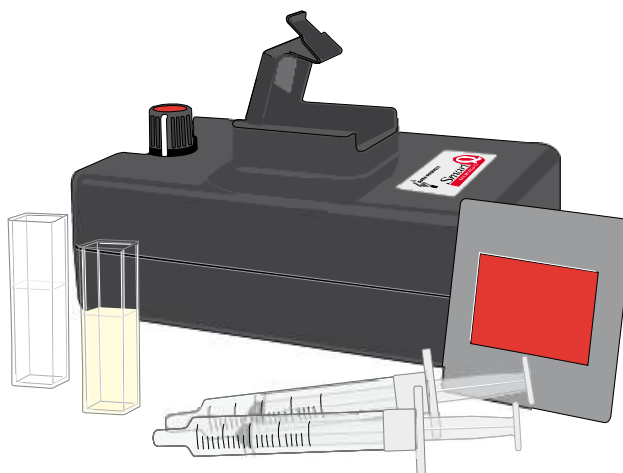
1. Does the concentration of substrate have any effect?
2. Does the source of enzyme have any effect e.g. bacterial, fungal, mammalian?
3. Does salivary amylase show the same pattern? Does this change through the day? Check with local regulations that there isn't a blanket ban on the use of salivary enzyme.
4. Does the type of substrate change the results?
5. How does the iodine influence the reaction?



## 7. Amylase and starch reaction

### Practical skills AT a, b, c, l

Enzymes break down large molecules into smaller molecules by a process called digestion. Enzyme activity depends upon several factors, in this experiment the effect of one of these factors, pH, is going to be studied. The large molecule being digested is starch and the product is a smaller sugar fragment. Starch reacts with dilute iodine solution to form a dark blue-black coloured compound. The sugars formed by the amylase digestion do not react with the iodine. If the starch is made blue-black and then digested, the colour will disappear at a rate equal to the rate of digestion (reaction). This colour change is going to be



monitored in this experiment.

### Apparatus

1. Colorimeter set to the Transmittance range
2. Red filter and two cuvettes
3. 0.1% Amylase solution.
4. Boiled soluble starch solution pre- treated with iodine
5. Graduated pipettes or syringes with a 2.5 ml capacity

### Risk assessment

Do not let liquid enzymes dry up.

Avoid direct contact of enzyme to skin and eyes.

### Method

1. Connect the Colorimeter to the data logger. Place the red filter supplied in the front slot of the Colorimeter.
2. Create a 'control' cuvette for calibrating the Colorimeter by adding 2.0 cm<sup>3</sup> of starch - iodine mixture, 1.0 cm<sup>3</sup> of amylase and 1.0 cm<sup>3</sup> of distilled water into a cuvette, mix and leave to one side.
3. Set up the recording time:

Recording method	Time	Intersample
Graph	5 minutes	500 ms

4. When the control cuvette has become clear place it into the Colorimeter. Make sure the ribbed faces of the cuvette are to the sides of the Colorimeter and close the lid.
5. Select Test Mode (Tools menu) and use the control knob on the Colorimeter to give a transmittance reading of 100%. Remove the cuvette.
6. Place  $1.0\text{ cm}^3$  of amylase and  $1.0\text{ cm}^3$  of water into a clean cuvette (do not add the starch iodine mixture yet) and place into the Colorimeter.
7. Add the starch iodine solution and immediately click on Start to begin logging. Close the lid.
8. Use Add Text to label the graph line. Remove the cuvette and rinse it clean. Save the data.

## Results

You will have a trace of increase in light transmittance against time.

## Questions

The change in transmission takes place because the enzyme is digesting the starch and producing sugars, which do not react with the iodine.

1. What happened to the light level? Explain the shape of the graph.
2. Look at the beginning middle and end sections of the graph, when was the reaction fastest?
3. Calculate the average gradient of the graph. (Hint: Use the Gradient function).

## Teacher's notes

### 8 How does enzyme activity (amylase) change with temperature?

#### Practical skills AT a, b, l

Studying the reaction between amylase and starch by a Colorimeter is possible but care needs to be taken in preparing for the practical.

The investigation assumes the rate of colour loss is directly related to the amylase digestion of the starch. As the starch is digested to the sugars the iodine - starch complex is also broken down and the solution turns from blue-black to pale brown (the colour of the enzyme solution and the dilute iodine mixture).

Due to the small quantities being used the starch is heated, and this carries the heat over into the experiment. There will be rapid cooling but a relationship between temperature and activity should be established. If the amylase is heated the temperature of the starch solution will quench the effect of the heat in the amylase, but you will see a better denaturing effect. Perhaps this area of experimental design can be discussed with the students for evaluation of the experiment.

#### Apparatus

1. Colorimeter set to Transmittance range
2. Red filter and 2 cuvettes
3. Amylase solution
4. Starch substrate (boiled soluble starch solution pre-treated with iodine) - several samples at different temperatures
5. Syringes or measuring pipettes
6. Water baths at 20, 30, 40, 50, 60°C

#### Set up

Recording method	Time	Intersample	Overlay
Graph	5 minutes	500 ms	On

It is advised to run a test before using the enzyme in class to get a measure of the time span needed. The set up uses a 5 minute time span. The starch and enzyme solutions will provide variation that will need accounting for.

#### Practical notes

##### General notes

The reaction between amylase and starch depends on the number of bonds on the starch molecule available for the amylase to attack. As you add iodine to the starch many of the attack sites become occupied and you start to get a competitive inhibition of the amylase digestion. The skill for making this experiment successful is in getting enough iodine blue-black colour without slowing down the amylase digestion.

Syringes were found to be the best way of measuring the small volumes needed for the cuvettes. If temperature was being studied the syringes could be placed in water baths for 3 - 5 minutes to bring the

solutions up to the desired temperature. Using the temperature of the water bath as the temperature of the reaction produces convincing results.

Alternately the stock starch solutions can be kept in water baths at the required temperature. The cooling of the solution while transferring to the cuvette will produce an error; this can give an opportunity for students in the analysis of the experiment.

With the small volume of the cuvettes it is easier to prepare and use an iodine treated starch solution from which further dilutions can be made.

If care is taken the cuvette can be placed into the Colorimeter and the solutions added to it while it is in the Colorimeter, this will help reduce errors in timing.

Adding the starch / iodine solution to the enzyme gives a clear start point and gives good mixing in the cuvette without the need for shaking the cuvette.

The cuvettes have nominal capacity of  $4.0\text{ cm}^3$  some are made to have a volume of  $4.5\text{ cm}^3$ . All instructions provide a final volume of  $4.0\text{ cm}^3$ . A smaller volume in the larger cuvette has no effect as the Colorimeter uses a light path through the cuvette about  $\frac{1}{3}$ <sup>rd</sup> of the distance up from the base of the cuvette.

### **Iodine solution**

A 1% iodine (w/v) in potassium iodide (aqueous) purchased from a chemical supplier was used as the stock iodine solution. This was further diluted to 0.1% by diluting a 1% stock 1:10 with distilled water.

### **Soluble starch**

1% w/v provides a good substrate. The starch needs to be boiled to make a clear solution.

### **Starch substrate**

The stock starch / iodine combined substrate was made using 1% w/v soluble starch and 0.1% iodine solution.

Treatment of  $100\text{ cm}^3$  starch with  $4\text{ cm}^3$  of the 0.1% iodine solution gives a deep blue-black mixture that gave good light transmission values in the experiments. The reaction, with the enzyme concentrations described, completes inside 2 to 3 minutes at the optimal conditions (i.e. pH 7.0 at  $32^\circ\text{C}$ ).

### **Enzyme**

The experiments described in these notes used bacterial liquid amylase purchased from NCBE\*. Trade name is TERMAMYL. It is a stable form of the enzyme and its activity not greatly affected by storage (in stock) or in overnight preparations. Refrigeration at  $4^\circ\text{C}$  is adequate for storage.

\* NCBE: The National Centre for Biotechnology Education at the University of Reading ([www.ncbe.reading.ac.uk](http://www.ncbe.reading.ac.uk)).

The enzyme was made up as a 0.1% v/v solution with distilled water and allowed to reach room temp ( $21^\circ\text{C}$ ). The high colour of the enzyme does have an effect on the final values shown in the Colorimeter. At this dilution a compromise has been reached between activity and colour.

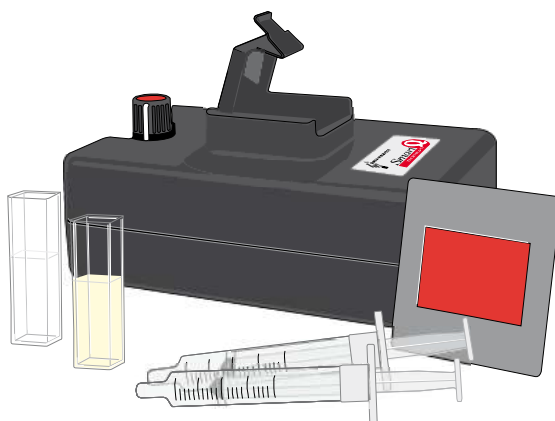
Powdered amylase will work. Care regarding allergies needs to be taken. Make up to the equivalent strength, a 1% w/v solution would be a good starting point. The activity of powdered enzyme does alter with storage so a little more "trial and error" is required to produce the ideal solution.

## 8. How does enzyme activity (amylase) change with temperature?

### Practical skills AT a, b, c, l

Enzymes break down large molecules into smaller molecules by a process called digestion. The large molecule being digested is starch and the product is smaller sugar fragments. Enzymes reactions like all chemical reactions are affected by heat. This investigation will see if heat affects an enzyme reaction in the same way as a normal chemical reaction.

Starch reacts with dilute iodine solution to form a dark blue-black coloured compound. The sugars formed by the amylase digestion do not react with the iodine. If the starch is made blue-black and then digested, the colour will disappear at a rate equal to the rate of digestion (reaction). This colour change is going to be monitored in this experiment.



### Apparatus

1. Colorimeter set to the Transmittance range
2. Red filter and two cuvettes
3. 0.1% Amylase solution
4. Boiled soluble starch solution pre-treated with iodine
5. Graduated pipettes or syringes with a 2.5 ml capacity
6. Water bath

### Risk assessment

Do not let liquid enzymes dry up

Avoid direct contact of enzyme to skin and eyes

### Method

1. Connect the Colorimeter to the data logger. Place the red filter in the front slot of the Colorimeter.
2. Create a 'control' cuvette for calibrating the Colorimeter by adding 2.0 cm<sup>3</sup> of starch-iodine mixture, 1.0 cm<sup>3</sup> of amylase and 1.0 cm<sup>3</sup> of distilled water into a cuvette, mix and leave to one side.
3. Set the recording time:

Recording method	Time	Intersample	Overlay
Graph	5 minutes	500 ms	On

4. When the control cuvette has become clear place it into the Colorimeter. Make sure the ribbed faces of the cuvette are to the sides of the Colorimeter and close the lid.
5. Select Test Mode (Tools menu) and use the control knob on the Colorimeter to give a transmittance reading of 100%. Remove the cuvette.
6. Place 1.0 cm<sup>3</sup> of amylase into a clean cuvette (do not add the starch solution yet) and place into the Colorimeter.
7. Collect 3.0 cm<sup>3</sup> of starch solution from a stock of known temperature. Make a note of the temperature used.
8. Add the starch solution to the cuvette in the Colorimeter and immediately click on Start to begin logging. Close the lid.
9. Use Add Text to label the graph line with the temperature of the starch solution. Remove the cuvette and rinse it clean. Save the data.
10. Make sure Overlay is selected. Repeat stages 6 - 9 until you have used all the starch solutions at different temperatures provided.

## Results

You will have a trace of light transmittance increasing against time. The starch solution will start dark and become lighter as the enzyme digests the starch.

## Questions

The change in transmission takes place because the enzyme is digesting the starch and producing sugars which do not react with the iodine.

1. What happened to the shape of each curve as the temperature of the starch solution was altered?
2. What is the relationship between temperature and the rate of the reaction?
3. Plot a graph of time taken to reach 40% transmission vs. temperature for each temperature of starch solution used. What does this show about the relationship between temperature and the amylase activity?
4. Find out what denatured means; explain the graph created in question 3 using the information about denaturing.
5. How does the effect of heat on 'chemical reaction' differ from how an enzyme reacts to temperature?

## Teacher's notes

### 9. How does enzyme (amylase) activity change with pH?

#### Practical skills AT a, b, c, l

The activity of any enzyme is affected by many factors including temperature, pH and concentration of the reactants. Amylase is a convenient model enzyme to study the effect of these factors on enzymes. The activity is studied by monitoring the removal of the starch molecule over time during the digestion. The indicator for starch, iodine, is used to colour the starch.

#### Apparatus

1. Colorimeter set to Transmittance range
2. Red filter and 2 cuvettes
3. Buffer solutions (pH 10, 7, 4)
4. Distilled water
5. 0.1% Amylase solution
6. Boiled soluble starch solution pre-treated with iodine
7. Graduated pipettes or syringes 2.5 ml capacity

#### Set up

Recording method	Time	Intersample	Overlay
Graph	5 minutes	500 ms	On

It is advised to run a test before using the enzyme in class to get a measure of the time span needed. The set up uses a 5 minute time span. The starch and enzyme solutions will provide variation that will need accounting for.

#### Practical notes

##### General notes

Studying the reaction between amylase and starch by a Colorimeter needs care to be taken in preparing for the practical. The reaction between amylase and starch depends on the number of bonds on the starch molecule available for the amylase to attack. As you add iodine to the starch many of the attack sites become occupied and you start to get a competitive inhibition of the amylase digestion. The skill for making this experiment successful is in getting enough iodine blue-black colour without slowing down the amylase digestion. The balance between the getting the colour required and loss of activity means it is easier to prepare an iodine treated starch solution from which further dilutions can be made.

If care is taken the cuvette can be placed into the Colorimeter and the solutions added to it while it is in the Colorimeter, this will help reduce errors in timing. Adding the starch / iodine solution to the enzyme / buffer gives a clear start point and gives good mixing in the cuvette without the need for shaking the cuvette.

The cuvettes have nominal capacity of  $4.0\text{ cm}^3$ , some are made to have a volume of  $4.5\text{ cm}^3$ . All instructions provide a final volume of  $4.0\text{ cm}^3$ . A smaller volume in the larger cuvette has no effect as the Colorimeter uses a light path through the cuvette about  $\frac{1}{3}$ <sup>rd</sup> of the distance up from the base of the cuvette.

## Solutions

Note: It is important that the two solutions cannot become mixed, even cross contamination from syringes and glassware can adversely affect results. The solutions should be geographically separated and provided with their own glassware.

### Iodine solution

1% (w/v) Iodine in potassium iodide (aqueous) purchased from a chemical supplier was used as the stock iodine solution. This was further diluted to 0.1% by diluting the 1% stock 1:10 with distilled water.

### Soluble starch

1% w/v provides a good substrate. The starch needs to be boiled to make a clear solution.

### Starch substrate

The stock starch / iodine combined substrate was made using 1% w/v soluble starch and 0.1% iodine solution. Treatment of  $100\text{ cm}^3$  starch with  $4\text{ cm}^3$  of the 0.1% iodine solution gives a deep blue-black mixture that gave good light transmission values in the experiments. The reaction, with the enzyme concentrations described, completes inside 2 - 3 minutes at the optimal conditions (i.e. pH 7.0,  $32^\circ\text{C}$ ).

### Buffer solutions

The use of buffer solutions purchased from a supplier is recommended. pH buffer tablets and distilled water will give good results. Follow the manufacturer's instruction when making up the solutions. Relatively small quantities are required for the experiments.

### Enzyme

The experiments described in these notes use bacterial liquid amylase purchased from NCBE\*. Trade name is TERMAMYL. It is a stable form of the enzyme and its activity is not greatly affected by storage (in stock) or in overnight preparations. Refrigeration at  $4^\circ\text{C}$  is adequate for storage.

\* NCBE: The National Centre for Biotechnology Education at the University of Reading ([www.ncbe.reading.ac.uk](http://www.ncbe.reading.ac.uk)).

The enzyme was made up as a 0.1% v/v solution with distilled water and allowed to reach room temp ( $21^\circ\text{C}$ ). The high colour of the enzyme does have an effect on the final values shown in the Colorimeter. At this dilution a compromise has been reached between activity and colour.

Powdered amylase will work. Make up to the same concentration (use w/v) and test carefully to adjust the activity. Care regarding allergies needs to be taken.

It is advised to run a test before use in class to get a measure of the time span needed. The starch and enzyme solutions will provide variation that will need accounting for.

## Extension work

1. Does the concentration of substrate have any effect?
2. Does the source of enzyme have any effect e.g. bacterial, fungal, mammalian?



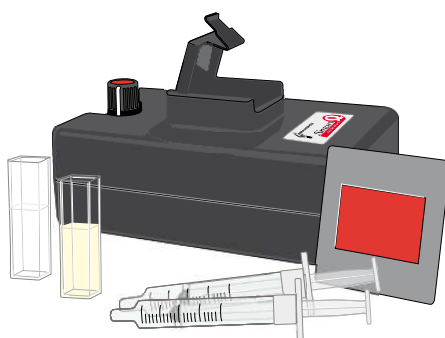
3. Does salivary amylase show the same pattern? Does this change through the day? Check with local regulations that there is no blanket ban on the use of salivary enzyme.
4. Does the type of substrate change the results?
5. How does the iodine influence the reaction?

## 9. How does enzyme (amylase) activity change with pH?

### Practical skills AT a, b, c, l

Enzymes break down large molecules into smaller molecules by a process called digestion. Enzyme activity depends upon several factors, in this experiment the effect of pH as one of these factors is going to be studied. The large molecule being digested is starch, and the product is smaller sugar fragments.

Starch reacts with dilute iodine solution to form a dark blue-black coloured compound. The sugars formed by the amylase digestion do not react with the iodine. If the starch is made blue-black and then digested, the colour will disappear at a rate equal to the rate of digestion (reaction). This colour change is going to be monitored in this experiment.



### Apparatus

1. Colorimeter set to the Transmittance range
2. Red filter and two cuvettes
3. Water bath
4. Buffer solutions (pH 10, 7, 4)
5. Distilled water
6. 0.1% Amylase solution
7. Boiled soluble starch solution pre- treated with iodine
8. Graduated pipettes or syringes with a 2.5 ml capacity

### Risk assessment

Do not let liquid enzymes dry up.

Avoid direct contact of enzyme to skin and eyes.

### Method

1. Connect the Colorimeter to the data logger. Place the red filter in the front slot of the Colorimeter.
2. Create a 'control' cuvette for calibrating the Colorimeter by adding 2.0 cm<sup>3</sup> of starch - iodine mixture, 1.0 cm<sup>3</sup> of amylase and 1.0 cm<sup>3</sup> of distilled water into a cuvette, mix and leave to one side.

3. Set the recording time:

Recording method	Time	Intersample	Overlay
Graph	5 minutes	500 ms	On

- When the control cuvette has become clear place it into the Colorimeter. Make sure the ribbed faces of the cuvette are to the sides of the Colorimeter and close the lid.
- Select Test Mode (Tools menu) and use the control knob on the Colorimeter to give a transmittance reading of 100%. Remove the cuvette.
- Make up the cuvette for the first set of solutions. Add the quantity of buffer/ amylase as listed in the table below (do not add the starch iodine solution yet).
- Add the starch solution to the cuvette in the Colorimeter and immediately click on Start to begin logging. Close the lid.
- Use Add Text to label the graph line with the pH value of the buffer used. Remove the cuvette and rinse it clean. Save the data.
- Make sure Overlay is selected.
- Repeat stages 6 – 8 using the buffers of different pH values.

Volume/pH of buffer	Starch /iodine solution (cm <sup>3</sup> )	0.1% Amylase (cm <sup>3</sup> )	Total volume (cm <sup>3</sup> )
1.0 cm <sup>3</sup> of pH 10 buffer	2.0	1.0	4
1.0 cm <sup>3</sup> of pH 7 buffer	2.0	1.0	4
1.0 cm <sup>3</sup> of pH 4 buffer	2.0	1.0	4

## Results

You will have a trace of increase in light transmittance against time. As you repeat the experiment for different pH values you may notice that the start points are not always the same. This is not a problem as the shape of the trace is more important.

## Questions

The change in transmission takes place because the enzyme is digesting the starch and producing sugars, which do not react with the iodine.

- What happened to the light level? Explain the shape of the graph.
- How does the graph change as the pH is increased?
- Pick a time on the trace and read the light value at that point. Plot this on graph paper against pH on the horizontal. If less light equals a slower reaction what does this graph tell you about how an enzyme reacts to pH?
- Look at the beginning middle and end sections of the graph, when was the reaction fastest? Calculate the average gradient of the graph. (Hint: Use the Gradient function).
- How does the pH of the mouth match to the most effective pH of this experiment?

## Teacher's notes

### 10. The breakdown of starch by the enzyme amylase (diastase) using a Light level sensor

#### Practical skills AT a, b, c, l

Saliva in the mouth contains amylase enzymes that catalyse the hydrolysis or breakdown of starch (a polysaccharide - long chain molecule) into maltose (a disaccharide - short molecule). Starch turns iodine dark-blue. As the amylase enzyme breaks down the starch, the blue colour gets lighter and lighter. A Light level sensor is used with a data logger to observe changing levels of light transmission through the iodine treated starch solution.

#### Apparatus

1. Light level sensor set to Transmission (T%) range. Alternatively a Colorimeter can be used.
2. Boiling tube / test tube (if using a test tube the volumes quoted will need altering).
3. Starch solution pre-treated with iodine to colour it blue-black.
4. Amylase solution.
5. Water bath.
6. Retort stand and clamp.
7. Test tube rack.
8. Light source (bench lamp, torch, white LED).

#### Set up

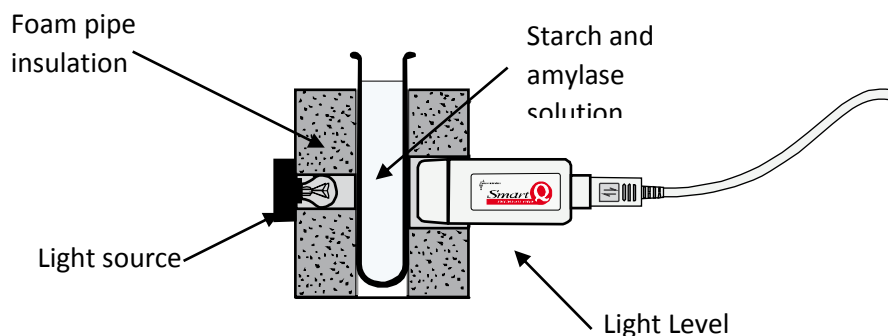
Recording method	Time	Intersample	Overlay
Graph	5 minutes	500 ms	On

It is advised to run a test before using the enzyme in class to get a measure of the time span needed. The set up uses a 5 minute time span. The starch and enzyme solutions will provide variation that will need accounting for.

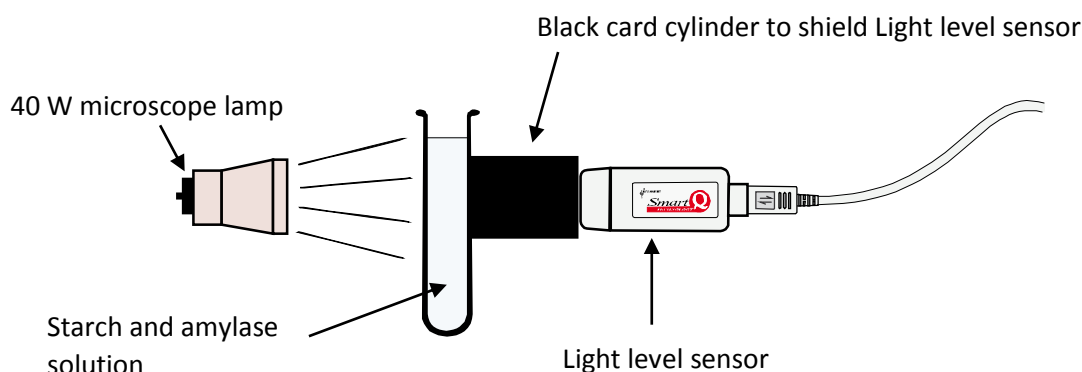
#### Making a simple colorimeter

Use a piece of piping insulation. The foam insulation designed for 15 mm standard copper pipe is ideal for the typical test tube. Cut windows for the sensor and light source. The insulation for the 22 mm copper tubing is ideal for boiling tubes.

#### Alternative 1



## Alternative 2



## Practical notes

### Solutions

Prepare **fresh** solutions of

- Soluble starch in a pH 7 buffer (0.2% w:v) and
- Amylase (1%)

If time allows these should be made up to give a black to clear result in about 5 minutes at room temperature, make allowance for the real room temperature of the room being used.

### General notes

The iodine addition to the starch is the key to this investigation. If the iodine is too strong the reaction is quenched, if it is too weak the colour formed is too weak for a well-defined data set. The 'standard' bench iodine used for food tests is 2.5% iodine in 5% potassium iodide w/v. This will need diluting by twenty fold with water to reach a dilution that gives a colour with the starch and does not quench (inhibit) the hydrolysis of the starch by amylase.

When using non saliva based amylases there is a real possibility that reducing sugars will be present in the preparation. In this investigation this will not be a problem as the rate is being monitored by the decrease in the substrate levels and not by the increase in the product. Be cautious about getting students to test for reducing sugars before and after, you need to be sure the stock amylase is free from reducing sugars.

Saliva is still a good way of relating the 'test tube' experiment to the real living world. Concerns over the use of saliva are more in the possibility than the reality. Check with appropriate bodies to see if it can be used. It is more likely it is the reaction of the student to its use that is the problem.

Liquid fungal amylase (e.g. Termamyl from NCBE Reading) can provide a better stock. It is easier to handle and dilutions can be made up easily.

Many of the commercial enzyme products have been selected for industrial practice. It may be found that the simple (mammal centric) description of enzymes being thermolabile is not found to be true, Termamyl will resist, for example, temperatures above 90°C. As we understand more about the extreme conditions in which life can exist, the narrow ideas of very limited ranges of enzyme activity seem less and less appropriate.

If you wish to use a white LED, the LED will need to be protected by a resistor. LEDs produce a very powerful light. Check the colour profile carefully; white LEDs can often have a pronounced blue cast. Advantage of using a LED is that the light source does not give out any appreciable heat and it is very compact.

## 10. The breakdown of starch by the enzyme amylase (diastase) using a Light level sensor

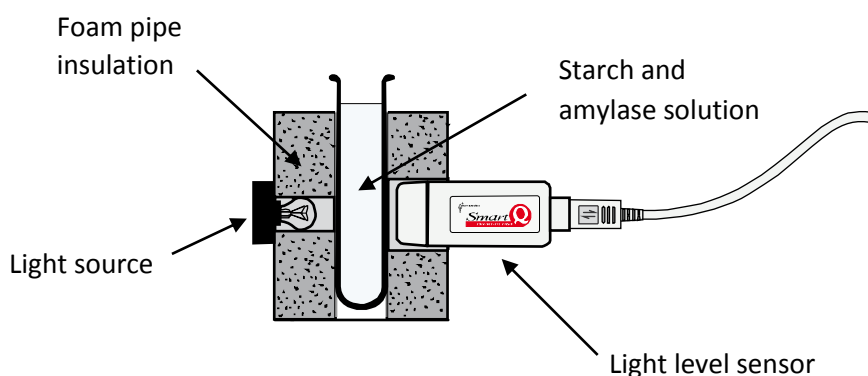
### Practical skills AT a, b, c, l

Saliva in the mouth contains amylase enzymes that catalyse that breakdown of starch (a big molecule) into maltose (a small molecule).

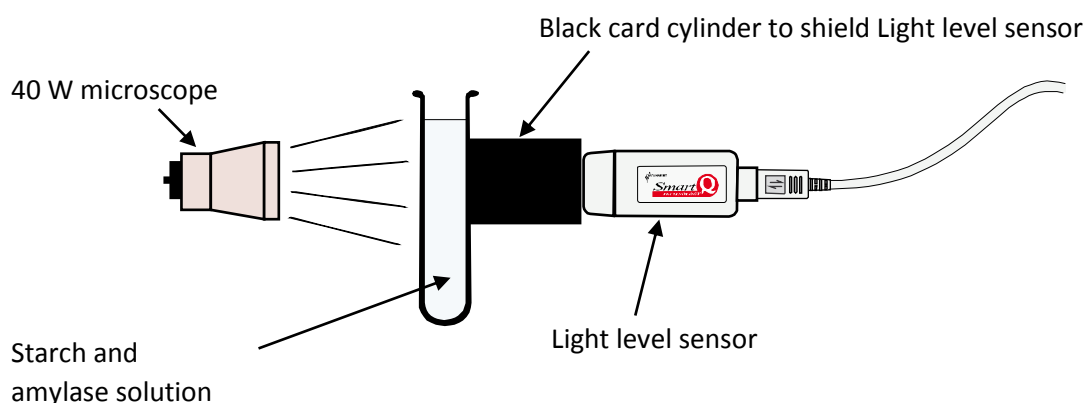
Starch turns iodine dark blue. Iodine is added to the starch at the beginning of the experiment to make a dark blue solution.

As the amylase enzyme breaks down the starch, the blue colour gets lighter and lighter. A Light level sensor is used with a data logger to observe changing levels of light transmission through the blue iodine treated starch solution.

#### Alternative 1



#### Alternative 2



Hint - place this set up in a small cardboard box or surround in black paper to exclude ambient light but leave a 'peep hole' so you can observe the colour change. If the lamp is found to 'heat up' the solution on test, use a glass heat shield or replace the lamp with a small torch.

If you have enough equipment set up a Control with starch solution and iodine only. If not, repeat the experiment at the end.

It is easier to make a comparison with the results from the control solution if you adjust the light and Light level sensor so that the value through the two boiling tubes is the same for both experiments before the amylase is added.

### Risk assessment

Keep iodine off your clothes and exposed skin.

### Apparatus

1. Light level sensor set to transmission range
2. Boiling tube
3. Starch solution pre-treated with iodine to colour it blue black
4. Amylase solution
5. Water bath
6. Retort stand and clamp
7. Test tube rack

### Method

1. Assemble the apparatus as shown. Connect the Light level sensor to the data logger.
2. The Light level sensor should be placed directly opposite the light source. The black paper tube or foam insulation is used to exclude ambient light.
3. Set the recording time:

Recording method	Time	Intersample	Overlay
Graph	5 minutes	500 ms	On

4. Select Test Mode (Tools menu).
5. Place a boiling tube of water where the experiment tube will be placed, with the light source turned on, move the Light sensor to get the highest light level. Make sure the sensor is not being over illuminated, if it is move the light source away from the apparatus.
6. When you are happy with the layout, fix the apparatus so it cannot be moved.
7. Swap the boiling tube with the one the experiment will take place in.
8. Add 10 cm<sup>3</sup> of the amylase solution to the boiling tube.
9. Click on Start to begin logging. Immediately add 20 cm<sup>3</sup> of the iodine and starch mixture, the addition should mix the starch with the amylase.
10. Leave the set-up and do not disturb any part of the apparatus. After 5 minutes logging will stop.
11. If the experiment is to be repeated use the Overlay function to collect all the data on the same graph. Remember to use the Add Text tool to label the graph lines collected.

Note: Be prepared to change the strength of the solutions, the light level or the time of the experiment. Enzymes do give different levels of activity.

## Results

When the experiment is over you should see a trace showing the light level over the course of the experiment. It should show an increase in light level with time as the blue colour is removed.

## Questions

1. What happened to the light level?
2. What does the graph tell you about the progress of the reaction? Investigate the gradient of the graph at different points. Compare the gradient at the start and towards the end of the reaction. When was the reaction working at its fastest? Calculate the average gradient of the graph.
3. How long did it take the enzyme to break down the starch?
4. Compare the results with the control experiment. Does the starch break down faster with or without the enzyme?
5. What do you think would happen if you boiled or cooled the enzyme before you add it to the starch? What would happen if the enzyme were at body temperature? Repeat the same experiment at three different starting temperatures. Each run of this experiment should start at the same light level reading. If this is difficult to achieve, use the Post-log Function, General, Subtract a constant, to remove the starting level from each set of readings to show the increase in light level from a zero start.
6. What could cause the temperature of the reaction mixture to change during the experiment? How could the design of the apparatus layout be adapted to ensure the temperature stayed the same?
7. Do you think the enzyme will work best in neutral, acidic or alkaline conditions?



## Teacher's notes

### 11. Colorimetric determination of glucose concentration

#### Practical skills AT a, b, c, f, l

Benedict's solution can easily reveal the presence of a reducing sugar. Making the Benedict's test give a quantitative result is much more difficult. The practical described enables the concentration of glucose in a solution to be measured relatively easily. There are limits to the application of the method e.g. Vitamin C will also cause a decolourisation of the manganate (VII).

The practical does provide a good model for the determination of the concentration of substances in a sample and can lead to good discussion about how a diabetic can sample their blood sugar levels or how an athlete can be tested for a performance enhancing compound.

The practical works because glucose is a reducing sugar; this means the glucose molecule is able to donate electrons. In the reaction the glucose provides an electron which is accepted by the manganate (VII) molecule reducing it to its colourless manganese ion form.



The glucose molecule, by losing the electron becomes oxidised. The rate of the reaction is concentration dependent so the more glucose is present the quicker the reaction. The rate of the reaction is followed by timing how long it takes for the colour to disappear.

The use of a Colorimeter allows a more accurate "time to completion" to be determined. The end point can be very difficult to determine by eye.

#### Apparatus

1. Colorimeter set to the Transmittance range
2. Green filter and five cuvettes
3. 3 x 2.5 ml syringes
4. Beakers
5. Glucose solutions of known concentration i.e. 2%, 4%, 6%, 8%, 12% w/v. Alternatively these could be made to molar or mg/L values if the experiment was quantitative.
6. Glucose solution of unknown concentration(s). Any number can be provided; they can be samples of the known concentration simply relabelled.
7. Potassium manganate (VII) solution. 0.5 g in a 1 litre. Ideally this should be made up just before the practical session.
8. 2N sulphuric acid

Note: An alternative version of this practical can be found on the excellent SAPS website [www.saps.plantsci.cam.ac.uk](http://www.saps.plantsci.cam.ac.uk)

#### Risk assessment

Sulphuric acid is an irritant, gloves and goggles are recommended for this strength of solution.

Potassium manganate (VII) is a powerful stain.

Please refer to local safety regulations for further advice and risk assessment data.

## Set up

Recording method	Time	Intersample	Overlay	Display Option
Graph	5 minutes	500 ms	On	Grid on

## Practical notes

The quantity of sulphuric added to each assay is important. If there is insufficient acid present the colour change does not go to colourless, instead a muddy brown intermediate colour is formed which slowly decolourises.

Using the concentrations suggested the weakest glucose solution should decolourise the manganate (VII) inside 5 minutes. This would enable the whole experiment to be completed in a one hour lesson.

## Results and analysis

Students will need to plot data onto graph paper.

Plotting the data as the time taken to reach a pre determined %Transmission value will give a good rate vs. concentration curve. The data to produce the graph can be easily collected from the graph(s) produced using the Values tool and revealing the table of data. The Data value box above the graph will show the %Transmission value and the Table will reveal the time in seconds.

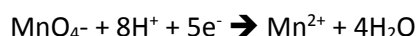
Using  $1/t$  should give a good straight line, but a best fit line may need to be drawn in.

## 11. Colorimetric determination of glucose concentration

### Practical skills AT a, b, c, f, l

Glucose is an important compound in biology. The ability to measure the concentration of glucose in fluids is important e.g. the presence of glucose in urine in the diagnosis of diabetes mellitus. In this practical a variety of solutions of known glucose concentration will be tested. The results from these tests will be used to construct a standard curve that will be used to determine the concentration of a glucose solution of unknown concentration.

Glucose ( $\text{C}_6\text{H}_{12}\text{O}_6$ ) is a monosaccharide, it will react with potassium manganate (VII) (a pink solution) and cause it to lose colour. The time taken for the colour to be lost is directly proportional to the concentration of glucose.



The manganate (VII) ion has a pink colour, when it accepts an electron it is reduced to the  $\text{Mn}^{2+}$  form, which is colourless.

The glucose molecule provides the electrons and becomes oxidised. The rate of reaction is concentration dependent so the more glucose is present, the quicker the reaction. The rate of the reaction is followed by timing how long it takes for the colour to disappear.

### Apparatus

1. Colorimeter set to the Transmission range
2. Green filter and five cuvettes
3. 3 x 2.5 ml syringes
4. Beakers
5. Glucose solutions of known concentration
6. Glucose solution of unknown concentration(s)
7. Potassium manganate (VII) (Potassium permanganate) solution
8. Sulphuric acid (2N)

### Method

1. Connect the Colorimeter to the data logger. Place the green filter in the front slot of the Colorimeter.
2. Create a 'control' cuvette for calibrating the Colorimeter by adding  $1.0\text{ cm}^3$  of the sulphuric acid and  $0.5\text{ cm}^3$  of the potassium manganate (VII) solution into a cuvette. Measure out  $2.5\text{ cm}^3$  of the strongest glucose solution. Add the glucose to the cuvette, mix and leave it to clear.
3. When the control cuvette has cleared place it in the Colorimeter. Make sure the ribbed faces on the cuvette are to the sides of the Colorimeter and close the lid.
4. Set the recording time:

Recording method	Time	Intersample	Overlay	Display Option
Graph	5 minutes	500 ms	On	Grid On

5. Select Test Mode (Tools menu). Adjust the Colorimeter to give a Transmittance reading of 100%. Remove the cuvette and keep to one side in case you need to check the calibration.
6. Add 1.0 cm<sup>3</sup> of sulphuric acid to a clean dry cuvette.
7. Add 0.5 cm<sup>3</sup> of potassium manganate (VII) to the cuvette.
8. Fill a syringe to 2.5 cm<sup>3</sup> with the 2% glucose solution (do not add to the cuvette).
9. Place the cuvette into the Colorimeter (wipe any solution off the outside with a soft tissue first) with the ribbed faces to the sides.
10. Click on the Start icon to begin logging and immediately add the glucose from the syringe to the cuvette, close the lid.
11. Use Add Text to label the graph line with the strength of the glucose solution used. Save a copy of the data before continuing.
12. Check that Overlay is selected. Repeat the investigation using the all other glucose solutions of known concentration.
13. Repeat using the unknown solution(s).
14. Add a Title to the graph and then Save the data.

## Results

The time taken to decolourise the manganate (VII) is proportional to the concentration of the glucose. The time taken to reach a set %Transmission (%T) needs to be read off the graph.

Select a % transmission value (for example 90%T) and draw a line from the axis across to intercept all the graph lines, draw lines from the intersects of the T% with the graphs down to the time axis.

Record into a table (like below) the time taken to reach the 90% transmission value for each glucose concentration. Plot a graph of time taken to decolourise against concentration of glucose.

% Transmission value (%T)	Time taken to reach %T (t)	Concentration of glucose (%)	1/t
		Unknown A	
		Unknown B	

Plot a graph of 1/t against concentration of glucose.

Use this graph to find out the concentration of glucose in your unknown solution(s).

## Questions

1. Why would it be important to measure the concentration of glucose in a solution?
2. Why does the colour change in this experiment?
3. What is meant by the expression 'reducing sugar'?
4. What is the difference between the concentration / (t) graph and the concentration / (1/t) graph?
5. What is the relationship between concentration and (1/t)?
6. Benedict's solution is used to test for sugars. What is the difference between that test and this one?

## Extension

Isotonic sports drinks are supposed to have the same concentration of minerals and sugars in them as is found in the blood. Can you devise an experiment to see how much glucose is in these drinks? (You may need to dilute the drink for it to fit into your calibration, remember to factor the dilution back in when calculating the concentration).

## Teacher's notes

### 12. Quantitative Benedict's test for glucose measurement

#### Practical skills AT a, b, c, f, l

The Benedict test is an established test for the identifying the presence of reducing sugars in a sample. You may have noticed that if the quantity of the reducing sugar is very low the test produces a green or yellow looking solution. The difference in colour with concentration should set pupils thinking that perhaps the exact quantity of the reducing sugar can be measured with the Benedict's test. Unfortunately the very variation in the colour seen is the weakness in creating a quantitative calibration curve.

A version of Benedict's is available that contains potassium hexacyanoferrate, this stops the production of the typical red precipitate of copper and produces a white precipitate that does not change the colour of the unreacted Benedict's.

In this investigation a calibration curve is created using quantitative Benedict's, this is then used to assay the concentration of a reducing sugar in an "unknown" sample.

The students are required to make a calibration curve using solutions containing known amounts of glucose. The unknown is treated in the same way and then the calibration curve is used to read off the glucose concentration in the unknown.

Normally an estimation of glucose using quantitative Benedict's solution would involve a titration. The rationale behind this exercise is that if Benedict's is used in excess in the test, the amount of un-reacted Benedict's left in the test tube will be proportional to the glucose that has reacted.

#### Apparatus

1. Colorimeter set to the Absorbance range with a red filter
2. Cuvettes, one for each sample is preferred
3. 5 test tubes and rack
4. Benedict's solution – quantitative
5. Glucose solution  $0.01 \text{ mol dm}^{-3}$
6. Distilled, purified water
7. Measuring pipettes, 2.5 ml and 10 ml syringes
8. Marker pen
9. Boiling water bath

Note: Distilled water may not be clean enough to allow the white precipitate only to develop. In trialling this worksheet purchased purified, analytical water gave the most consistent results.

#### Set up

Record the data using SnapShot.

Use the sample with the highest glucose content as the standard for the Colorimeter; this will be the palest colour. Set the Colorimeter to read to maximum absorbance with a red filter against this sample.

## Practical notes

It is possible to make up the quantitative Benedict's solution, but for reliability it is probably better to purchase it from a stockist. If you look up methods of making you will find slight variations. The method outlined may need modification for your stock solution.

The precipitate formed by the quantitative version of Benedict's settles out quite quickly, approx. 10 minutes after removal from the water bath should give a clear supernatant suitable for colorimeter assay.

As this is essentially an assay method the emphasis on consistency of method and volumes is important, this potentially makes the exercise a good candidate for assessing practical skill. For example the heating time should be kept constant for all tubes. Over cooking of the tubes can create a false positive result.

If possible use a clean cuvette for each solution, if this is not possible wash each cuvette thoroughly with distilled water. If you are using plastic cuvettes be careful about overzealous use of bottle brushes, they can scratch the plastic material and alter the optical characteristics.

The method has limitations. The range of glucose concentration it can reliably produce results for are in the range 0 – 8 mMol, even the upper limit of 8 mMol will depend upon the concentration of Benedict's used. If too little is used the Benedict's is all reduced by the glucose and there is no remaining blue colour. If the Benedict's solution is too concentrated then the colour remaining will be too intense and not provide sufficient separation of colour.

In the scheme laid out in the students notes a nod to the skill of the students is built in, so quantities suggested to use have been inflated to match the potential measuring skill of the students.

## Sample data

Sample set of data as collected. The samples ranged from 0 to 8 mMol in 1 mMol steps.



Fig 12.1 Absorbance against reading (concentration). There is a good linear fit to the data.

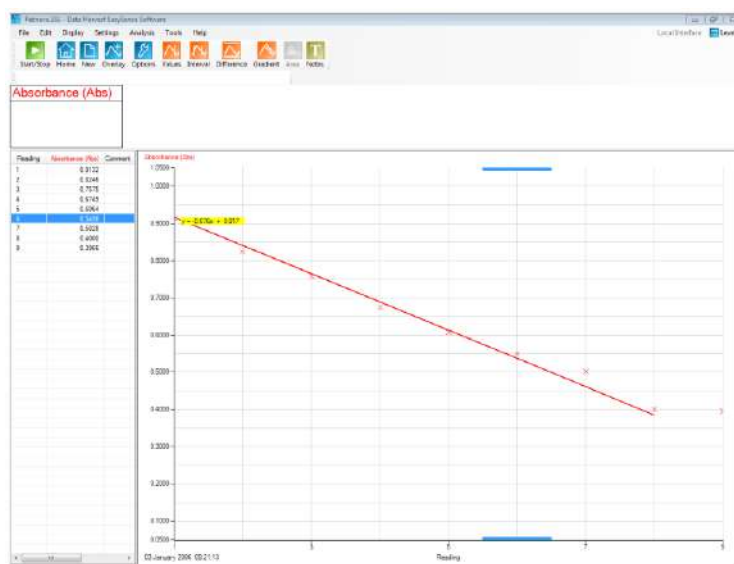


Fig 12.2 Graph converted to a line graph, no line, points shown and best fit line superimposed. The absorbance data for 7 mMol and 8 mMol were the same, the limits of the assay with this method had been reached at 7 mMol.

Use the table to extract the data and produce a graph of concentration (x axis) vs. absorbance (y axis) to use for finding the unknown.

Note: If you have the concentration for each sample predetermined before starting the assay, you can use the Pre-log Function, General, Asks for Value. When you click in the graph area a dialogue box will pop up asking for the value, enter the mMol value. You will then be able to change the x – axis to channel and select the y axis as absorbance and the x axis as mMol. Values can now be interpolated along the line of best fit.



## 12. Quantitative Benedict's test for glucose measurement

### Practical skills AT a, b, c, f, I

The Benedict's test is an established test for the identification of reducing sugars in a sample. You may have noticed that if the quantity of the reducing sugar is very low the test produces a green or yellow looking solution. This difference in colour with concentration may set you thinking that perhaps the exact quantity of the reducing sugar can be measured with the test. In this experiment you will see if it is possible to assay (measure) the concentration of a reducing sugar in a sample.

Unfortunately the very variation in the colour seen is the weakness in creating a quantitative calibration curve.

A version of Benedict's is available that contains potassium hexacyanoferrate, this stops the production of the typical red precipitate of copper and produces a white precipitate that does not change the colour of the unreacted Benedict's.

In this investigation a calibration curve is created using quantitative Benedict's, this is then used to assay the concentration of a reducing sugar in an 'unknown' sample.

You are required to make a calibration curve using solutions containing known amounts of glucose. The unknown is treated in the same way and then the calibration curve is used to read off the glucose concentration in the unknown.

The rationale behind this exercise is that if Benedict's is used in excess in the test, the amount of unreacted Benedict's left in the test tube will be proportional to the glucose that has reacted.

### Apparatus

1. Colorimeter set to the absorbance range with a red filter
2. Cuvettes, one for each sample is preferred
3. 5 test tubes and rack
4. Benedict's solution – quantitative
5. Glucose solution  $0.01 \text{ mol dm}^{-3}$  (10 mMol)
6. Distilled, purified water
7. Measuring pipettes, 2.5 ml and 10 ml syringes
8. Marker pen
9. Boiling water bath

### Method

#### Preparing the standard curve

You will need to prepare 8 standards (solutions of known glucose concentration) to produce a calibration curve.

1. Collect  $40 \text{ cm}^3$  of the glucose standard in a small beaker or conical flask.
2. Make up eight standards as indicated in the table below. Note the tube containing the most glucose will be the calibration standard for the Colorimeter.

Test tube number	Volume of glucose standard (cm <sup>3</sup> )	Volume of distilled water (cm <sup>3</sup> )	Volume of Benedict's (cm <sup>3</sup> )	Concentration of glucose (mMol)	Absorbance
1	8.0	2.0	4.0		
2	7.0	3.0	4.0		
3	6.0	4.0	4.0		
4	5.0	5.0	4.0		
5	4.0	6.0	4.0		
6	3.0	7.0	4.0		
7	2.0	8.0	4.0		
8	1.0	9.0	4.0		
9	0.0	10.0	4.0		

- Place all the prepared test tubes into a boiling water bath and leave for 5 minutes (this needs to be timed carefully; extra heating time can affect the final colour). The water needs to be boiling at the point of adding the test tubes. After the 5 minutes heating time remove the test tubes and cool rapidly (iced water is ideal, or if not use cold water and change it at least once to speed cooling).
- Place the tubes in order in a rack and leave for approximately 10 minutes for any precipitate to settle.

The solutions are now ready to be used in the Colorimeter.

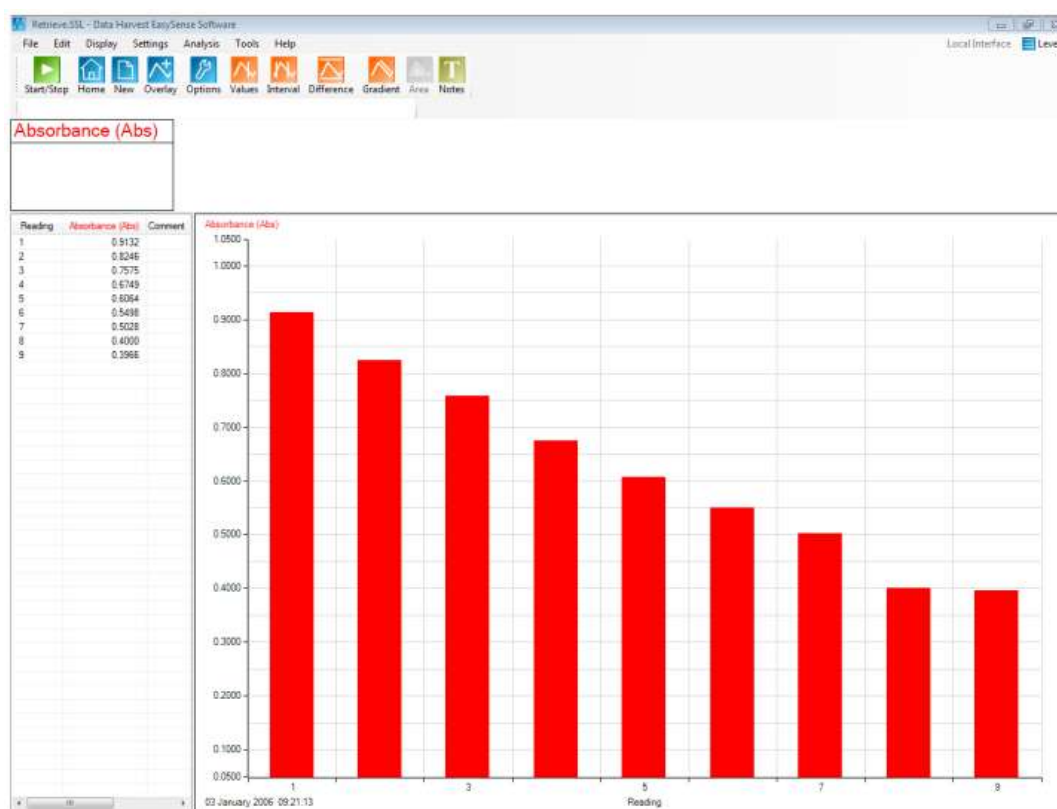
### Absorbance of the solutions

- Connect the Colorimeter to the data logger. Place the red filter supplied in the front slot of the Colorimeter.
- Set up a SnapShot recording.
- Fill a cuvette with the contents of test tube 8 (the tube that contained the maximum glucose standard). Place this 'control' cuvette in the Colorimeter. Make sure the ribbed faces of the cuvette are to the sides of the Colorimeter and close the lid.
- Select Test Mode (Tools menu) and use the control knob on the Colorimeter to give the highest absorbance reading possible. Remove the control cuvette. Keep the cuvette to one side in case you need to check the Colorimeter calibration again.
- Fill another cuvette with the contents of test tube 1, place in the Colorimeter and close the lid.
- Click on the Start icon to start snapshot mode.

7. Click once in the graph area to record the value from the Colorimeter.
8. Remove the cuvette.
9. Repeat with the contents of each of the test tubes. If possible use a clean cuvette for each solution, if not wash the cuvette with distilled water after each reading.
10. When you have recorded the absorbance values for all solutions click on Stop to finish logging. Save the data.

## Results

The data will be shown as a set of bars, depending on the order you tested the tubes the graph will either be as shown or have the bars increasing in height left to right.



When you are happy the data produces a good linear calibration, plot a graph of concentration (x axis) vs. absorbance (y axis) to use for finding the unknown.

- Draw in a line of best fit.
- Place an unknown sample into the Colorimeter to find its absorbance value.
- Use the calibration graph to find its concentration.

## Teacher's notes

### 13 (a – b). Titration of amino acid (alanine)

#### Practical skills AT a, b, c, f, l

Amino acids, with certain exceptions, are soluble in water and insoluble in non-polar organic solvents such as ether, chloroform and propanol. This is not in keeping with known observations of the properties of carboxylic acids and organic amines. The solubility information on amino acids suggests structures which have charged highly polar structures.

Amino acids contain both amino and carboxyl groups and should react with both acids and alkalis. Substances that react to both alkalis and acids are known as amphoteric substances.

In this investigation the amino acid alanine is used. Alanine has been chosen as it is a low cost, simple to obtain amino acid with the data for alanine titrations widely available for comparison. Other amino acids can be used.

When alanine is dissolved into water it will give a solution of neutral pH. The solution of alanine in water does not show migration of ions to electrodes if an electric current is passed through it. The same behaviour will also be shown if the molecule exists as a zwitterion, a condition in which negative and positive charges exist at the same time.

In this investigation a solution of acidified alanine will have sodium hydroxide added to it to produce a titration curve from which the isoelectric point (acidic and base dissociation pH values) can be determined.

#### Apparatus

1. pH sensor
2. Drop / Bubble counter set to the correct volume range (see calibrating the Drop counter) with alignment adapter fitted
3. The drop counter reagent reservoir fitted with two stopcocks and tip
4. 2 x 200 ml beakers
5. Magnetic stirrer and stir bar
6. 40 cm<sup>3</sup> of 0.1 mol dm<sup>-3</sup> Sodium hydroxide (NaOH)
7. 30 cm<sup>3</sup> of acidified Alanine solution, pH 1 (see Notes)
8. Measuring cylinders (50 ml capacity)

#### Set up

Recording method
EasyLog

Check and if necessary set the Drop counter to the 27 Volume range.

#### Alternative:

Use SnapShot and a burette to collect the data with a more traditional titration method. You may not get the same fine data collection but if the practical is for skill assessment this may be a worthwhile trade off.

## Practical notes

Published data for alanine

- Isoelectric point = pH 6.02
- $\text{Pka}_1$  (Acidic dissociation) = pH 2.34
- $\text{Pka}_2$  (Base dissociation) = pH 9.69

Using a Drop counter to measure the volume of titrated fluid with the pH sensor we have obtained values of pH 6.58, 2.3 and 9.5 (respectively) with good repeatability of results.

The sample investigations that lead to this published investigation used,

- Alanine 0.5 g in 30 cm<sup>3</sup> of analytical water (0.18 mol dm<sup>-3</sup>)
- 0.1 mol dm<sup>-3</sup> reagent quality sodium hydroxide
- 2.0 mol dm<sup>-3</sup> reagent quality hydrochloric acid

The alanine solution was acidified to pH 1.0 using drops of the 2.0 mol dm<sup>-3</sup> hydrochloric acid. Most published information starts with the acidified alanine and titrates alkali into it. To make extension work / study easier the same method was used. Acid titration into the alkali alanine is possible, use 1.0 mol dm<sup>-3</sup> sodium hydroxide to make the solution alkaline (pH 12 will be sufficient).

## Calibrating the Drop counter

This investigation uses the Drop counter with one of its pre-set calibrated ranges e.g. 27 drops / cm<sup>3</sup>, so the drops counted are automatically converted and displayed as Volume in cm<sup>3</sup>.

If accuracy is not critical and you are using the reagent reservoir and tip supplied with a low viscosity liquid (like water) and the flow rate set to: -

- Fast e.g. 10 plus drops per second, use the **24 drops/cm<sup>3</sup>** range.
- Medium e.g. between 5 – 10 drops per second, use the **25 drops/cm<sup>3</sup>** range.
- Slow e.g. between 1.5 – 5 drops per second, use the **26 drops/cm<sup>3</sup>** range.
- Very slow e.g. less than 1.5 drops per second, use the **27 drops/cm<sup>3</sup>** range

## To calculate the number of drops in a cm<sup>3</sup>

1. Set up the reagent reservoir in the alignment adapter of the Drop / Bubble Counter. Close both stopcocks and fill the reservoir with the type of solution being used.
2. The first step is to adjust the flow rate. Place a beaker under the stopcock to catch the drops. Fully open the lower stopcock. Slowly turn the top stopcock round until it begins to produce drops and then finely adjust the drop rate. When the correct flow rate of drops is achieved close the lower stopcock to stop the flow. Now the 'flow rate' is set, do not adjust the top stopcock – leave in this position. Use the lower stopcock to turn the drops on and off.
3. Top up the reservoir. Place an accurate measuring container e.g. volumetric flask (10 mls or less) under the dropping tip. Open the lower stopcock fully and count the number of drops required to fill up to the volume mark on the measuring container. (You can use the Drop Counter to count the total number of drops by setting it to the Drop / Bubble count range - make sure you zero the Sensor before each run). Close the lower stopcock to stop the drops.
4. Divide the number of drops by the volume (in cm<sup>3</sup>) to get the drops per cm<sup>3</sup> value e.g. 272 drops fill a capacity of 10 mls = 27.2 drops/cm<sup>3</sup>. Top up the reservoir and repeat three times to get an average value.

## Results

The data will have been collected as a Volume and pH vs. time graph. When the Values tool is used to read pH or Volume values, the data from both the graph lines will appear in the data value boxes.

The determination of isoelectric point and  $\text{Pka}_2$  are relatively straightforward and take advantage of the advanced features of the software. The determination of the  $\text{Pka}_1$  value requires a little more work, and it is worth spending time to understand the process involved.

## Advanced

To find the isoelectric point of alanine use the maximum rate of pH change. The graph produced is known as the first derivative and is the method used in automated titrations to determine 'end points'. If the process is repeated a second derivative is created which increases the accuracy of finding the end point. The response time of the pH electrode is such that the second derivative should be regarded as an extension point in this investigation.

The **a dx/dt** function can be applied to the pH data to produce a first derivative curve.

From the Tools menu select Post-log Function. Choose either

- A) Preset function and select Titration, First derivative of pH, and select the pH sensor as the data channel
- B) Formula and select the function  $a \, dx/dt$ , select the pH channel as x.

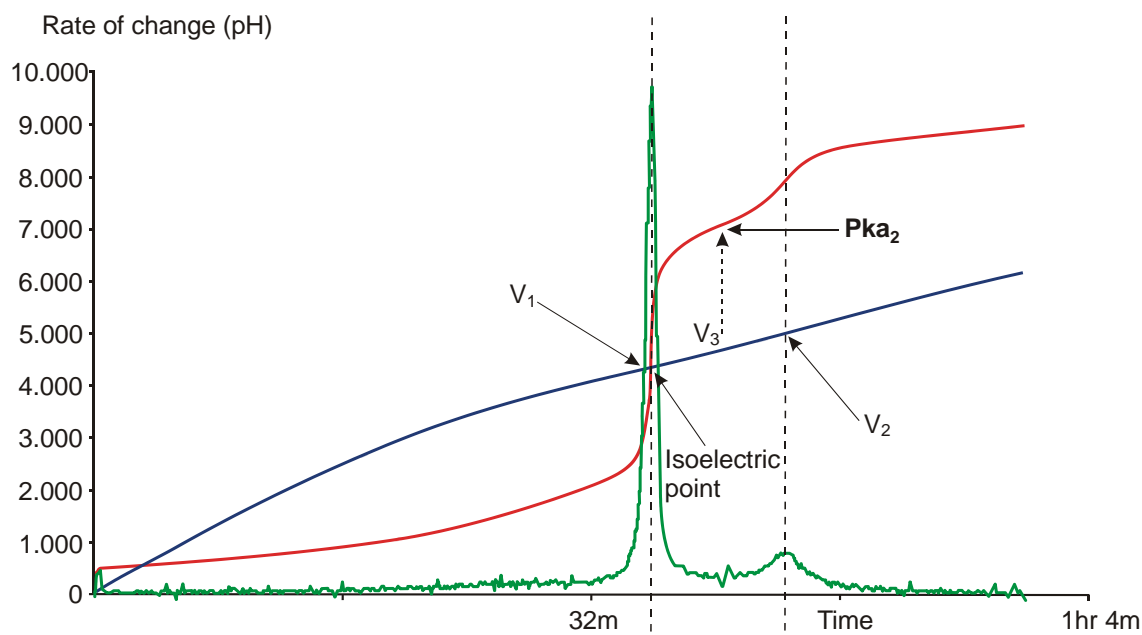
If the titration was of alkaline alanine to acidic alanine the value for  $a = -100$ , the falling rate of change will give a negative peak, using a negative sign converts the peak back to a positive value.

The value of  $a$  is set at 100 to make sure the peak on the new plot fits the same axis limits. If a value of 1 is used the sensor axis limits will need to be adjusted for the new rate of change plot.

The new plot should reveal 2 sharp peaks.

The first peak will indicate the isoelectric point of the alanine molecule. Click on Values and line the cursor to the first peak on the Rate of change of pH plot, read off the pH value and volume of titrate from the data value boxes, record the information. The pH value is the isoelectric point; the volume value is used to determine  $\text{Pka}_2$ . The method for determining the two  $\text{Pka}$  values is outlined in the student's notes.

The second peak will represent the point at which the alanine molecule became basic.



### Extension work

If you have not seen a titration of sodium hydroxide vs. hydrochloric acid, use 0.1 mol dm<sup>-3</sup> solutions of each to conduct a titration. Use at least 30 cm<sup>3</sup> in the beaker to ensure the tip of the pH electrode is covered.

Try a titration of other amino acids, dissolve the amino acid in water and acidify to pH 1 with hydrochloric acid (sample titration graphs and methods are available on the web, try searching for the “amino acid name” and titration).

## 13a. Titration of amino acid (alanine)

### Practical skills AT a, b, c, f, I

Amino acids, with certain exceptions, are soluble in water and insoluble in non-polar organic solvents such as ether, chloroform and propanol. This is not in keeping with known observations of the properties of carboxylic acids and organic amines. The solubility information on amino acids suggests structures which have charged highly polar structures.

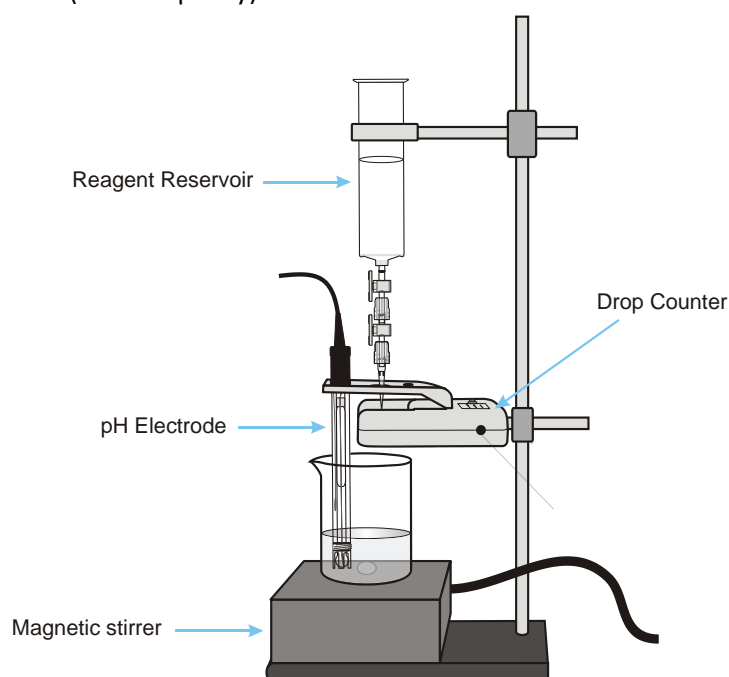
Amino acids contain both amino and carboxyl groups and should react with both acids and alkalis. Substances that react to both alkalis and acids are known as amphoteric substances.

In this investigation the amino acid alanine is used. Alanine when dissolved into water should give a solution with a neutral pH. The solution of alanine in water does not show migration of ions to electrodes if an electric current is passed through it. The same behaviour will also be shown if the molecule exists as the zwitterion, a condition in which a negative and positive charge exists at the same time.

In this investigation a solution of acidified alanine will have sodium hydroxide added to it to produce a titration curve.

### Apparatus

1. pH sensor
2. Drop / Bubble counter set to the correct volume range with alignment adapter fitted
3. The drop counter reagent reservoir fitted with two stopcocks and tip
4. 2 x 200 ml beakers
5. Magnetic stirrer and stir bar
6. 40 cm<sup>3</sup> of 0.1 mol dm<sup>-3</sup> Sodium hydroxide (NaOH)
7. 30 cm<sup>3</sup> of acidified Alanine solution, pH 1.0
8. Measuring cylinders (50 ml capacity)





## Method

1. Connect the Drop counter and the pH sensor to a data logger. Set up the apparatus as shown.
2. Fill the reagent reservoir with  $0.1 \text{ mol dm}^{-3}$  sodium hydroxide (NaOH). Open both stopcocks to allow a small amount of NaOH to pass through. Use the top stopcock to adjust the rate of flow e.g. to about 1 drop per second, leave in that position and close the lower stopcock. Pour the NaOH from the beaker back into the reagent reservoir.
3. Pour  $30 \text{ cm}^3$  of the acidified alanine solution into another beaker and place under the reservoir. Check that the alanine solution in the beaker covers the bulb end of the pH electrode. Add the magnetic stir bar to the beaker and turn on the stirrer. Check the stirrer is free to rotate and is rotating slowly and evenly.
4. Press the button on the Drop counter to set the counter to zero.
5. Set the recording to EasyLog.
6. The label at the top of the y-axis for the Drop counter will indicate which calibration range is currently selected e.g. 27 Volume for the 27drops/ $\text{cm}^3$  range. If this is not correct change the range of the sensor.
7. Click on Start and then open the lower stopcock to let the sodium hydroxide drip into the alanine. The LED on the Drop counter will blink as a drop passes through the infrared beam. Top up the reagent reservoir if necessary.
8. When you are satisfied that the titration is complete close the lower stopcock and click on the Stop icon to finish logging. Save the data.

## Results

The data will be displayed as a volume and pH vs. time graph. To alter the display to a pH vs. volume graph select Options, X-Axis and select Channel. If necessary click in the space outside the graph area to alter the data channel displayed so pH is on the y-axis (vertical) and Volume is on the x-axis (horizontal).

## Advanced

To find the isoelectric point of alanine point you will need to find the maximum rate of pH change.

The **a dx/dt** function can be applied to the pH data to produce a first derivative curve.

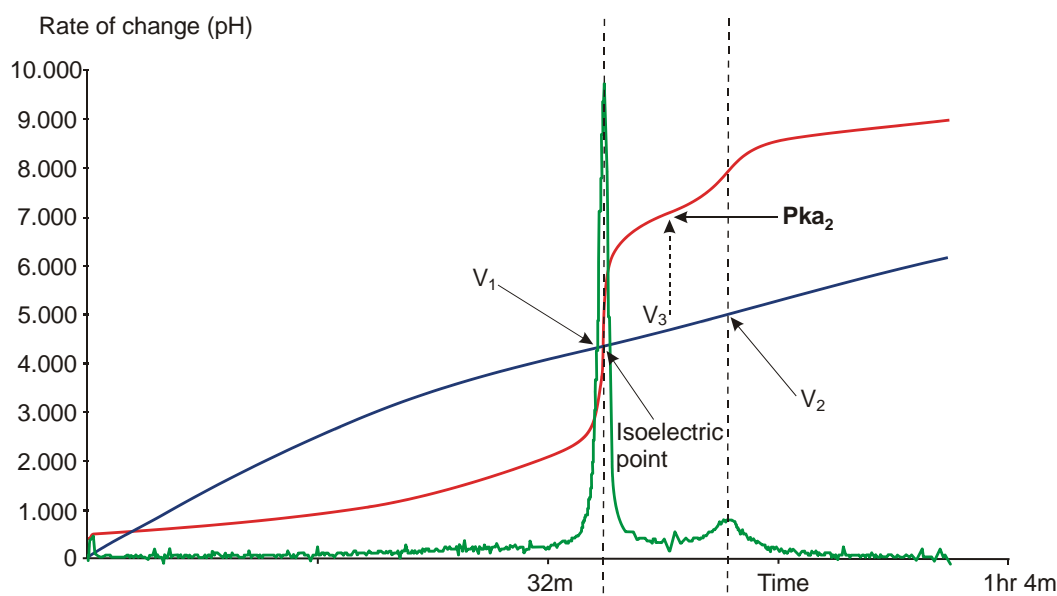
From the Tools menu select Post-log Function. Choose either

- C) Preset function and select Titration, First derivative of pH, and select the pH sensor as the data channel
- D) Formula and select the function  $\text{a dx/dt}$ , select the pH channel as x.

Display the data as a pH, Volume and rate of change vs. time graph. The rate of change trace should reveal 2 sharp peaks.

The first peak will indicate the isoelectric point of the alanine molecule. Use Values on the first peak of the 'rate of change' trace to find the pH value and volume of titrate at this point (**V<sub>1</sub>**) (the value will be displayed in the data boxes). The pH value is the isoelectric point; the volume value will be used to determine  $\text{Pka}_2$ . Make a note of both these values.

The second peak will represent the point at which the alanine molecule became basic. Use Values to find the volume of titrate (**V<sub>2</sub>**) used at this peak. Make a note of this value; it will be used to determine Pk<sub>a2</sub>.



There are 3 points of interest to determine:

1. The isoelectric point, revealed by the sudden change in pH, this is the first peak revealed by applying the first derivative (a  $dx/dt$ ).
2. As the solution becomes more alkali there is a second rapid change in pH. The halfway distance between this second change and the isoelectric point (first rapid change) ( $V_3$ ) determines Pk<sub>a2</sub>
3. The Pk<sub>a1</sub> of the solution. This point is more difficult to determine, see below for method.

#### To find the Pk<sub>a2</sub> value

Find the volume at the first peak ( $V_1$ ) (the isoelectric point) and the second peak ( $V_2$ ) (where the alanine became basic). To find the halfway difference add the two volumes and divide by 2 ( $(V_1 + V_2) \div 2 = V_3$ )

Use Values to place the cursor at the calculated volume point ( $V_3$ ) and read the pH at this point from the data box in the bar above the graph. This is the Pk<sub>a2</sub> value.

#### To find the Pk<sub>a1</sub> Value

The Pk<sub>a1</sub> value is the halfway point between the initial stable pH and the rapid change of pH as the isoelectric point is reached. It is not easily seen and the rate of change of pH that marks the Pk<sub>a1</sub> point is not sufficient for it to be revealed as first or second derivative. If you look carefully at the first part of the graph you will notice that at first the rate of change of pH with each addition of the sodium hydroxide is a linear and very slight. As the volume of sodium hydroxide increases the rate of change of pH also increases. What we are looking for is the point at which the slow change in pH becomes the faster change in pH. To find this you will need to print the graph.

1. Display Volume on the y-axis (vertical) and Time on the x-axis (horizontal).
2. Click on File and select Print Graph. If possible print onto graph paper with a printed grid in landscape mode.



**Extension work**

1. If you have not seen a titration of sodium hydroxide vs. hydrochloric acid, use  $0.1 \text{ mol dm}^{-3}$  solutions of each to conduct a titration. Use  $30 \text{ cm}^3$  of the solution in the beaker to ensure the pH electrode tip is covered.
2. Try a titration of other amino acids, dissolve the amino acid in water and acidify to pH 1 with hydrochloric acid.

## 13b. Titration of amino acid (alanine) using a burette

### Practical skills AT a, b, c, f, l

Amino acids, with certain exceptions, are soluble in water and insoluble in non-polar organic solvents such as ether, chloroform and propanol. This is not in keeping with known observations of the properties of carboxylic acids and organic amines. The solubility information on amino acids suggests structures which have charged highly polar structures.

Amino acids contain both amino and carboxyl groups and should react with both acids and alkalis. Substances that react to both alkalis and acids are known as amphoteric substances.

In this investigation the amino acid alanine is used.

Alanine when dissolved into water should give a solution with a neutral pH. The solution of alanine in water does not show migration of ions to electrodes if an electric current is passed through it. The same behaviour will also be shown if the molecule exists as the zwitterion, a condition in which a negative and positive charge exists at the same time.

In this investigation a solution of acidified alanine will have sodium hydroxide added to it to produce a titration curve.

### Apparatus

1. pH sensor
2. Conical flask
3. Stirrer
4. Retort stand and clamp
5. 2.5 ml pipettes or syringe
6. 100 ml beaker
7. 40 cm<sup>3</sup> of 0.1 mol dm<sup>-3</sup> Sodium hydroxide (NaOH)
8. 30 cm<sup>3</sup> of acidified Alanine solution, pH 1.0
9. Measuring cylinders (50 ml capacity)

Note: Solutions should all be at the same temperature.

### Risk assessment

Sodium hydroxide. Eye protection should be used. Corrosive, Irritant

### Method

1. Connect the pH sensor to the data logger. Set up the apparatus as shown.
2. Fill the burette with the sodium hydroxide and adjust level in the burette to zero.
3. Pour 30 cm<sup>3</sup> of the acidified alanine solution into another beaker and place under the reservoir. Check that the alanine solution in the beaker covers the bulb end of the pH electrode.
4. Set up the software:

Recording method	Display	Pre-log Function
SnapShot	Table and graph	Titration, Asks for the Volume added

5. Click on Start to begin logging.
6. Click in the graph area to record the pH value of the alkali solution in the flask. A prompt box will open and ask you for a value. Enter 0 (zero). This records the pH of the alkali before adding any acid (0 volume).
7. Using the burette add 1 cm<sup>3</sup> of sodium hydroxide into the flask. Gently stir the solution, wait 10 seconds and click in the graph area to record the new pH value. In the prompt box enter the volume of sodium hydroxide added as shown on the burette scale.
8. Repeat step 6, remember to enter the volume shown on the burette when prompted (not the volume you've just added).
9. Repeat until pH is at 10.0 or until the burette has run dry then select Stop.

## Results and analysis

You will have a graph of Volume of alkali added and the pH of the solution vs. Reading.

To plot volume against pH directly:

1. Save the data (in case you make a mistake and need to get back the original data).
2. Select Options. Select the X-Axis tab and click on the Channel button, then OK.
3. Alter the graph so the data is shown as pH on the y-axis (vertical axis) and Volume on the x-Axis (horizontal).

Add a Title to the graph and then Save the results.

Use Add Text to label the parts of the graph which show an acid solution, an alkaline solution and a neutral solution.

Calculate the pK<sub>a</sub>.

## Advanced analysis

### Using first and second derivative

If a first derivative function (a  $dx/dt$ ) is applied to the pH data you will get a "spike" when the rate of change in pH is greatest. The point of the derived spike is the "end point" of the reaction and gives a very accurate definition of the end point / point of neutralization.

Note: a  $dx/dt$  means the difference between points x1 and x2 divided by the change in time that separates x1 and x2. d is Delta, which in science indicates a change between two defined points / times. It is often written in texts as d to get round the need to insert  $\Delta$  as a symbol.

The a  $dx/dt$  function can be accessed by two routes,

1. As a Preset function: From the Tools menu select Post-log Function, Preset function, Titration, First derivative of pH.
2. As a Formula function: This does the same work as the First derivative of pH but shows the underlying maths in a more obvious manner. From the Tools menu select Post-log Function, Formula, a  $dx/dt$ .

Follow the wizard, you will need to indicate the channel that contained the pH data, the name of the new channel ( $\Delta$ pH) and give the axis limits

A multiplier is also asked for as the value 'a', if pH is falling a will equal '-1' (or bigger number) this will be needed to convert the values to a positive, and to make them large enough to be seen. The exact value of the multiplier will be subject to trial and error, it depends upon the strength of the reagents and the reaction. A useful starting value is -10 or +10.

## Teacher's notes

### 14. A Margaria Kalamen power test

#### Practical skills AT a, b, h, l

A different practical from the standard biology exercises.

The Margaria Kalamen power test is a classic test of power of the lower extremities. It is a simple test to conduct and set up. The test requires a straight flight of stairs with at least nine steps ideally leading onto a landing. Timing mode helps remove one of the variables in the test, the time from the first step to the last step.

Students start approximately 6 metres in front of the first step, they sprint up to the steps and up the flight 3 steps at a time (stepping on the 3<sup>rd</sup>, 6<sup>th</sup> and 9<sup>th</sup> steps). The time from the 3<sup>rd</sup> step to the 9<sup>th</sup> step is recorded with the time starting when the foot touches the 3<sup>rd</sup> step and stopping when the foot touches the 9<sup>th</sup> step.

3 trials should be allowed, with a resting period of 2 – 3 minutes between runs.

When using stop clocks and a staircase the position of the timers can prove to be intrusive if they stand on the steps, but if they stand away from the steps there can be errors in the observation of the step time.

The other problem is that times for the step are often below 0.5 of a second and start to blend with the reaction times of the timers and the mechanical errors of the stopwatches they are using.

The activity is included in biology as an exercise (model) in physiology and measurement of muscle power.

#### Apparatus

1. Pair of Timing mats
2. Sensor extension leads
3. Metal expanding rule
4. A straight staircase (at least 9 steps), more is better, avoid ending on a landing!
5. Steps 3, 6 and 9 clearly marked (the timing mats will usually identify steps 3 and 9)
6. Duct tape, masking tape or ties to secure the timing mats.
7. A set of metric weighing scales for body weight

#### Set up

This exercise is ideal for use with logger un-tethered to a computer, using the loggers display. If selecting on the logger,

- Select Timing from the Main menu
- Select Time from A to B from the Time menu.

If using a logger connected to a PC:

Recording method		
Timing	Time	From A to B



## Practical notes

You need a set of stairs that has clear run up to them.

Make sure the Timing mats are attached to the steps and do not move around. There will normally be rings in the corners of the Timing mat for attaching pull ties, string, etc. Duct tape around the edges works well but can leave a sticky residue.

Make sure the students have weighed themselves and they have measured the vertical height between the start and end Timing mat for calculations.

Make sure the start mat is connected to input A on the logger; this is the most common reason for lack of results.

Push button switches can be used in a similar manner to stopwatches; however reliability of the test is reduced if Timing mats are not used.

Using a PC to run the software and record the data will create a semi-permanent record of student's achievements, you will need to add the students name to identify the students or make an identification key.

Published versions of the test can also suggest three steps at time. Which you use will depend on the size of the flight of steps; stairs with turn at a half landing may not allow a 3-step test.

Practice time is necessary, you cannot expect the best data from a first experience; the process of sprinting upstairs in multiple step segments is not always intuitive. You may have to do a dry run on a prior occasion before collecting data.

## Analysis

The purpose of the test is to calculate the power developed by the student.

Power is energy expended per unit time (seconds) (watts).

Energy is the mass x distance x force. In this case, the mass is the students mass in kg, the distance is the vertical height travelled – the height of the stairs and the force is gravity.

The calculation can take several routes;

1. Power for each trial can be calculated.
2. Power for the average of the 3 trials can be calculated
3. Energy and power can be calculated separately.

The formula below is used, where P = Power (watts), M = Body mass (kg), D = Vertical distance, between steps 3 & 9 (meters), t = Time (seconds). 9.8 is the constant of gravity:

$$P = ((M \times D) \times 9.8) / t$$

Energy (joules) = Mass x Distance x 9.8

## 14. A Margaria Kalamen power test

### Practical skills AT a, b, h, l

The Margaria Kalamen power test is a classic test of power of the lower extremities. It is a simple test to conduct and set up. The test requires a straight flight of stairs with at least nine steps ideally leading onto a landing. You sprint to the stairs and power up them, landing on step 3, which has the timing mat on it, to start the clock and landing on the 9th step to stop the clock.

The time is used with your weight and vertical distance climbed to create a score in watts.

### Apparatus

1. Pair of Timing mats
2. Sensor extension leads
3. Metal expanding rule
4. A straight staircase (at least 9 steps) more is better, avoid ending on a landing!
5. Steps 3, 6 and 9 clearly marked (the timing mats will usually identify steps 3 and 9)
6. Duct tape, masking tape or ties to secure the Timing mats.
7. A set of metric weighing scales for body weight

### Set up

This exercise is ideal for use with logger un-tethered to a computer, using the loggers display. If selecting on the logger,

- Select Timing from the Main menu
- Select Time from A to B from the Time menu.

If using a logger connected to a PC:

Recording method		
Timing	Time	From A to B

### Method

Practice time is necessary, you cannot expect the best data from a first experience; the process of sprinting upstairs in multiple step segments is not always intuitive. You may have to do a dry run on a prior occasion before collecting data.

You need a set of stairs that has clear run up to them, and space beyond the test to slow down.

Make sure the Timing mats are attached firmly to step 3 and 9 and will not move around.

You need to have weighed yourself (in kg) and measure the vertical height between the start and end Timing mat for calculations.

Make sure the start mat on the lower step is connected to input A on the logger, and the end mat is connected to input B on the logger.

1. Set the logger or software to Time from A to B and click on Start.

2. Sprint towards the steps and land on the 3<sup>rd</sup> step to start timing, then to the 6<sup>th</sup> step followed by the final 9<sup>th</sup> step which will stop the timing.
3. Record the time against the individual.
4. Allow 2- 3 minutes between repeats.

## Analysis

The purpose of the test is to calculate the Power developed as a score.

Power is energy expended per unit time (seconds) and is measured in watts (W).

Energy is the mass x distance x force.

In this case,

- The mass is your mass in kg
- The distance is the vertical height travelled – the height of the stairs in metres
- The force is gravity, 9.81 m/s/s

The calculation can take several routes;

1. Power for each trial can be calculated.
2. Power for the average of the 3 trials can be calculated
3. Energy and power can be calculated separately.

The formula below is used, where P = Power (watts), M = Body mass (kg), D = Vertical distance, between steps 3 and 9 (meters), t = Time (seconds), 9.8 is the constant of gravity:

$$P = ((M \times D) \times 9.8) / t$$

Enter your collected data into the formula and calculate your power scale

## Teacher's notes

### 15 (a – d). Photosynthesis and CO<sub>2</sub>

#### Practical skills AT a, b, h, l

A modern alternative to study photosynthesis. This sheet covers the basics of setting up and working with the Carbon dioxide sensor. Specific worksheets give examples of how to use the sensor to study the effect of light intensity on rate of photosynthesis.

In photosynthesis carbon dioxide is used by chlorophyll containing areas of a plant to make basic metabolic sugars.

A modern Carbon dioxide sensor is sufficiently sensitive to measure the changes in carbon dioxide concentration around photosynthesising plant materials.

The basic idea of the practical is to create a small “vivarium” with some leaves in it, load the atmosphere around the leaves with carbon dioxide and then measure the rate of disappearance of the carbon dioxide.

The assumption being made is that carbon dioxide changes measured by the sensor are due to the leaves respiring or photosynthesising.

Changes in CO<sub>2</sub> are nett changes, i.e. they represent the combined CO<sub>2</sub> produced from respiration and the consumption by photosynthesis.

#### Practical notes

Is the change in carbon dioxide due to the plant or...?

It is understood that carbon dioxide is a gas denser than standard atmospheric air. It is not unreasonable to expect the CO<sub>2</sub> to settle to the base of the vivarium. We could place a stir fan into the apparatus, but the reality is that time and the need for a simple student friendly apparatus work against us. We do need to quantify the rate of settling, leaking from and within the apparatus of the CO<sub>2</sub>.

The change in CO<sub>2</sub> levels within the apparatus was tested with:

1. Sensor at the top
2. Sensor inverted with sensor at base
3. Sensor at top with light on (do heat thermals create mixing?)
4. Sealing the sensor in place with Blu-Tack

Data was recorded for at least 20 minutes. In all cases CO<sub>2</sub> was introduced into the beaker from a generator and recording was started once the level of CO<sub>2</sub> had entered the range of the sensor.

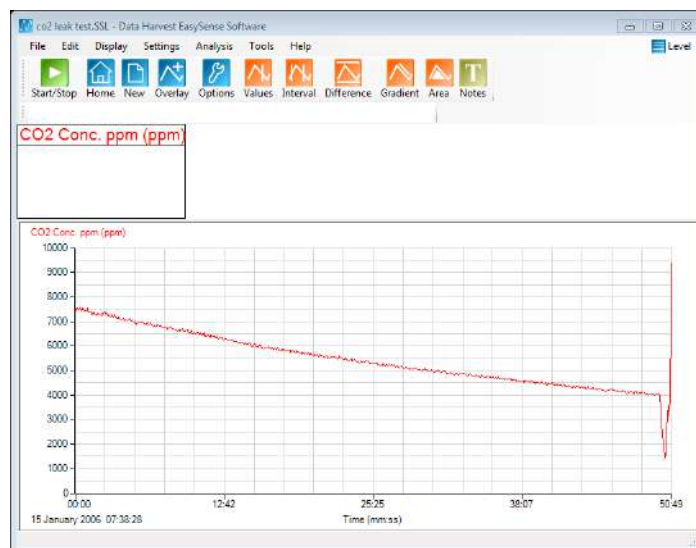


Fig 15.1. Change in CO<sub>2</sub> levels with sensor at top of apparatus (-1.11 ppms-1)

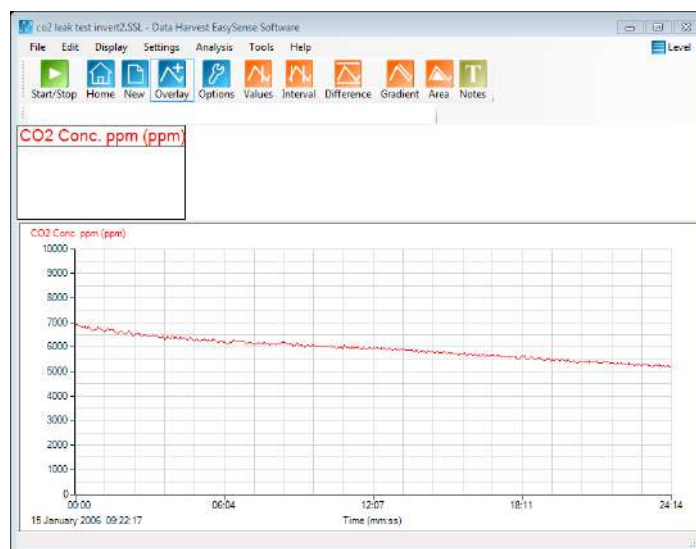


Fig 15.2 Change in CO<sub>2</sub> levels with sensor in base of apparatus (-0.931 ppms-1)

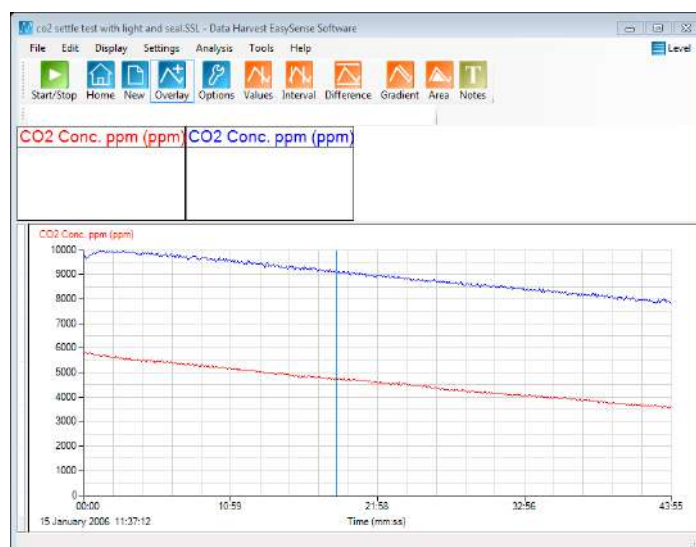


Fig 15.3 Leak test with sensor at top of apparatus, red graph with light shining on apparatus (-0.76ppms-1), blue graph with additional sealing around apparatus (-0.86 ppms-1).

The graphs tend to show that there is a slow decrease in measured CO<sub>2</sub> regardless of the apparatus setup. No doubt with care you could quantify the effect. There is limited evidence that CO<sub>2</sub> does pool to the base of the apparatus and that heating does create some mixing effect through the changed rate of CO<sub>2</sub> decrease. What is perhaps, more important is that the change in CO<sub>2</sub> in the control apparatus represents a constant and can be 'neutralised' out of the final results once a control rate of decrease has been found. The extent of how the control change is dealt with will depend upon the level of the practical and/or the time available to create the control levels. Suffice to say there is a downward change in CO<sub>2</sub> levels that should be commented upon.

### **How do I control the CO<sub>2</sub> introduced into the apparatus?**

It was found that gently exhaling into the apparatus was sufficient to raise the CO<sub>2</sub> levels to above the limit of the sensor. It was also relatively simple to tip the apparatus and pour out the excess CO<sub>2</sub> using the sensor as a meter to get a level that was close to a standard i.e. between 8,000 ppm and 9,000 ppm.

If you have a source of CO<sub>2</sub> from a limestone generator you could use a syringe to introduce a measured volume. Check the apparatus first to find the background level and then add a cm<sup>3</sup> at a time to bring the level to the desired value. In theory with experience of the apparatus and the generator this could provide a qualitative method of adding and creating different CO<sub>2</sub> atmospheres when investigating the role of CO<sub>2</sub> as a limiting factor.

What was found equally effective was to place the leaves in 'darkness' and allow respiration to fill the apparatus with CO<sub>2</sub> up to a pre-decided level.

Alternatively, raise the CO<sub>2</sub> and illuminate the plant, use Test Mode in the software to monitor the CO<sub>2</sub> levels and start recording when the CO<sub>2</sub> reaches a standard level e.g. 4,000 ppm (you could use a software trigger). This takes a little more time but ultimately was a simpler method of control, it also let the leaves reach a stable rate of photosynthetic activity for the level of illumination

### **What plant material should I use?**

There are several clones to this practical that exist, SSERC have published a short paper on this as a class practical, and the suggested leaves are spinach leaves. Spinach leaves are cheap to buy and seem to be good photo synthesisers in the intensity of light from a standard incandescent lamp. SSERC also suggest basil leaves, no doubt due to the availability of pot basil plants through the year in most local supermarkets.

One wonders if you get a good reliable standard protocol working if you could make a comparison of leaves from different plants e.g. beech, vs. red beech or dogs mercury (shade plant) vs. dock leaves, etc. Initially use baby spinach leaves, they seem to work reliably.

## Sample data

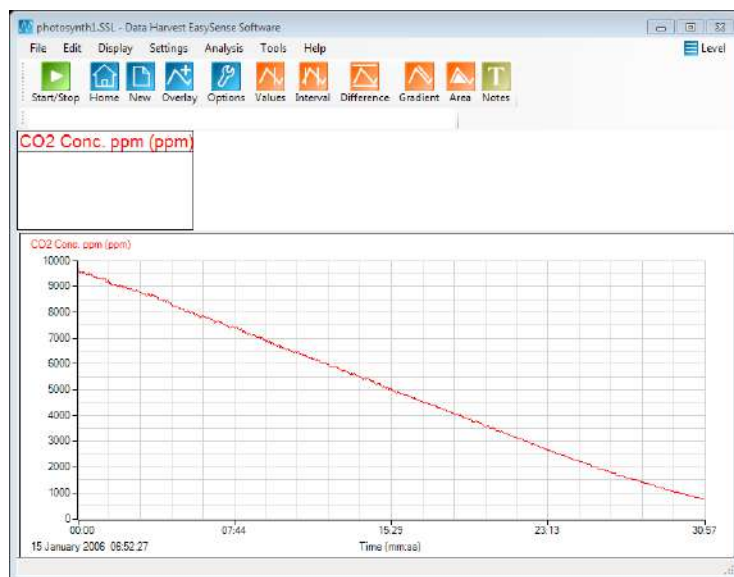


Fig 15.4 Simple test of spinach leaves in the apparatus, light shining on the leaves and left to run. Rate of loss of CO<sub>2</sub> is -5.0 ppms<sup>-1</sup>, considerably greater than change due to leaks and settling.

### Gradient of the graph can be worked out by

1. Simple (max-min) ÷ time interval in seconds
2. Using the Best fit line function in the software

If the recording is left long enough the drop in CO<sub>2</sub> for a given light intensity will eventually show a slowdown, this is a result of the CO<sub>2</sub> being used up and the remaining CO<sub>2</sub> becoming the rate limiting factor.

## Teacher's notes

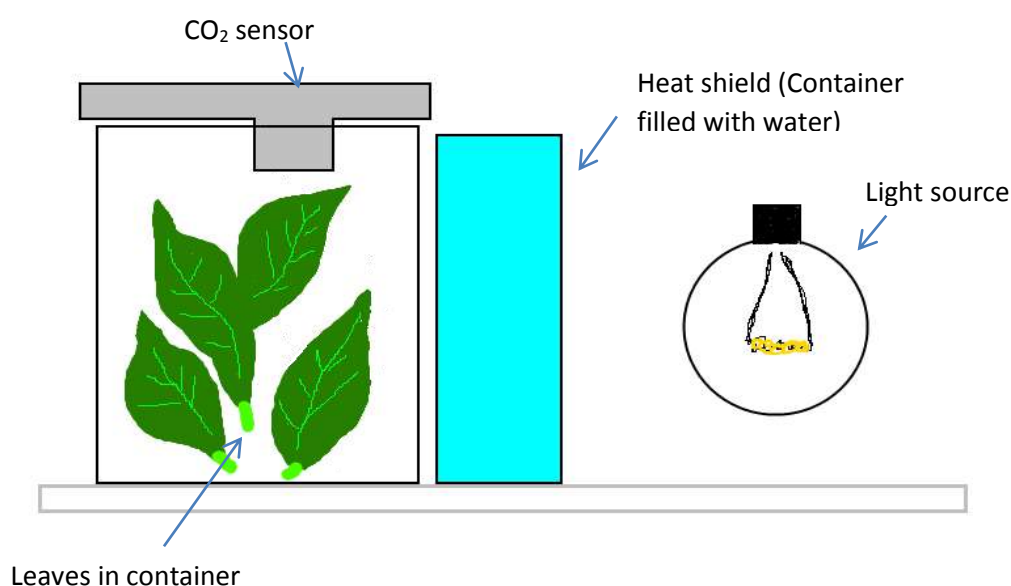
### 15a. Effect of CO<sub>2</sub> on the rate of photosynthesis

#### Practical skills AT a, b, h, l

This activity is to look at the effect of CO<sub>2</sub> levels on the rate of photosynthesis.

For advice on the apparatus, refer to the separate 15a – d teacher's notes on Photosynthesis and the CO<sub>2</sub> sensor.

The idea is to set the light source at a set distance from the leaves. Protect the leaves from the heating effect of the light by filtering out the infrared with water. Different quantities of CO<sub>2</sub> can be introduced around the leaves and the rate of CO<sub>2</sub> reduction recorded as a measure of photosynthetic activity.



Typical apparatus layout



Fig 15a.1 Photograph of typical bench layout of apparatus, the light source would normally be a bench lamp. Note the position of the optional Light sensor.



## Apparatus

1. Carbon dioxide sensor set to 0 -10,000 ppm range
2. Two matching transparent, colourless glass containers
3. Light source with photosynthetically active light output e.g. tungsten filament lamp
4. Small leaf spinach
5. Metal foil (to help reflect light to apparatus)
6. Dark cloth (to cover apparatus between runs)

## Set up

Recording method	Recording time	Intersample time
Graph	5 minutes	2 s

## Practical notes

Small leaf spinach was used as it allows the leafy material to be placed into the apparatus without creating too much damage to the leaf blade. Other versions of this practical have suggested basil leaves.

At least one of the containers should be flat / square faced e.g. a small brandy, whisky bottle or flat culture bottle. The reason for the flatness is that this vessel is used to absorb the heat from the lamp and will be placed between the container with the leaves in it and the lamp. If this heat shield container is round it will act as a lens and concentrate the light in a non-consistent way (the focus will be a result of the curvature of the container and the distance of the lamp to apparatus).

LED lights and fluorescents (except gro-lux) do not give an even spectral curve, having several peaks that are perceived by our vision as white. The peaks produced by these light sources are not in the region of wavelengths that chlorophyll can use.

You can use the non-illuminated periods to build up the CO<sub>2</sub> in the apparatus.

Equally you can exhale gently into the apparatus; this will initially go beyond the range of the sensor but with the light turned on the level of CO<sub>2</sub> can be expected to fall quickly. You would then start the data collection once the level had reached a predetermined point e.g. 8,000, 7,000, 6,000 ppm.

As you are using two factors that are known to be rate limiting you may find it difficult to control the relationship between the variables, at least to the point of seeing a fall in the increase of rate with CO<sub>2</sub>.

There is a temptation to change the range of the CO<sub>2</sub> sensor to its higher range. This is not advised as the sensitivity of the sensor is non-linear, while values can be adequate for simple comparison they are unlikely to be up to detailed analysis.

## Treatment of data

You will want to present the data as starting CO<sub>2</sub> level vs. photosynthetic rate. You are hoping to see that the rate of photosynthesis rises with an increase in CO<sub>2</sub> but that there reaches a point at which the increase in CO<sub>2</sub> does not give a linear increase in activity, i.e. something other than light is controlling the rate of photosynthesis.

There are several ways the data can be extracted.

### Extracting data using the statistics tool

1. Select the Show statistics option from the Analysis menu.
2. This will show the maximum and minimum of the data set and the average.
3. For Light intensity record the Average.
4. For Rate of photosynthesis take the max and minimum values, subtract from each other and divide by the time interval in seconds (simple gradient).
5. To change which statistics are shown click in the left of graph margin, the statistics shown are for the data set indicated at the top of the y axis.
6. You will need a table to record results into.

### Using the Best fit line

1. From the Tools menu select Best Fit.
2. In the Add line of best fit box select Manual (freehand) and OK.
3. Click on the screen to start the line and draw it out using the mouse. Click again to fix the line on the graph.
4. Use the mouse to grab and drag the end of the line onto the data line to fine tune the fit. The gradient data will appear in the form  $y=mx+c$ , the gradient is the "m".
5. Use the Show or Hide option to reveal the next data set and move the best fit line over the new data. This is a shortcut method that prevents the need to constantly reselect the data set to be used.

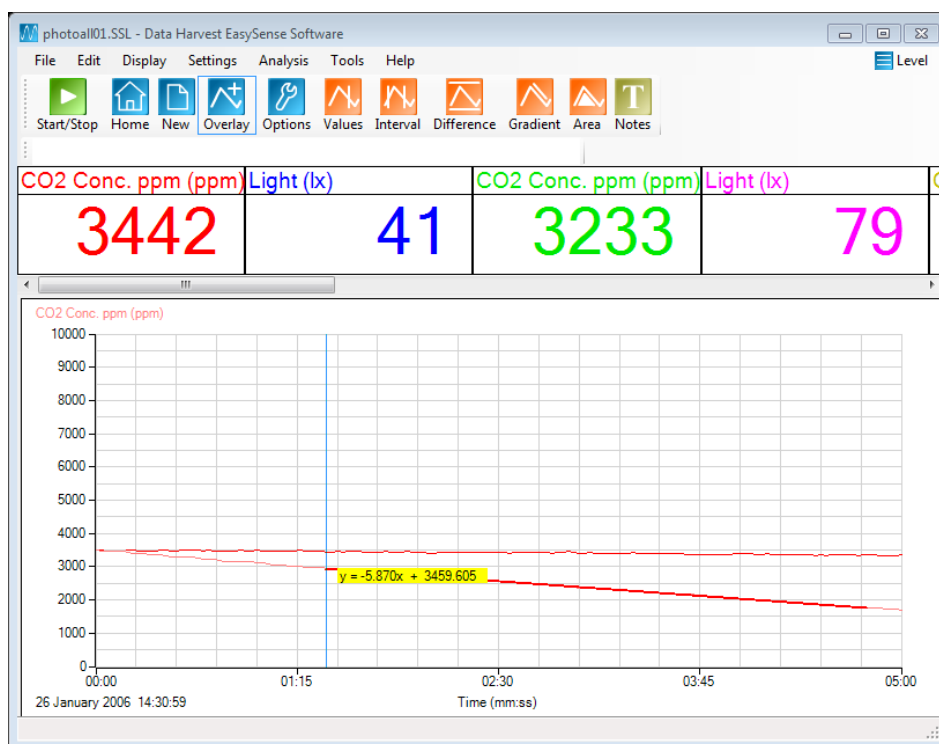


Fig 15a. 2 Using the best fit line to extract rate data from a single shown data set.

Using the best fit line method give greater control over the data used, you do need a linear decrease section of data. Sometimes due to the latency in photosynthesis getting up to a standard rate the initial data can be flat. Taking a simple max – minimum divided by time gradient will not give the true working rate.

Data Harvest acknowledges the work carried out by SSERC in the development of this as a viable school practical. Reference: SSERC Bulletin No 248 Autumn 2014 Limiting factors in photosynthesis – carbon dioxide.

## 15a. Effect of CO<sub>2</sub> on the rate of photosynthesis

### Practical skills AT a, b, h, i.

This activity is to look at the effect of CO<sub>2</sub> on the rate of photosynthesis.

The light stays at a fixed location in this practical. Its position should be close enough to give a good rate of photosynthesis, but not so close that the plant material is over illuminated or could be damaged by heat from the lamp (even with a heat shield present). The analysis of the data should allow you to see the effect of the CO<sub>2</sub> level in the apparatus acting as a rate limiting factor.

Set up the apparatus as shown, use containers that let the CO<sub>2</sub> sensor cover the opening to the leaf chamber. If the chamber is larger than the diameter of the sensor cover the opening of the chamber with cling film (or cooking foil) to create a better gas tight seal, push the snout of the sensor through the film (foil).

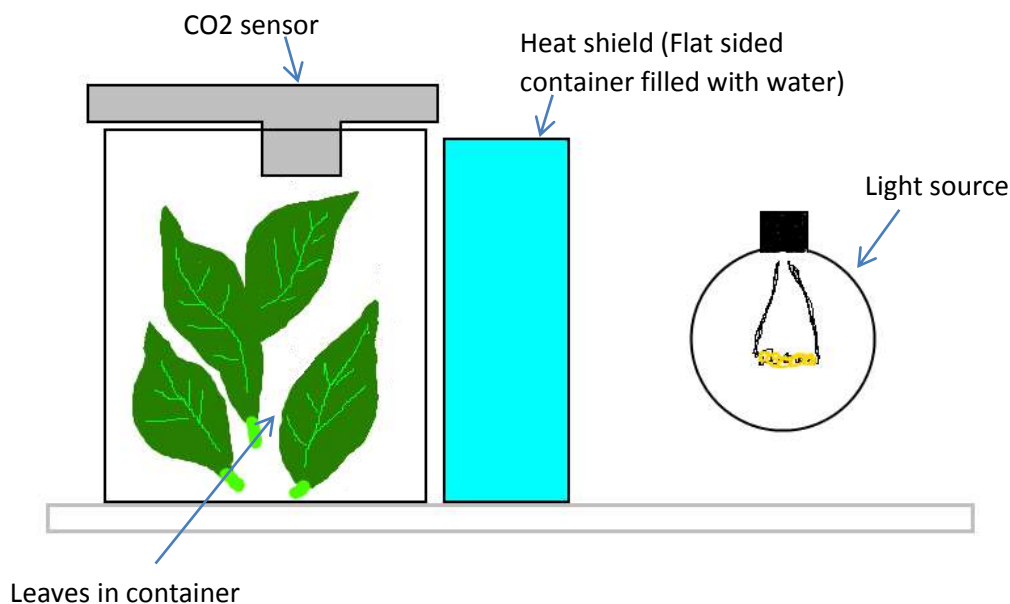


Fig 15a.1 Photograph of typical bench layout of apparatus, the light source would normally be bench lamp. Note the position of the optional Light sensor.

## Apparatus

1. Carbon dioxide sensor set to the 0 -10,000 range
2. Two matching transparent, colourless glass containers
3. Light source with photosynthetically active light output e.g. tungsten filament lamp
4. Small leaf spinach
5. Metal foil (to help reflect light to apparatus)
6. Dark cloth (to cover apparatus between runs) (optional)

## Method

1. Set up the apparatus as shown. Don't over pack the leaves but make sure the apparatus looks full.
2. Set to record for 5 minutes with at least 2 seconds between samples. Select Overlay to collect all runs on one large data set.

Recording method	Recording time	Intersample time	Overlay
Graph	5 minutes	2 seconds	On

3. Select Test Mode (Tools menu) to monitor the CO<sub>2</sub> levels.
4. Get the CO<sub>2</sub> in the leaf chamber to approx. 4,000 ppm – you may find that simply leaving the apparatus in the dark will be enough for respiration of the leaves to raise the level. If this looks unlikely, exhale slightly into the apparatus and watch the CO<sub>2</sub> levels. Turn on the light and let photosynthesis remove the CO<sub>2</sub> to a predetermined level.
5. When the CO<sub>2</sub> in the apparatus gives a reading of 4,000 ppm click on Start.
6. At the end of the recording save the data as Run1 (or similar).
7. Change the CO<sub>2</sub> level around the leaves by either breathing into the chamber or by letting photosynthesis remove CO<sub>2</sub> down to the next chosen level.
8. Try to collect 6 sets of data with at least 2 sets at the very high CO<sub>2</sub> level end, this may involve working from highest light to lowest\*.
9. Remember to save the data after each run.

\*if you work from high to low you can simply select Start again as soon as each run has finished, the CO<sub>2</sub> will constantly be falling and giving a new low start point for the next run.

## Treatment of data

You will want to present the data as Starting CO<sub>2</sub> level vs. photosynthetic rate.

Extracting data using the statistics tool:

1. Use the Show Statistics (Analysis) option. This will show the maximum and minimum of the data set and the average.
  - a. For Light intensity record the Average.
  - b. For Rate of photosynthesis calculate the simple gradient.
2. To change which statistics are shown click to the left of the graph margin, the statistics shown are for the data set indicated at the top of the y axis.

Using the best fit line

1. Select Best Fit (Tools).
2. In the Add line of best fit box select Manual (freehand) and OK.
3. Click on the screen to start the line and draw it out using the mouse. Click again to fix the line on the graph.
4. Use the mouse to grab and drag the ends of the line onto the data line to fine tune the fit. The gradient data will appear in the form  $y=mx+c$ .
5. Use the Show or Hide option to reveal the next data set and move the best fit line over the new data. This is a shortcut method that prevents the need to constantly reselect the data set to be used.

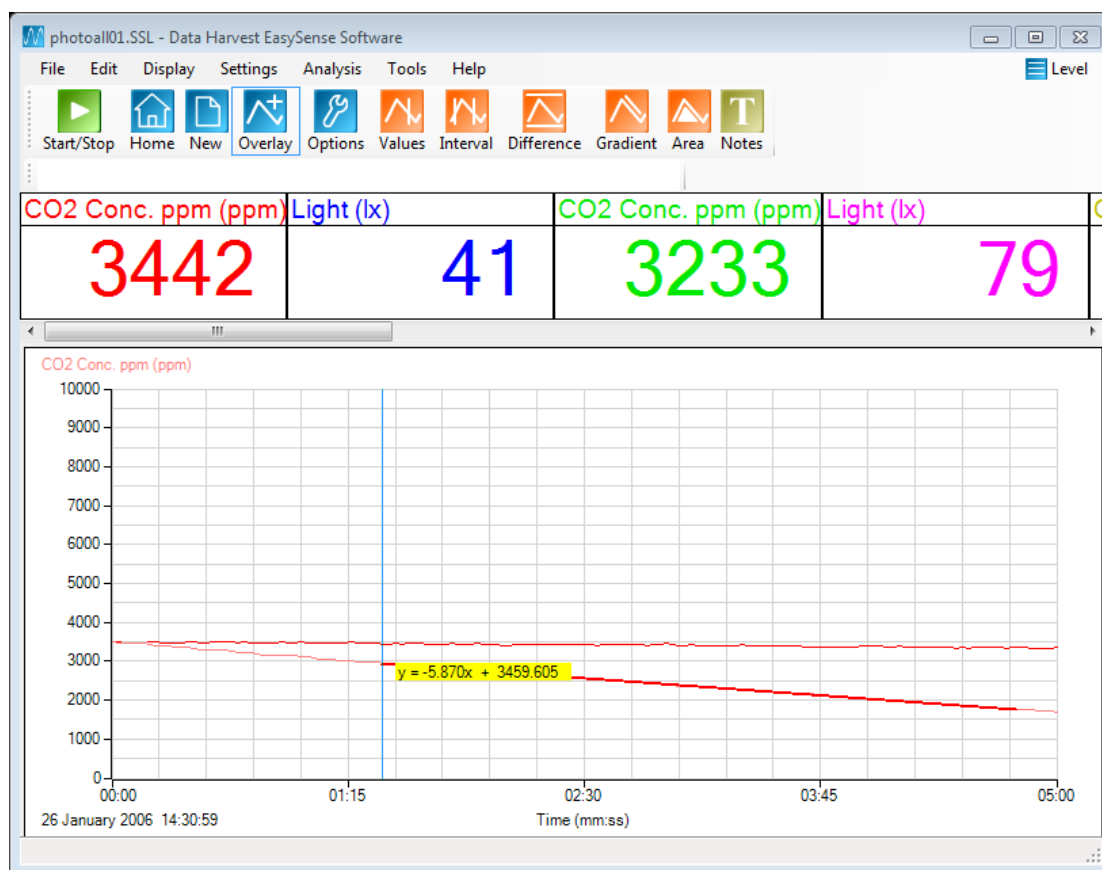


Fig 15a.1 Using the best fit line to extract rate data from a single shown data set

Data Harvest acknowledges the work carried out by SSERC in the development of this as a viable school practical.

Reference: SSERC Bulletin No 248 Autumn 2014 Limiting factors in photosynthesis – carbon dioxide.

## Teacher's notes

### 15b. Effect of colour of light on the rate of photosynthesis

#### Practical skills AT a, b, h, l

This activity is to look at the effect of the colour of the light on the rate of photosynthesis. For advice on the apparatus, refer to the separate teacher's notes 15a-d Photosynthesis and CO<sub>2</sub>.

The light remains at a fixed distance from the apparatus. Colour filters can be inserted between the heat shield and the leaf chamber to ensure consistency of placement.

There is one problem with the practical as it stands, the colour filters have different transmission profiles. The intensity of light may change with the filter, and as the data is collected you have no way of identifying if the effect seen is due to changes in light intensity or colour. The problem is further compounded in that the Light level sensor records in lux, which means its response curve has been modified to match our visual perception of light with an enhancement to red light over blue. You will find that this is a problem of many Light sensors either by design or due to the chemistry of the sensing element. There is a reason why light detectors in high end physics work are significantly expensive.

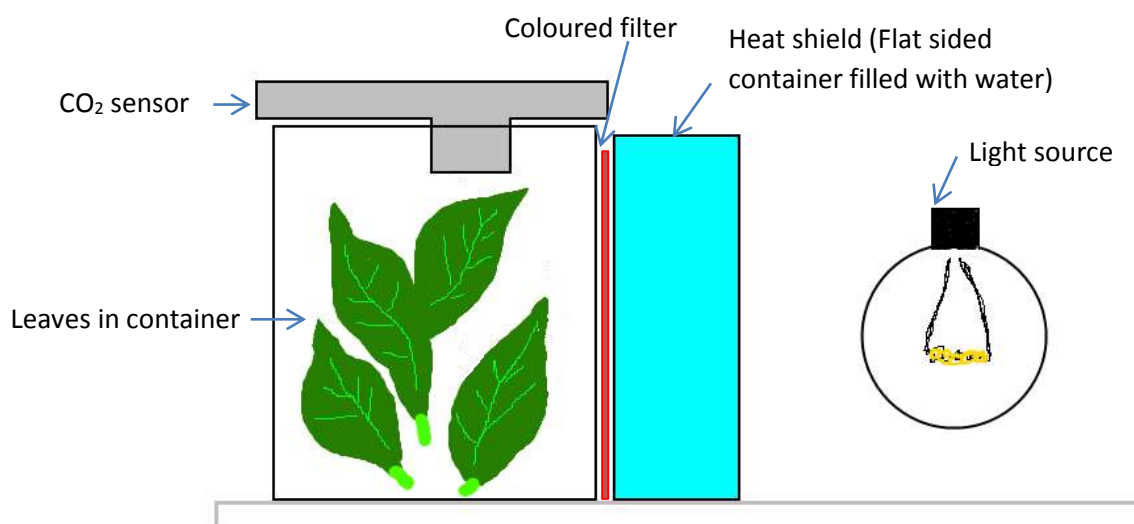


Fig 15b.1 Photograph of typical bench layout of apparatus, the light source would normally be a bench lamp. Note the position of the optional Light sensor.

## Apparatus

1. Carbon dioxide sensor set to 0 -10,000 ppm range
2. A Light level sensor 0 - 1 k lux range (slow). (This may have to be changed according to light and size of containers)
3. Two matching transparent, colourless glass containers
4. Light source with photosynthetically active light output e.g. tungsten filament lamp
5. Small leaf spinach
6. Coloured filter (e.g. Lee Theatre filters)
7. Metal foil (to help reflect light to apparatus)
8. Dark cloth (to cover apparatus between runs)

## Set up

Recording method	Recording time	Intersample time
Graph	5 minutes	2 s

## Practical notes

Small leaf spinach was used as it allows the leafy material to be placed into the apparatus without creating too much damage to the leaf blade. Other versions of this practical have suggested basil leaves.

At least one of the containers should be flat / square faced e.g. a small brandy or whisky bottle. The reason for the flatness is that this vessel is used to absorb the heat from the lamp and will be placed between the container with the leaves in it and the lamp. If this heat shield container is round it will act as a lens and concentrate the light in a non-consistent way (the focus will be a result of the curvature of the container and the distance of the lamp to apparatus).

LED lights and fluorescents (except gro-lux) do not give an even spectral curve, having several peaks that are perceived by our vision as white. The peaks produced by these light sources are not in the region of wavelengths that chlorophyll can use. However you can get clusters of LEDs in one colour which could present a way of providing a coloured and uniformly intense light.

You can use the non-illuminated periods to build up the CO<sub>2</sub> in the apparatus.

## Treatment of data

You will want to present the data as light colour vs. photosynthetic rate. You are hoping to see that photosynthesis changes with light colour, as the action spectra diagrams of photosynthesis indicate.

There are several ways the data can be extracted.

### Extracting data using the statistics tool

1. Use the Show Statistics (Analysis menu) option. Use data to create gradient / rate value.
2. To change which statistics are shown click in the margin to the left of the graph, the statistics shown are for the data set indicated at the top of the y axis.

### Using the Best fit line

1. Use the Best fit line (linear) (Tools menu). To produce a best fit line it is best to only have the data you are working with on screen.

2. Select Best fit, select Manual (freehand) and OK.
3. Click on the screen to start the line and draw it out using the mouse. Click again to fix the line on the graph.
4. Use the mouse to grab and drag either end of the line onto the data to refine the position of the best fit. The gradient data will appear in the form  $y=mx+c$ , the gradient is the “m”.
5. Use the Show or Hide option to reveal the next data set and move the best fit line over the new data. This is a shortcut method that prevents the need to constantly reselect the data set to be used.

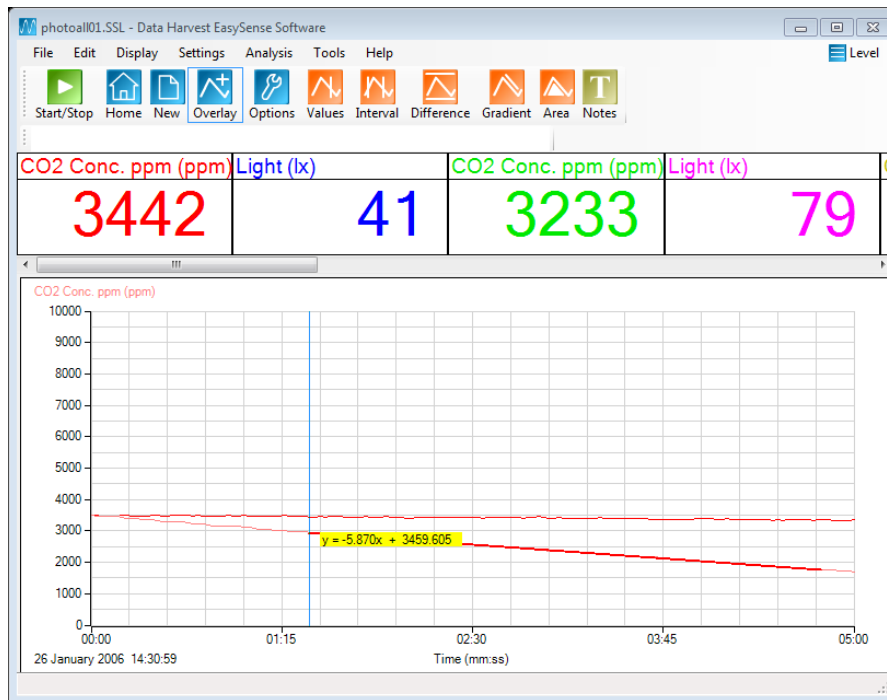


Fig 15b.2 Using the best fit line to extract rate data from a single shown data set.

Data Harvest acknowledges the work carried out by SSERC in the development of this as a viable school practical.

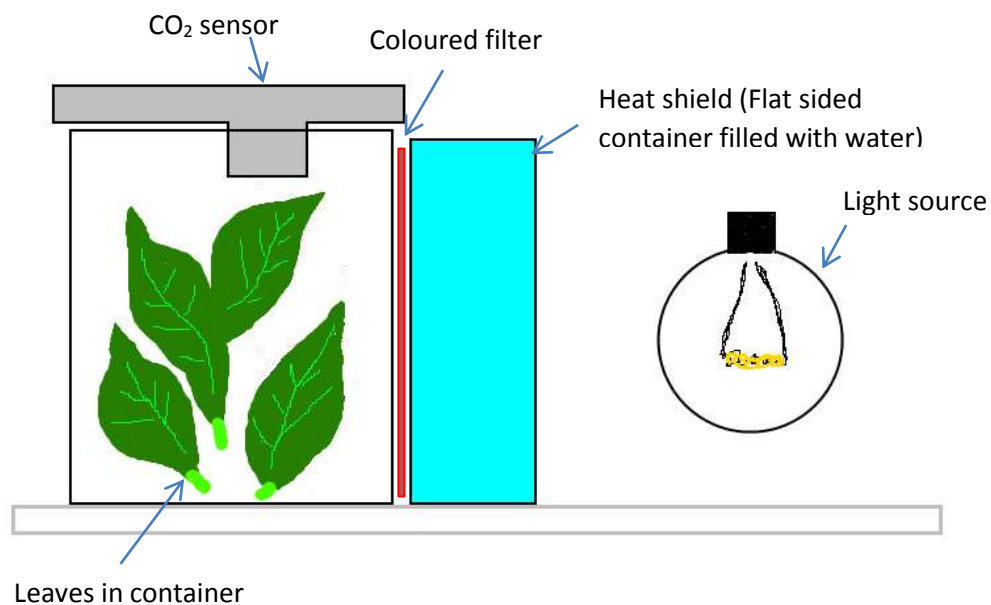
Reference: SSERC Bulletin No 248 Autumn 2014 Limiting factors in photosynthesis – carbon dioxide.



## 15b. Effect of colour of light on the rate of photosynthesis

### Practical skills AT a, b, h, I

This activity is to look at the effect of colour on the rate of photosynthesis.



Typical apparatus layout



Fig 15b.1 Photograph of typical bench layout of apparatus

### Apparatus

1. Carbon dioxide sensor set to 0 -10,000 ppm range
2. Two matching transparent, colourless glass containers
3. Light source with photosynthetically active light output e.g. tungsten filament lamp
4. Small leaf spinach

5. Metal foil (to help reflect light to apparatus)
6. Coloured filters
7. Dark cloth (to cover apparatus between runs) (optional)

## Method

1. Set up the apparatus as shown. Don't over pack the leaves but make sure the apparatus looks full.
2. Set the software to record for 5 minutes with at least 2 seconds between samples. Select Overlay to collect all runs in one large data set.

Recording method	Time	Intersample	Overlay
Graph	5 minutes	2 s	On

3. Place a sheet of coloured filter between the heat shield and the leaf chamber; use the heat shield to trap the filter in place.
4. Use Test Mode (Tools) to monitor the CO<sub>2</sub> levels.
5. Get the CO<sub>2</sub> in the leaf chamber to approx. 4,000 ppm – you may find that simply leaving the apparatus in the dark will be enough for respiration of the leaves to raise the level. If this looks unlikely, exhale slightly into the apparatus and watch the CO<sub>2</sub> levels. Turn on the light and let photosynthesis remove the CO<sub>2</sub> to the predetermined level.
6. When the CO<sub>2</sub> in the apparatus gives a reading of 4,000 ppm click on Start and record for the 5 minutes.
7. At the end of the recording save the data as Run1 (or similar).
8. Change the colour filter and repeat. Keep the starting CO<sub>2</sub> and light intensity the same.
9. Remember to save the data after each run.

## Treatment of data

You will need results showing light colour and a rate of photosynthesis value.

Compare your data to diagrams for action spectra for chlorophyll. How well does your data from the practical support the text book explanation?

## Teacher's notes

### 15c. Effect of light intensity on the rate of photosynthesis

#### Practical skills AT a, b, h, I

This activity is to look at the effect of light on the rate of photosynthesis. For advice on the apparatus, refer to the separate teacher's notes 15a-d Photosynthesis and CO<sub>2</sub>.

The Light level sensor is used to determine the value of the light from a fixed position to the apparatus. Using a Light sensor to record the light present takes away the uncertainty in using the change of distance as a measure of a fall in light intensity. Light will respond to the inverse square law, so halving the distance from light to apparatus does not simply double the light intensity. The Light sensor allows you to predetermine the variable of light intensity and create a suitable protocol for changing it relative to the apparatus. In the sample data included in these notes the light changed by 40 lx on each run.

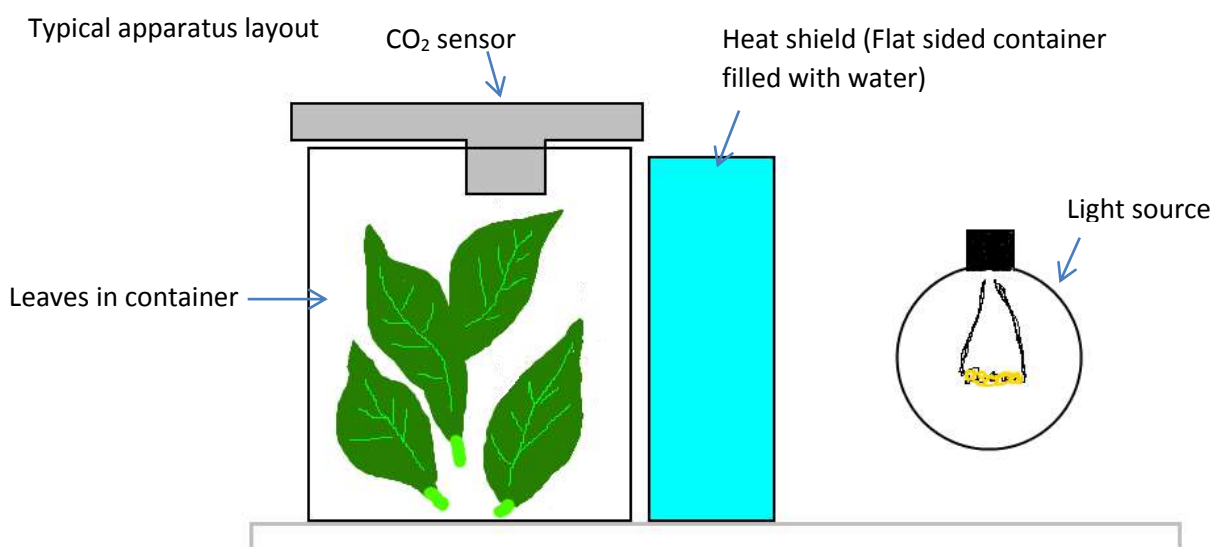


Fig 15c.1 Photograph of typical bench layout of apparatus, the light source would normally be bench lamp.  
Note the position of the Light level sensor

## Apparatus

1. Carbon dioxide sensor set to 0 – 10,000 lx range
2. Light level sensor 1 k Lx (slow) range (this may have to be changed according to light and size of containers)
3. Two matching transparent, colourless glass containers
4. Light source with photosynthetically active light output e.g. tungsten filament lamp
5. Small leaf spinach
6. Metal foil (to help reflect light to apparatus)
7. Dark cloth (to cover apparatus between runs)

## Set up

Recording method	Recording time	Intersample time
Graph	5 minutes	2 seconds

## Practical notes

Small leaf spinach was used as it allows the leafy material to be placed into the apparatus without creating too much damage to the leaf blade. Other versions of this practical have suggested basil leaves.

At least one of the containers should be flat / square faced e.g. a small brandy or whisky bottle. The reason for the flatness is that this vessel is used to absorb the heat from the lamp and will be placed between the container with the leaves in it and the lamp. If this heat shield container is round it will act as a lens and concentrate the light in a non-consistent way (the focus will be a result of the curvature of the container and the distance of the lamp to apparatus).

LED lights and fluorescents (except gro-lux) do not give an even spectral curve, having several peaks that are perceived by our vision as white. The peaks produced by these light sources are not in the region of wavelengths that chlorophyll can use.

You can use the non-illuminated periods to build up the CO<sub>2</sub> in the apparatus. CO<sub>2</sub> is a limiting factor and needs to be controlled or the results will become ambiguous.

## Sample data

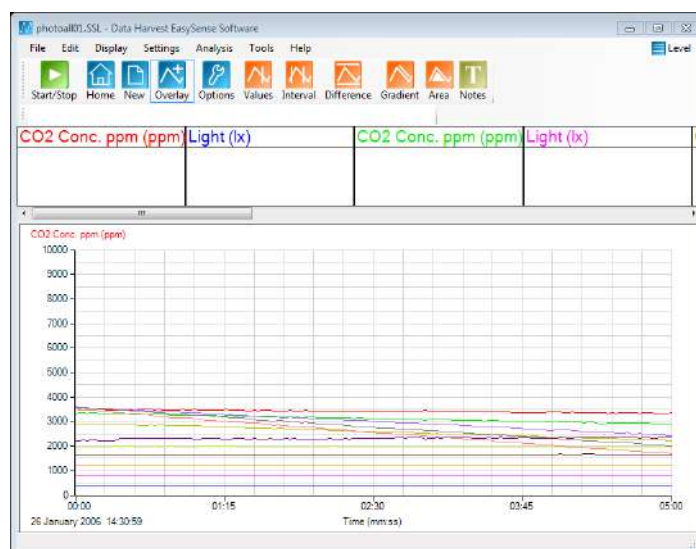


Fig 15c.2 Data as collected. A lot of data on one screen.

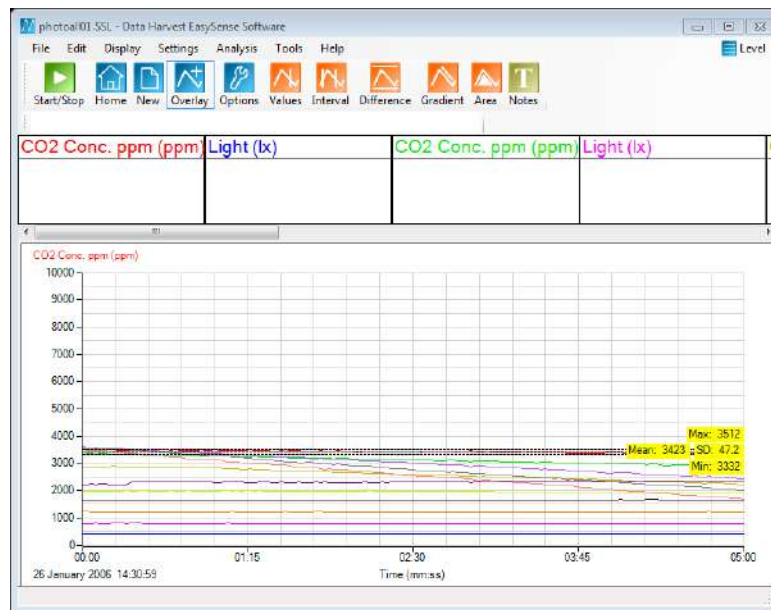


Fig 15c.3 Using Show Statistics (Analysis) to show details of labelled y axis.

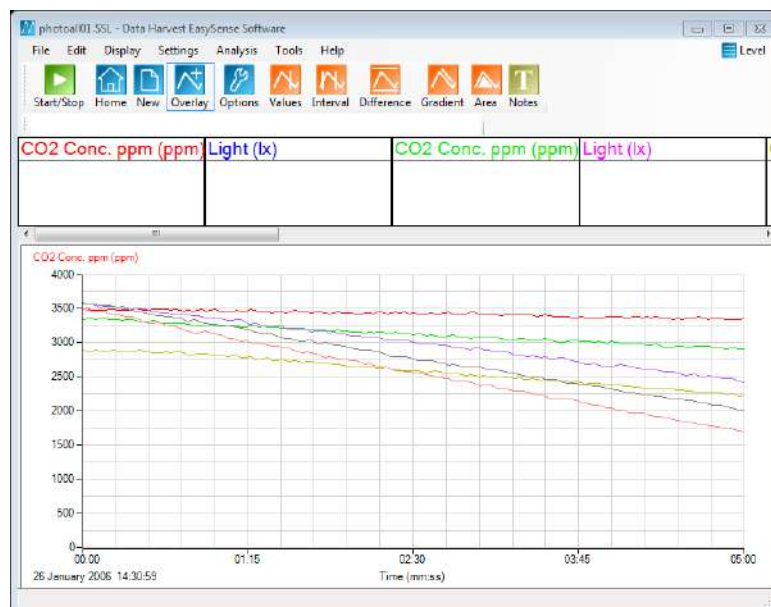


Fig15c.4 Light data hidden, CO<sub>2</sub> data on a unified limited scale (0 – 4,000 ppm).

## Treatment of data

Plot data as light intensity vs. photosynthetic rate. You are hoping to see that photosynthesis rises with an increase in light but that there reaches a point at which the increase in light does not give a linear increase in activity, i.e. something other than light is controlling the rate of photosynthesis.

There are several ways the data can be extracted.

### Extracting data using the statistics tool

- Select the Show Statistics option from the Analysis menu.
- This will show the maximum and minimum of the data set and the average.
- For Light intensity record the Average.

- For Rate of photosynthesis take the max and minimum values, subtract from each other and divide by the time interval in seconds (simple gradient).
- To change which statistics are shown click in the left of the graph margin, the statistics shown are for the data set indicated at the top of the y axis.
- You will need a table to record results into.

### Using the Best fit line

- To produce a best fit line it is best to hide all the data (right click, Show or Hide option) apart from the set you are working with on screen.
- From the Tools menu select Best Fit.
- In the Add line of best fit box select Manual (freehand) and OK.
- Click on the screen to start the line and draw it out using the mouse. Click again to fix the line on the graph.
- Use the mouse to grab and drag either end of the line onto the data line being analysed, lay the best fit line over the data line. The gradient data will appear in the form  $y=mx+c$ , the gradient is the "m".
- Use Show & Hide to reveal the next data and move the best fit line over the new data. This is a shortcut method that prevents the need to constantly reselect the data set to be used.

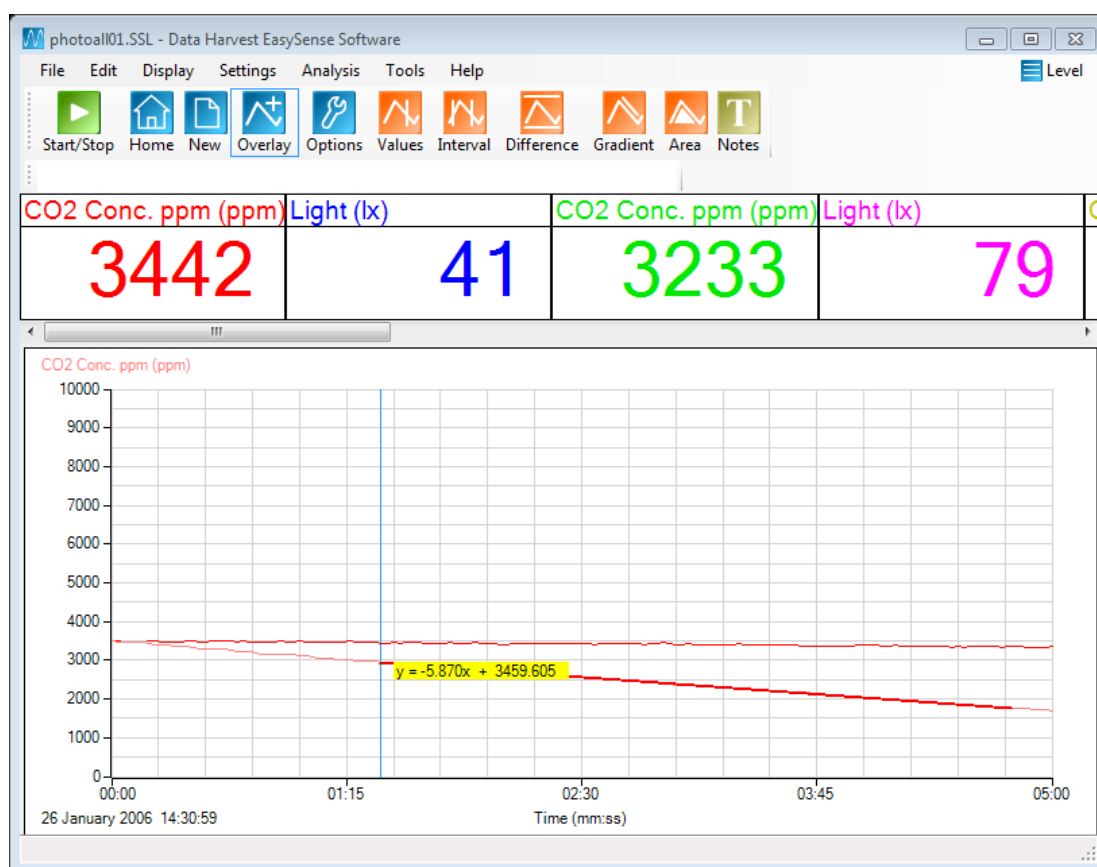


Fig 15c.5 Using the best fit line to extract rate data from a single shown data set.

Using the Best fit line method gives greater control over the data used. You need a linear decrease section of data. Sometimes due to the latency in photosynthesis getting up to a standard rate the initial data can be flat. Taking a simple max – min divided by time gradient will not give the true working rate.

### Comparison of data

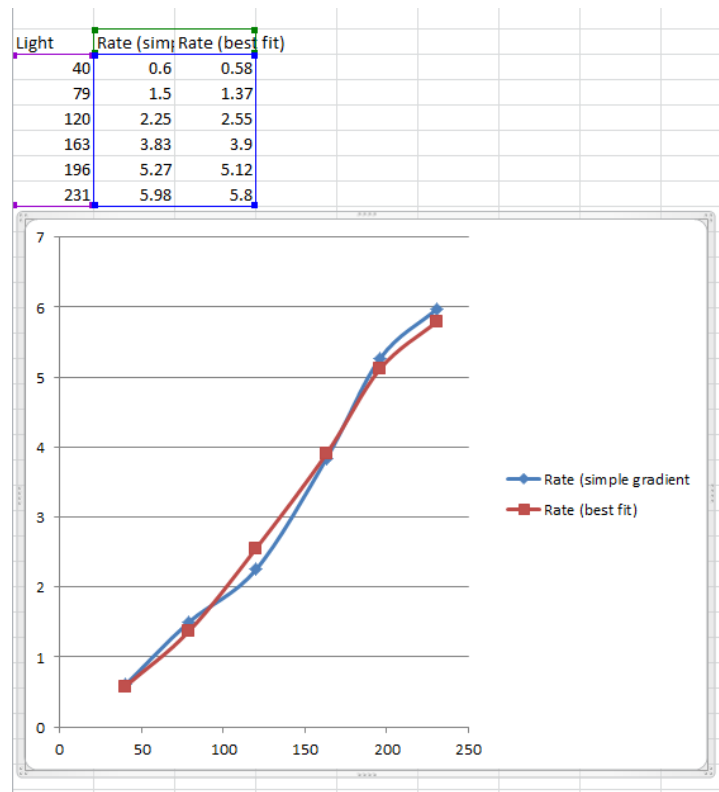


Fig 15c.6 Rate gradients calculated by both methods described transferred to Excel. The blue line is from a simple gradient over the whole data set, the red line is the gradient from the best fit approach. Both data sets show a linear increase in photosynthesis with increase in light intensity with a beginning of a sharp tail of at the highest light intensities available in the practical. The best fit approach gives a slightly less ambiguous curve with a better defined linear phase.

The fall in the increase in rate due to increased light is due to some other limiting factor coming into play, most likely  $\text{CO}_2$  concentration as we tried to control the starting level of  $\text{CO}_2$  in each run in this investigation.

You could use a fixed light intensity and use different  $\text{CO}_2$  start levels to see the effect of light as a limiting factor. The basic method of collecting the data and analysing it would be the same.

Data Harvest acknowledges the work carried out by SSERC in the development of this as a viable school practical.

Reference: SSERC Bulletin No 248 Autumn 2014 Limiting factors in photosynthesis – carbon dioxide.



## 15c. Effect of light intensity on the rate of photosynthesis

### Practical skills AT a, b, h, i

This activity is to look at the effect of light level on the rate of photosynthesis.

The Light level sensor is used to determine the value of the light detected at a fixed position to the apparatus. Light will respond to the inverse square law, so halving the distance from light to apparatus does not simply double the light intensity. The Light sensor allows you to predetermine the variable of light intensity and create a suitable protocol for changing it relative to the apparatus.

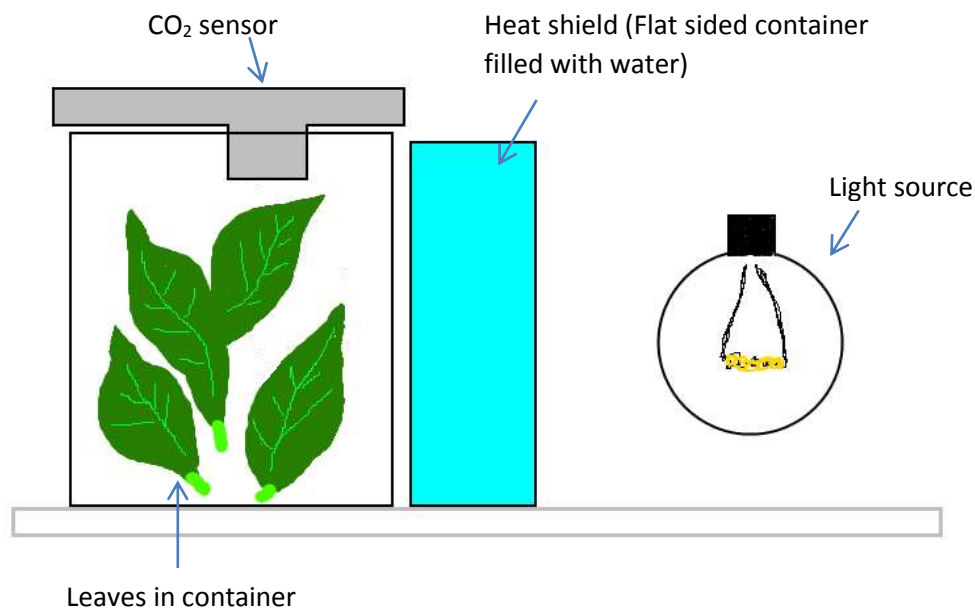


Fig 15c.1 Photograph of typical bench layout of apparatus, the light source would normally be bench lamp. Note the position of the Light sensor.



## Apparatus

1. Carbon dioxide sensor set to 0 -10,000 ppm range
2. Light level sensor 1 kLx (slow) range. (This may have to be changed according to light and size of containers)
3. Two matching transparent, colourless glass containers
4. Light source with photosynthetically active light output e.g. tungsten filament lamp
5. Small leaf spinach
6. Metal foil (to help reflect light to apparatus)
7. Dark cloth (to cover apparatus between runs) (optional)

## Method

Recording method	Time	Intersample	Overlay
Graph	5 minutes	2 seconds	On

1. Set up the apparatus as shown and use the Light sensor to test that you can get a range of light levels. Decide on how many increments of light you are going to test. Make sure the interval between light level is enough to move the CO<sub>2</sub> rate data beyond the potential of simple variation e.g. 40 lx would be a minimum difference. Don't over pack the leaves but make sure the apparatus looks full.
2. Use Test Mode (Tools menu) to monitor the light and CO<sub>2</sub> levels. Move the light away from the apparatus to the first collection point.
3. Get the CO<sub>2</sub> in the leaf chamber to approx. 4,000 ppm – you may find that simply leaving the apparatus in the dark will be enough for respiration of the leaves to raise the level. If this looks unlikely, exhale slightly into the apparatus and watch the CO<sub>2</sub> levels. Turn on the light and let photosynthesis remove the CO<sub>2</sub> to the predetermined level.
4. When the CO<sub>2</sub> in the apparatus gives a reading of 4,000 ppm click on Start and record for the 5 minutes. At the end of the recording save the data as Run1 (or similar).
5. Move the light to the next intensity position and repeat. Remember to save the data after each run.

## Sample data

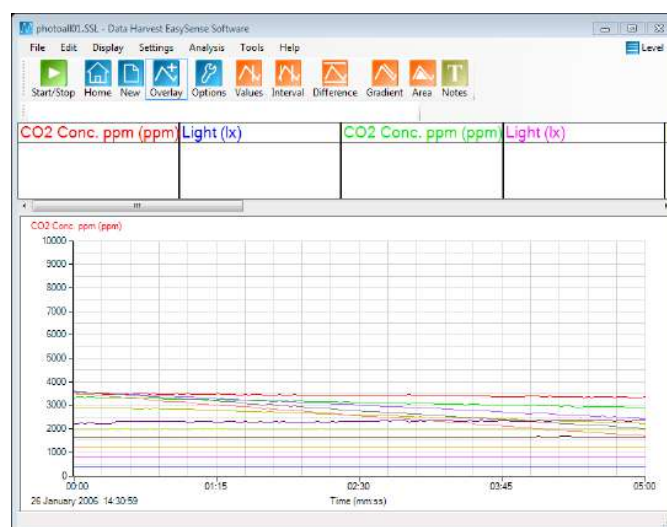


Fig 15c.2 Your collected data should look something like the above, this is a set of 6 runs.

**Treatment of data**

You will want to present the data as light intensity vs. photosynthetic rate (gradient).

Controlling light intensity without a Light sensor: If you halve the distance from light to the detector you do not halve the light received. What you need to do is make the assumption that the first halving of the distance does halve the light received. You make a note of how much you changed the distance. The next decrement of distance will be half of the previous half, etc. this will give a fairly good linear reduction in light intensity.

Distance (arbitrary units)	Light Intensity (arbitrary units)
100	200
50	100
25	50
12.5	25
6.25	12
3.125	6.25
1.563	3.125

## Teacher's notes

### 15d. Respiration and CO<sub>2</sub>

#### Practical skills AT a, b, h, l

Respiration is the reverse of photosynthesis. It is the use of oxygen in the environment to breakdown energy containing compounds (usually sugars, are there others? Other systems?) to release energy for the organism to use in metabolism. The waste products of respiration are water and CO<sub>2</sub>. We have difficulty measuring the net change in water levels due to homeostatic mechanisms but CO<sub>2</sub> levels will change in the immediate environment of the respiring organism. CO<sub>2</sub> is potentially toxic; water is not so while water may be conserved CO<sub>2</sub> will be disposed of.

In this practical we use a basic apparatus for studying photosynthesis and eliminate the light source. Although this does miss an opportunity to show the link between photosynthesis and respiration. Turning the light on and off would show the change in CO<sub>2</sub> levels.

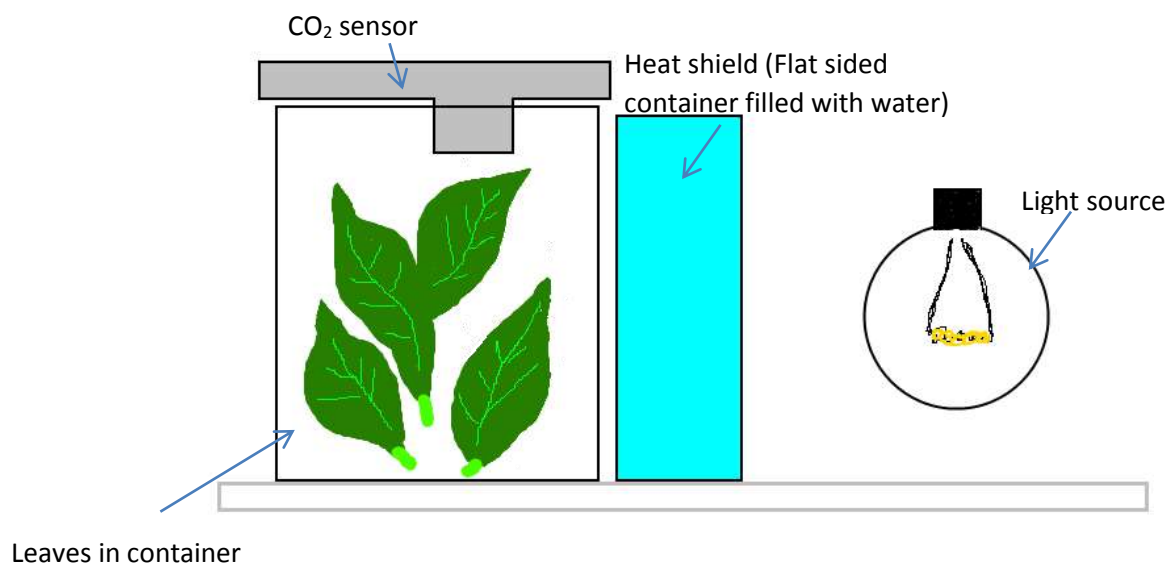


Fig 15d.1 Photograph of typical bench layout of apparatus, the light source would be removed for respiration studies as could the heat sink. We did find that turning the light on was convenient way of bringing the CO<sub>2</sub> levels round the leaves back down to a lower value again.

## Apparatus

1. Carbon dioxide sensor set to 0 -10,000 ppm range.
2. Two matching transparent, colourless glass containers
3. Light source with photosynthetically active light output e.g. tungsten filament lamp
4. Small leaf spinach
5. Metal foil (to help reflect light to apparatus)
6. Dark cloth (to cover apparatus between runs)

## Set up

Recording method	Time	Intersample	Overlay
Graph	5 minutes	2 seconds	On

## Practical notes

Small leaf spinach was used as it allows the leafy material to be placed into the apparatus without creating too much damage to the leaf blade. Other versions of this practical have suggested basil leaves.

At least one of the containers should be flat / square faced e.g. a small brandy or whisky bottle. The reason for the flatness is that this vessel is used to absorb the heat from the lamp and will be placed between the container with the leaves in it and the lamp. If this heat shield container is round it will act as a lens and concentrate the light in a non-consistent way (the focus will be a result of the curvature of the container and the distance of the lamp to apparatus).

LED lights and fluorescents (except gro-lux) do not give an even spectral curve, having several peaks that are perceived by our vision as white. The peaks produced by these light sources are not in the region of wavelengths that chlorophyll can use.

You can use the light to illuminate the leaves and turn photosynthesis on and recover the CO<sub>2</sub> produced by respiration. This does have the coincidence of showing the relationship between photosynthesis and respiration.

## Sample data

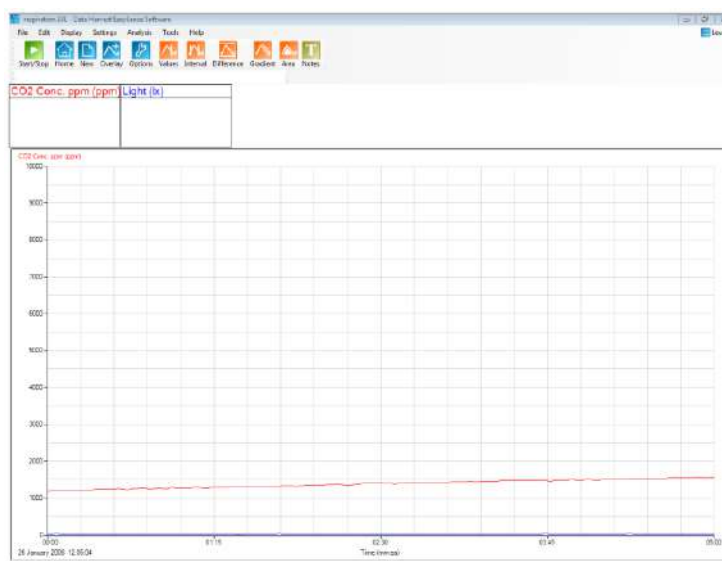


Fig 15d.2 Data as collected.

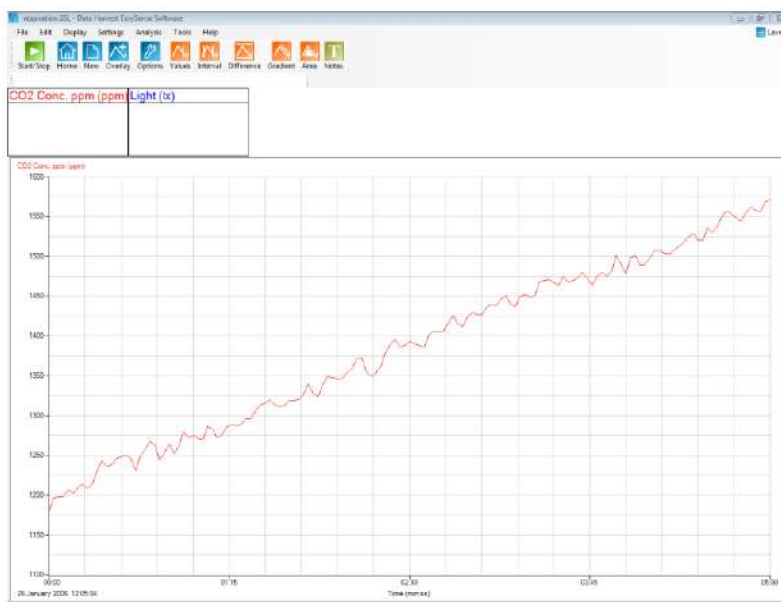
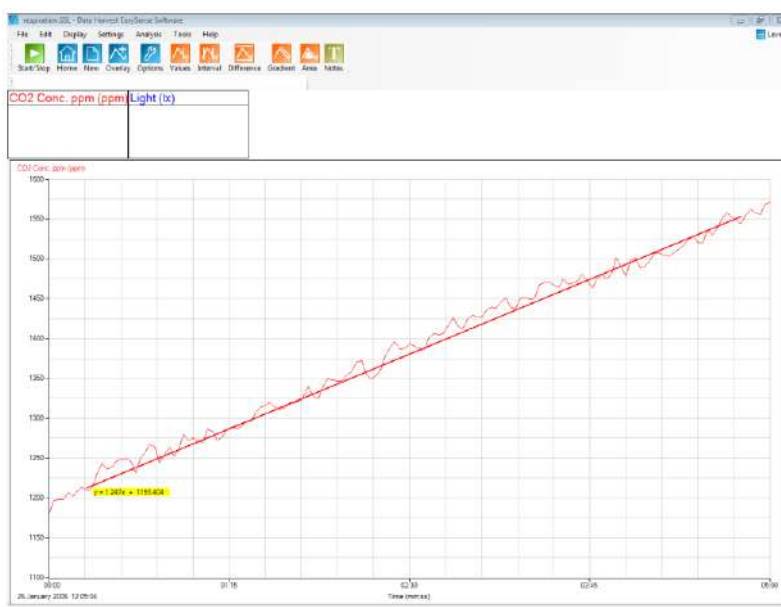


Fig 15d.3 Autoscale used. Light data collected hidden from view

Fig 15d.4 Manual best fit line to show the rate of respiration. In this example  $+1.247 \text{ ppm s}^{-1}$ 

### Using the Best fit line

- Use the Best Fit line (linear) tool (Tools menu) to manually overlay the data for the  $\text{CO}_2$  and read off the gradient of the line.
- To produce a best fit line it is best to hide all the data (right click, Show or Hide option) and only have the data you are working with on screen.
- Select Best fit and in the Add line of best fit box select Manual (freehand) and OK.
- Click on the screen to start the line and draw it out using the mouse. Click again to fix the line on the graph.
- Use the mouse to grab and drag either end of the line onto the data line being analysed, lay the best fit line over the data line.
- The gradient data will appear in the form  $y=mx+c$ , the gradient is the “m”.

**Extension**

1. If the leaves were placed in water bath(s) one would suspect that data linking respiration to temperature could be investigated.
2. Equally with mass of the leaves identified the rate of respiration per mass unit could be calculated.

## 15d. Respiration and CO<sub>2</sub>

### Practical skills AT a, b, h, l

This activity links the study of photosynthesis to respiration.

Respiration is the reversal of photosynthesis and vice versa. If we take the apparatus used to study photosynthesis and eliminate the light we stop photosynthesis and changes in CO<sub>2</sub> due to respiration will become apparent.

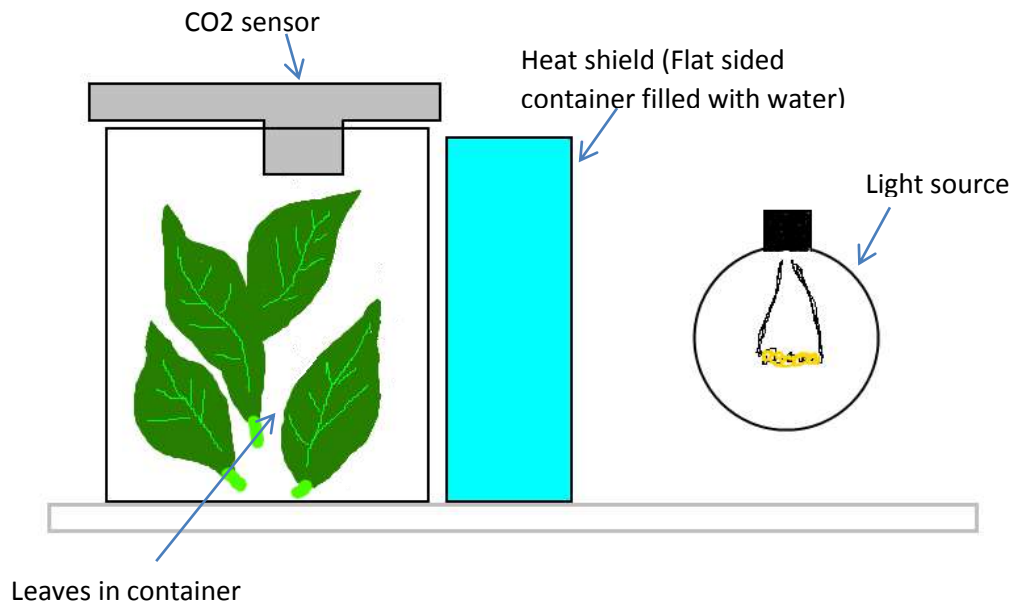


Fig 15d.1 Photograph of typical bench layout of apparatus, the light source would normally be bench lamp. You can use the light source to show the reversal of CO<sub>2</sub> production when light is present.

## Apparatus

1. Carbon dioxide sensor set to 0 -10,000 ppm range
2. Two matching transparent, colourless glass containers
3. Light source with photosynthetically active light output e.g. tungsten filament lamp
4. Small leaf spinach
5. Metal foil (to help reflect light to apparatus)
6. Dark cloth (to cover apparatus between runs) (optional)

## Method

Recording method	Time	Intersample	Overlay
Graph	5 minutes	2 seconds	On

1. Set up the apparatus as shown. Don't over pack the leaves but make sure the apparatus looks full.
2. Set the software to record for 5 minutes with at least 2 seconds between samples.
3. Click on Start to record the data.
4. At the end of the recording save the data as Run1 (or similar).
5. Repeat if necessary to collect more data.
6. Remember to save the data after each run.
7. If time allows try a run where after 2 minutes you turn the light on and see what happens.

## Results

Find the rate of CO<sub>2</sub> change.

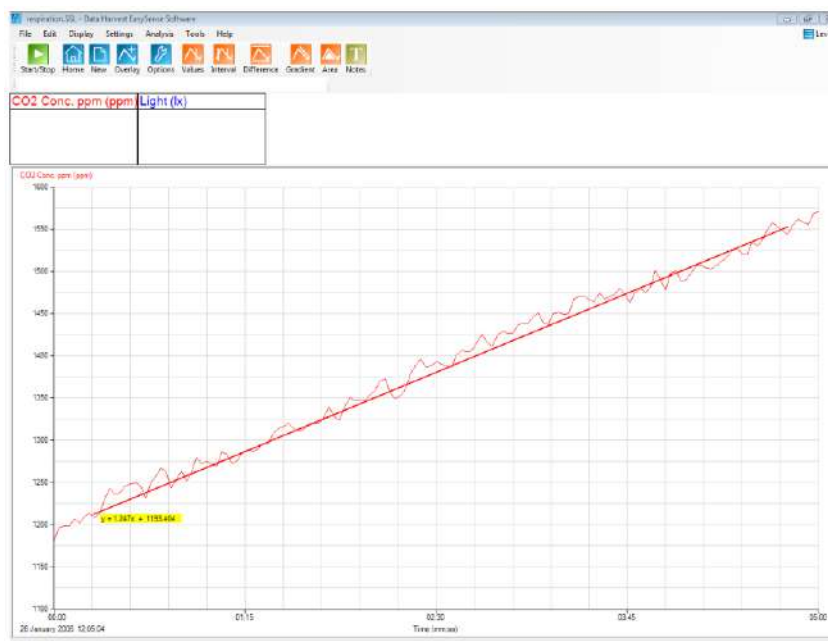


Fig 15d.2 Using the best fit line to extract rate data, the rate is shown in the yellow box at one end of the best fit line.



# CHEMISTRY

## CONTENTS

Teacher's notes: 1. Measurement of enthalpy changes: Calorimetry .....	4
1. Measurement of enthalpy changes: Calorimetry .....	6
Teacher's notes: 2. Measurement of enthalpy changes: Endothermic reaction .....	8
2. Measurement of enthalpy changes: Endothermic reaction .....	11
Teacher's notes: 3. To determine an enthalpy change indirectly .....	13
3. To determine an enthalpy change indirectly .....	20
Teacher's notes : 4. Hess's law: The reaction between sodium hydroxide and hydrochloric acid .....	24
4. Hess's law: The reaction between sodium hydroxide and hydrochloric acid .....	27
Teacher's notes : 5. Heat of combustion: Magnesium and oxygen .....	30
5. Heat of combustion: Magnesium and oxygen .....	32
Teacher's notes: 6. Acid, alkali titration using a burette .....	35
6. Acid, alkali titration using a burette .....	39
Teacher's notes : 7. Acid base titration: Sodium carbonate with hydrochloric acid .....	42
7. Acid base titration: Sodium carbonate with hydrochloric acid .....	46
Teacher's notes: 8. Rate of reaction: Marble chips and hydrochloric acid .....	49
8. Rate of reaction: Marble chips and hydrochloric acid .....	51
Teacher's notes: 9. Rate of reaction: Light transmittance through a reaction mixture of hydrochloric acid and sodium thiosulfate .....	54
9. Rate of reaction: Light transmittance through a reaction mixture of hydrochloric acid and sodium thiosulfate .....	57
Teacher's notes: 10. Thiosulfate and acid, following the rate of reaction .....	59
10. Thiosulphate and acid, following the rate of reaction .....	64
Teacher's notes: 11. A kinetic study to determine the order of a reaction (iodine clock) .....	67
11. A kinetic study to determine the order of a reaction (iodine clock) .....	72
Teacher's notes: 12. A kinetic study to determine the order of a reaction (iodination of propanone) .....	76
12. A kinetic study to determine the order of a reaction (iodination of propanone) .....	80
Teacher's notes: 13. A kinetic study to determine the order of a reaction (iodination of propanone) .....	82
13. A kinetic study to determine the order of a reaction (iodination of propanone) .....	86

## Chemistry

The table below lists the practical worksheets (in order) in the chemistry section. For each practical there is a student worksheet and a teachers' guidance. Practical skills are indicated from the guidance given by the examination boards.

Practical name	Sensors	Practical skills
1. Measurement of enthalpy changes: Calorimetry	Temperature	a, d,
2. Measurement of enthalpy changes: Endothermic reaction	Temperature	a, d
3. To determine an enthalpy change indirectly. Conversion of anhydrous copper(II) sulfate into hydrated copper(II) sulfate.	Temperature	a, d
4. Hess's law: The reaction between sodium hydroxide and hydrochloric acid	Temperature	a, d
5. Heat of combustion: Magnesium and oxygen	Temperature	a, d
6. Acid, alkali titration using a burette	pH	a, c, d
7. Acid base titration: Sodium carbonate with hydrochloric acid	pH, Drop / Bubble counter	a, c, d
8. Rate of reaction: Marble chips and hydrochloric acid	Drop / Bubble counter	a, d, l
9. Rate of reaction Light transmittance through a reaction mixture of hydrochloric acid and sodium thiosulfate	Colorimeter	a, d, e, l
10. Thiosulfate and acid, following the rate of reaction.	Light level sensor (set to transmission range)	a, d, e, l
11. A kinetic study to determine the order of a reaction (iodine clock)	Light level	a, d, e, l
12. A kinetic study to determine the order of a reaction (iodination of propanone). Hydrochloric acid catalyst	Colorimeter	a, d, e, l
13. A kinetic study to determine the order of a reaction (iodination of propanone). Sulfuric acid catalyst	Colorimeter	a, d, e, l

**Apparatus and Techniques.** Skills identified in chemistry where data logging, data loggers or sensors should be considered.

- AT a - Use appropriate apparatus to record a range of measurements (to include mass, time, volume of liquids and gases, temperature)
- AT c - Measure pH using pH charts, or pH meter or pH sensor on a data logger

- AT d - Use laboratory apparatus for a variety of experimental techniques
- AT e - Use volumetric flask, including accurate technique for making up a standard solution
- AT f - Use acid-base indicators in titrations of weak/strong acids with weak/strong alkalis
- AT I - Measure rates of reaction by at least two different methods for example:
  - An initial rate method such as a clock reaction
  - A continuous monitoring method

## Teacher's notes

### 1. Measurement of enthalpy changes: Calorimetry

#### Practical skills AT a, d

Heat released or absorbed by a reaction can be measured by the increase or decrease in temperature. The measuring of the temperature changes in an experiment is calorimetry. In its simplest form calorimetry only needs a reaction vessel and a thermometer.

Accuracy in the measurement comes from using non heat conducting materials and more accurate thermometers. In this investigation the main improvement in the measurements come from the ability to capture the whole heat change in the reaction. When using a thermometer the observer can often miss the peak change, the data logger does not wander in its concentration.

Results for the simple experiments indicated produce good values close to published results.

#### Apparatus

1. Temperature sensor
2.  $1 \text{ mol dm}^{-3}$  Hydrochloric acid (HCl)
3. 0.5 g strip of magnesium ribbon (exact mass to be checked)
4. Polystyrene cup
5.  $250 \text{ cm}^3$  beaker
6. Measuring cylinders
7. Accurate balance

#### Set up

Data logging is conducted in real time and each data collection is timed at 5 minutes, this allows a good margin for capturing the whole experiment.

Recording method	Time
Graph	5 minutes

#### Practical notes

The polystyrene cups usually fit into the  $250 \text{ cm}^3$  beakers with an air gap all-round the cup. The air gap adds to the insulating properties of the cup. If the polystyrene cups cannot be found then a standard vending style cup can be used with additional insulating material to fill the air gap around the cup.

A lid to go over the apparatus can make a significant difference to the accuracy of the results and should be used if possible. The lid also helps prevent the acid vapour produced by the heat of the reaction from escaping into the classroom.

The experiment is a very simple measurement of the heat produced by an exothermic reaction. The practical is extended by the logging of the temperature information and the mathematics used to calculate the enthalpy change. Enthalpy does not have to be calculated for there to be value in the practical.

## Sample results

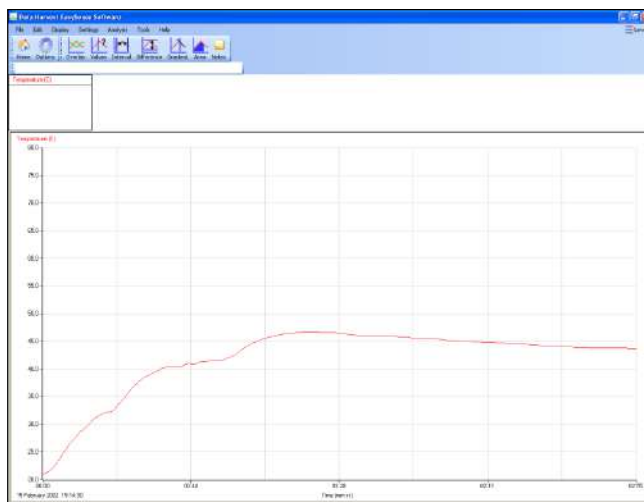


Fig 1.1. Sample results of the exothermic reaction of  $\text{Mg}_{(s)} + \text{HCl}$ .

0.55 g of Magnesium was used

$$\Delta T = 46.7 - 20.7 = 26.0^{\circ}\text{C}$$

Heat released =  $M \times C \times \Delta T$

$M$  = the mass of water and the mass of the magnesium ribbon

$$100.55 \times 4.18 \times 26.0 = 10927 \text{ J g}^{-1}$$

Moles of  $\text{Mg} = 0.55/24.3 = 0.0226$  mole

$\text{kJ per mole} = 483.5 \text{ kJ mol}^{-1}$

Published values give  $442 \text{ kJ mol}^{-1}$

The error difference should be calculated and reasons given for the errors.

Errors include,

- Assuming specific heat capacity of the reaction is mass of acid + mass of magnesium = same mass of pure water.
- Accurate mass measurement of magnesium.
- Accurate measurement of acid volume (and hence mass).
- Heat loss in the system, absorbed by sensor housing, lost to air by evaporation, lost to stirrer if used.

The data collected can be used to calculate the entropy change of the system

### Extension to calculations (simplified)

$\Delta S$  (entropy) can be calculated

$$\Delta S = -\Delta H/T$$

Taking value of  $\Delta H$  from this experiment

$T$  = Kelvin temperature of room

$$\Delta S = - - 106.7/298 = 0.355$$

(Note the double negative above produces a positive number)

Or  $355 \text{ JK}^{-1} \text{ mol}^{-1}$  (This reaction will take place spontaneously)

All temperature should be in degrees Kelvin. There is a Pre or Post-log Function (Tools menu), Conversions to Convert Celsius to Kelvin.

# 1. Measurement of enthalpy changes: Calorimetry

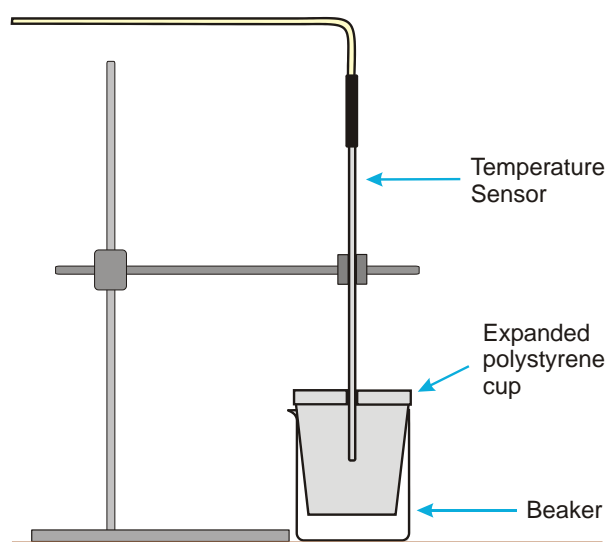
## Practical skills AT a, d

Heat released or absorbed by a reaction can be measured using calorimetry. The device used to capture and record the heat change is a calorimeter. A very simple calorimetric experiment can be undertaken using a polystyrene cup and a reaction taking place in an aqueous solution.

### Assumptions made

- If the reaction is exothermic, the heat evolved is only transferred to the solution.
- If the reaction is endothermic, the heat is only absorbed from the solution.
- The reaction takes place sufficiently rapidly for the maximum temperature change to be reached before the mixture begins to return to room temperature.
- The reaction vessel does not gain or lose heat.
- There is no heat exchange with the environment.
- The specific heat capacity of the aqueous solution is taken to be that of water.

The experiment uses Magnesium + Hydrochloric acid as an example exothermic reaction.



## Apparatus

1. Temperature sensor
2. 1 mol dm<sup>-3</sup> Hydrochloric acid (HCl)
3. 0.5 g strip of Magnesium ribbon (exact mass to be checked)
4. Polystyrene cup
5. 250 cm<sup>3</sup> beaker
6. Measuring cylinders
7. Accurate balance

## Method

1. Place 100 cm<sup>3</sup> of the acid into the polystyrene cup.
2. Put the cup into a glass beaker (best if arranged so that the cup is suspended in the glass beaker).

3. Connect the Temperature sensor to the data logger. Position the Temperature sensor in the acid, making sure the tip of the sensor is not touching any of the sides of the cup.
4. Set up the recording time:

Recording method	Time
Graph	5 minutes

5. Click on Start and record for approximately 30 seconds to give a good start temperature line.
6. Add the magnesium ribbon and allow the reaction to continue until the recording is finished.

## Results and analysis

Use Values to find the temperature at the start ( $T_{\text{start}}$ ) and final temperature reached ( $T_{\text{final}}$ ).

## Calculations

Heat released by reaction = heat gained by the solution

1. Heat gained by the solution =  $M \times C \times \Delta T$
2.  $M$  = Mass of solution (mass of acid + mass of magnesium ribbon)
3.  $C$  = specific heat capacity, assumed to be 4.18 joules per kelvin ( $\text{J g}^{-1} \text{K}^{-1}$ )
4.  $\Delta T$  = temperature change ( $T_{\text{final}} - T_{\text{start}}$ )

Use the values of  $T_{\text{start}}$  and  $T_{\text{final}}$  substituted into the calculation to find the energy transferred. Make sure the volume of the acid and magnesium that were actually used, are used, and not the suggested volumes and masses.

### Worked example

In a similar experiment 100.5  $\text{cm}^3$  of acid was used, 4.2 g of magnesium ribbon added and a temperature increase of 5.2°C was measured from the graph:

Substituting the experimental data into the calculation,  $M \times C \times \Delta T$

$$104.7 \times 4.18 \times 5.2 = 2275 \text{ J}$$

1. The atomic mass of Magnesium = 24.3
2. Moles of Magnesium in the reaction is  $0.500 \div 24.3 = 0.0206 \text{ mol}$

Therefore, the heat released per mole of magnesium =  $2275 \div 0.0206 = 110\,436 \text{ J mol}^{-1}$  or  $110.4 \text{ kJ mol}^{-1}$ .

## Extension

The experiment can be repeated using Citric Acid and Sodium Bicarbonate to give an Endothermic reaction.

### Extension to calculations

$\Delta S$  (entropy) can be calculated

$$\Delta S = -\Delta H/T$$

Taking value of  $\Delta H$  from this expt.

- $T$  = Kelvin temperature of room (298)

$$\Delta S = - - 110.4 \div 298 = 0.370$$

(Note the double negative above produces a positive number)

Or  $370 \text{ J K}^{-1} \text{ mol}^{-1}$  (This reaction will take place spontaneously).

All temperatures used in the calculations should be in degrees Kelvin.

## Teacher's notes

### 2. Measurement of enthalpy changes: Endothermic reaction

#### Practical skills AT a, d

Heat released or absorbed by a reaction can be measured by the increase or decrease in temperature. The measuring of the temperature changes in an experiment is calorimetry. In its simplest form calorimetry only needs a reaction vessel and a thermometer.

Accuracy in the measurement comes from using non heat conducting materials and more accurate thermometers. In this investigation the main improvement in the measurements come from the ability to capture the whole heat change in the reaction. When using a thermometer the observer can often miss the peak change, the data logger does not wander in its concentration.

#### Apparatus

1. Temperature sensor
2.  $1.5 \text{ mol dm}^{-3}$  Citric acid ( $\text{C}_6\text{H}_8\text{O}_7$ )
3. 10 g Sodium hydrogen carbonate ( $\text{NaHCO}_3$ )
4. Polystyrene cup
5.  $250 \text{ cm}^3$  beaker
6. Measuring cylinders
7. Accurate balance

#### Set up

Each data collection is timed at 5 minutes; this allows a good margin for capturing the whole experiment.

Recording method	Time
Graph	5 minutes

#### Practical notes

The polystyrene cups usually fit into the  $250 \text{ cm}^3$  beakers with an air gap all around the cup. The air gap adds to the insulating properties of the cup. If the polystyrene cups cannot be found then a standard vending style cup can be used with additional insulating material to fill the gap around the cup.

A lid to go over the apparatus can make a significant difference to the accuracy of the results and should be used if possible. The lid also helps prevent the acid vapour produced by the heat of the reaction from escaping into the classroom.

The experiment is a very simple measurement of the heat produced by an endothermic reaction. The practical can be extended by the logging of the temperature information and the mathematics used to calculate the enthalpy change. Enthalpy does not have to be calculated for there to be value in the practical.



## Sample data

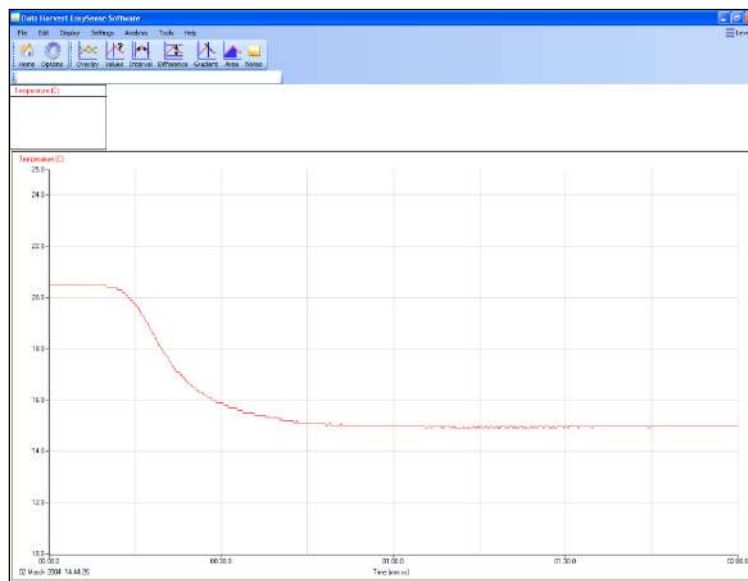


Fig 2.1 Graph of the endothermic reaction of Citric acid and Sodium hydrogen carbonate

## Calculations

Heat released by reaction = heat gained by the solution

5. Heat gained by the solution =  $M \times C \times \Delta T$
6.  $M$  = Mass of solution (mass of acid + mass sodium hydrogen carbonate)
7.  $C$  = specific heat capacity, assumed to be  $4.18 \text{ J g}^{-1} \text{ K}^{-1}$
8.  $\Delta T$  = temperature change

Use the values of  $T_{\text{start}}$  and  $T_{\text{final}}$  substituted into the calculation to find the energy transferred.

Make sure the volume of the acid and sodium hydrogen carbonate actually used are entered and not the suggested volumes and masses.

### Worked example

In a similar experiment  $100.5 \text{ cm}^3$  of acid were used, 4.2 g of sodium hydrogen carbonate added and a temperature decrease of  $-5.2^\circ\text{C}$  was measured from the graph:

Substituting the experimental data into the calculation

$$M \times C \times \Delta T$$

$$104.7 \times 4.18 \times -5.2 = -2276 \text{ J (rounded up)}$$

3. The formula mass of sodium hydrogen carbonate = 84
4. Moles of sodium hydrogen carbonate in the reaction is  $0.500 \div 24.3 = 0.0206 \text{ mol}$

Therefore, the heat absorbed per mole of sodium hydrogen carbonate =  $2195 \div 0.0206 = 110\,473 \text{ J mol}^{-1}$  or  $110.4 \text{ kJ mol}^{-1}$

Errors include,

1. Assuming specific heat capacity of the reaction is mass of acid + mass of sodium bicarbonate = same mass of pure water.
2. Accurate mass measurement of sodium bicarbonate.

3. Accurate measurement of acid volume (and hence mass).
4. Heat loss in the system, absorbed by sensor housing, lost to air by evaporation, lost to stirrer if used.

The data collected can be used to calculate the entropy change of the system.

### Extension to calculations

$\Delta S$  (entropy) can be calculated

$$\Delta S = -\Delta H \div T$$

Taking value of  $\Delta H$  from this expt:

- $T$  = Kelvin temperature of room (298)

$$\Delta S = - + 219.50 \div 298 = + 0.736$$

Or  $+ 736 \text{ J K}^{-1} \text{ mol}^{-1}$  (This reaction will take place spontaneously)

## 2. Measurement of enthalpy changes: Endothermic reaction

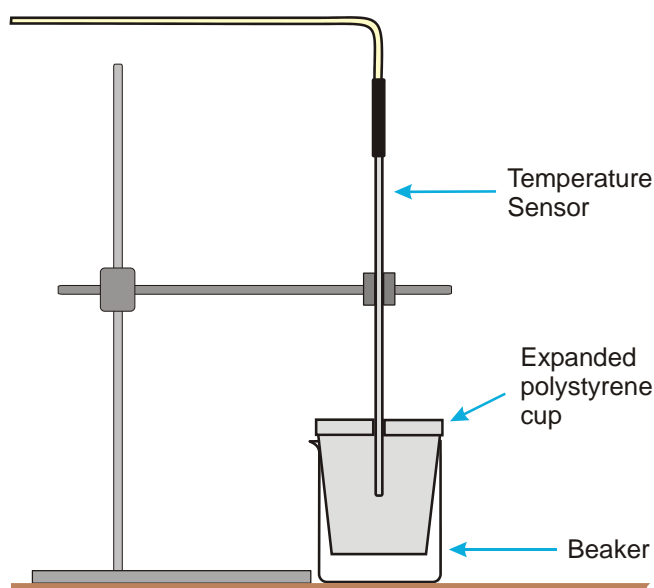
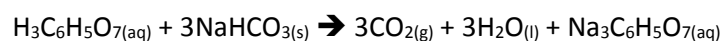
### Practical skills AT a, d

Heat released or absorbed by a reaction can be measured using calorimetry. The device used is a calorimeter. A very simple calorimetric experiment can be undertaken using a polystyrene cup and a reaction taking place in an aqueous solution.

### Assumptions made

1. If the reaction is exothermic, the heat evolved is only transferred to the solution.
2. If the reaction is endothermic, the heat is only absorbed from the solution.
3. The reaction takes place sufficiently rapidly for the maximum temperature change to be reached before the mixture begins to return to room temperature.
4. The reaction vessel does not gain or lose heat.
5. There is no heat exchange with the environment.
6. The specific heat capacity of the aqueous solution is taken to be that of water.

The experiment uses Citric acid and Sodium hydrogen carbonate as an example endothermic reaction.



### Apparatus

1. Temperature sensor
2.  $1.5 \text{ mol dm}^{-3}$  Citric acid
3. 10 g Sodium hydrogen carbonate
4. Polystyrene cup
5.  $250 \text{ cm}^3$  beaker
6. Measuring cylinders
7. Accurate balance

## Method

1. Place 30 cm<sup>3</sup> of the acid into the polystyrene cup.
2. Put the cup into a glass beaker (best if arranged so that the cup is suspended in the glass beaker).
3. Connect the Temperature sensor to the data logger. Position the Temperature sensor in the acid, making sure the tip of the sensor is not touching any of the sides of the cup.
4. Set up the recording time:

Recording method	Time
Graph	5 minutes

5. Click on Start and record for approximately 30 seconds to produce a good start temperature line.
6. Add the sodium hydrogen carbonate and allow the reaction to continue until the recording is finished.

## Results and analysis

Use Values to find the temperature at the start ( $T_{\text{start}}$ ) and final temperature reached ( $T_{\text{final}}$ ).

## Calculations

Heat released by reaction = heat gained by the solution

1. Heat gained by the solution =  $M \times C \times \Delta T$
2.  $M$  = Mass of solution (mass of acid + mass sodium hydrogen carbonate)
3.  $C$  = specific heat capacity, assumed to be  $4.18 \text{ J g}^{-1} \text{ K}^{-1}$
4.  $\Delta T$  = temperature change

Use the values of  $T_{\text{start}}$  and  $T_{\text{final}}$  substituted into the calculation to find the energy transferred. Make sure the volume of the acid and sodium hydrogen carbonate actually used are entered and not the suggested volumes and masses.

## Worked example

In a similar experiment 100.5 cm<sup>3</sup> of acid were used, 4.2 g of sodium hydrogen carbonate added and a temperature decrease of  $-5.2^\circ\text{C}$  was measured from the graph:

Substituting the experimental data into the calculation:  $M \times C \times \Delta T$

$$104.7 \times 4.18 \times -5.2 = -2276 \text{ J (rounded up)}$$

1. The formula mass of Sodium hydrogen carbonate = 84
2. Moles of sodium hydrogen carbonate in the reaction is  $0.500 \div 24.3 = 0.0059 \text{ mol}^{-1}$

Therefore, the heat absorbed per mole of sodium hydrogen carbonate =  $2195 \div 0.0206 = 110\,473 \text{ J mol}^{-1}$  or  $110.4 \text{ kJ mol}^{-1}$ .

## Extension to calculations

$\Delta S$  (entropy) can be calculated

$$\Delta S = -\Delta H/T$$

Taking value of  $\Delta H$  from this experiment

$T$  = Kelvin temperature of room (298)

$$\Delta S = - +110.4 \div 298 = +0.370$$

Or  $370 \text{ J K}^{-1} \text{ mol}^{-1}$  (This reaction will take place spontaneously).

## Teacher's notes

### 3. To determine an enthalpy change indirectly

#### Conversion of anhydrous copper(II) sulfate into hydrated copper(II) sulfate

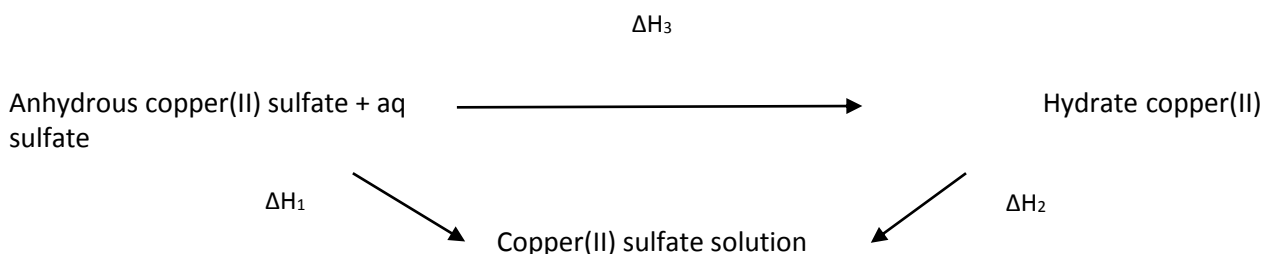
##### Practical skills AT a, d

Hess's law indicates that no matter what the route a reaction takes the energy change will be the same. In this practical you are to measure the energy change of anhydrous copper (II) sulfate to the hydrated copper (II) sulfate form.

This is not an energy change that can be measured directly as the water is added to the crystalline structure and is not available in a form or location that is possible to measure.

However we can hydrate to excess by dissolving the anhydrous form in water. If we then dissolve a same quantity of hydrated copper sulphate in a same volume of water we can use the energy changes of both to find the unknown value.

The Hess's law cycle for the change is described below



Hess's law tells us that:

$$\Delta H_1 = \Delta H_2 + \Delta H_3$$

It follows that:

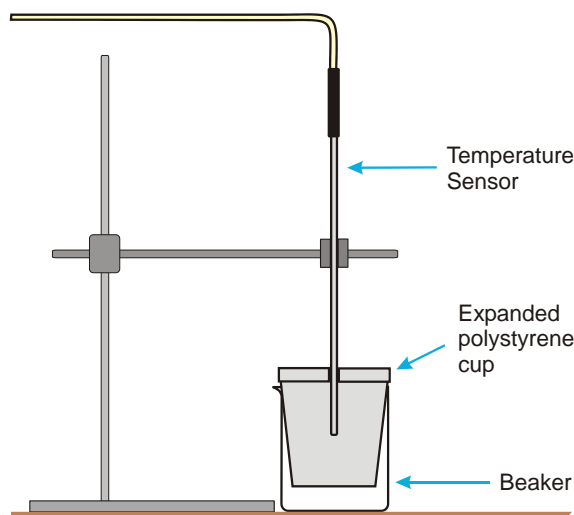
$$\Delta H_3 = \Delta H_1 + \Delta H_2$$

##### Assumptions made

1. If the reaction is exothermic, the heat evolved is only transferred to the solution.
2. If the reaction is endothermic, the heat is only absorbed from the solution.
3. The reaction takes place sufficiently rapidly for the maximum temperature change to be reached before the mixture begins to return to room temperature.
4. The reaction vessel does not gain or lose heat.
5. There is no heat exchange with the environment.
6. The specific heat capacity of the aqueous solution is taken to be that of water.

The experiment uses anhydrous copper(II) sulfate and hydrated copper(II) sulfate.

The worksheet has been written to be compliant with the practical skills assessment and therefore has a lower level of detail to test the student's ability to handle practical instructions and equipment.



## Apparatus

1. Temperature sensor
2. 0.025 moles anhydrous copper(II) sulfate, students should weigh out between 3.90 and 4.10 g
3. 0.025 moles hydrated copper(II) sulfate, students should weigh out between 6.20 and 6.30 g
4. Polystyrene cup
5. Deionised water
6. 100 cm<sup>3</sup> beaker (polystyrene or well insulated)
7. Measuring cylinders (25 cm<sup>3</sup>)
8. Accurate balance
9. Stirrer and magnetic flea or glass stirring rod
10. Retort stand, boss, clamps

## Set up

The practical can be used with EasyLog and just let it run for 20 minutes.

However standard methods ask for a 4 minute period of water temperature measurement followed by 15 minutes of data collection. To follow this pattern the software should be run in Graph mode, set total recording time to 20 minutes and the intersample time to 1 minute to give 20 data points.

Recording method	Time	Intersample	No of samples
Graph	20	1 minute	20

## Practical notes

If this is to be used as part of the formal assessment of practical skills you will need to refer to the examination boards marking scheme (if one exists) and ensure compatibility.

If the practical is to be used for practical skills then the final calculation is optional, students are not to be downgraded by inability (in this context only) to complete the calculations. But accuracy and completeness of data gathering are essential.

It was noticed that in trialling this work that the anhydrous copper(II) sulfate tended to form a concretion in the bottom of the beaker after it was added. It was found that a magnetic stirrer on a vigorous spin reduced this effect significantly.

The results can be treated within the software or transferred to graph paper. The collection of data at 1 minute periods gives 20 samples and is more in line with hand drawn data. The Easylog collection will give many hundreds of data points and will require the students to select out 20 evenly spaced data points.

The specific heat capacity of a polystyrene cup is negligible compared to the mass of water. This may not be true for a glass beaker. It could be a worthwhile diversion to repeat the work using standard lab glass ware and comparing the results.

For aqueous solutions the specific heat capacity of the solutions can be taken as the same as water.

Heat loss to the environment is ignored in this work.

## Results and analysis

It is recommended that the analysis within the software is shown and practised.

Either

Reveal the table (Display > Show Table) to find the temperature at each minute and plot a graph on paper. Use the data for the first four minutes to create a best fit base temperature line and make a best fit line for the data after the addition of the compounds. Extend both lines to find  $T_0$  to find  $T_2$  and hence  $\Delta\theta$ .

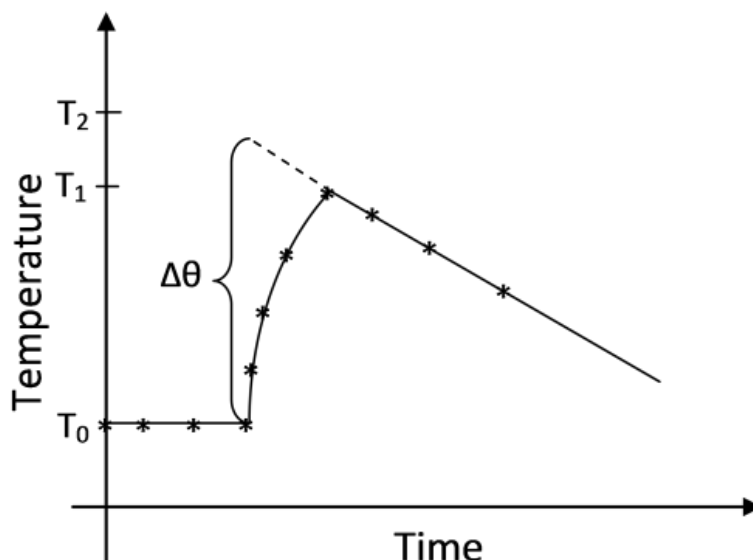


Figure 3.1 finding the maximum temperature rise.

Or

Use the Post log Function tools within EasySense to find  $T_0$  and  $T_2$  and hence  $\Delta\theta$ .

Convert the time to a data channel.

1. Use the Post log Function, Formula and select  $ax^2 + bt + c$ . Make  $a = 0$ ,  $b = 1$  and  $c = 0$ . Name the new data set Time(2) and set the units to (s)
2. Use Display, X-Axis, Channel to convert the graph display to a channel vs. channel graph.
3. Click on the x axis label to use the Time(2) channel and the y axis to be Temperature.
4. Use Best Fit lines to create the  $T_0$  line and the extrapolated cooling phase best fit line.
5. Use Values to find  $T_0$  and  $T_2$ .
6. Calculate  $\Delta\theta$ .

## Sample data

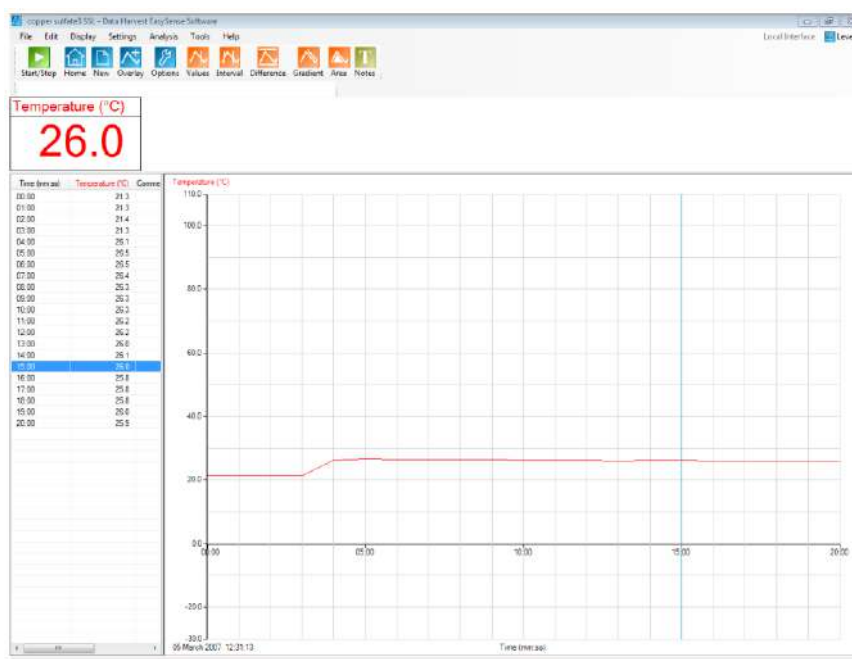


Fig 3.2 Data for 4.01 g of anhydrous copper(II) sulfate added to 50 cm<sup>3</sup> water using the 20 minute logging period with a sample period of 1 m. Table revealed and the values tool positioned at the 15 minute sample point.

First we create the time data set that can be used as an axis.

- Tools > Post Log Function > Formula >  $at^2 + bt + c$ .
- $A = 0$ ,  $b = 1$  and  $c = 0$ . This means that time data is multiplied by 1 and is passed through unaltered to the new channel data.
- New data set named as Time(2) and given units of (s).

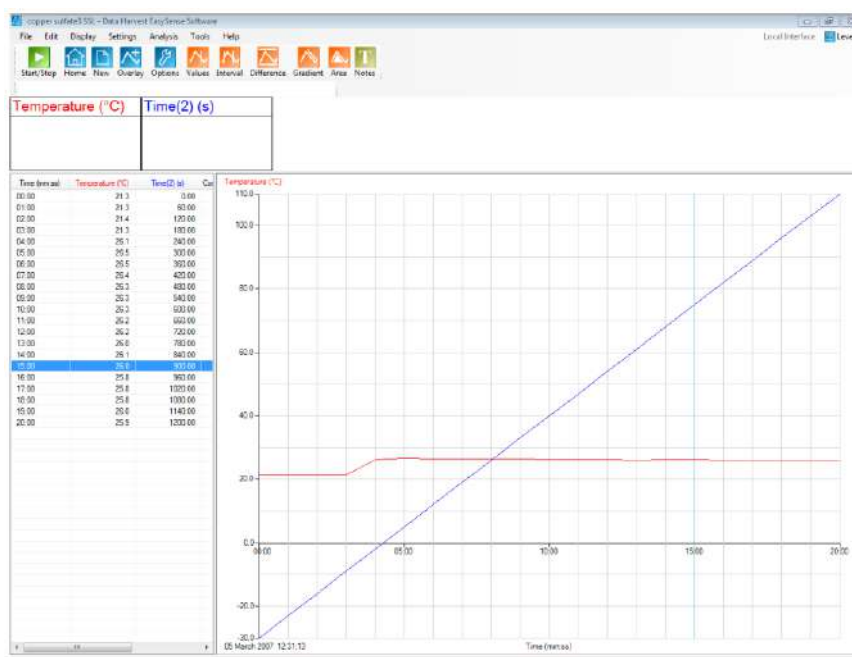


Fig 3.3 Graph showing the new data set table revealed to show time as seconds.



Plot the data as Temperature vs. Time(2).

Display > X-Axis > Channel > OK. When the graph appears click on the red Temperature name on the x-axis and select the x-axis as Time(s).

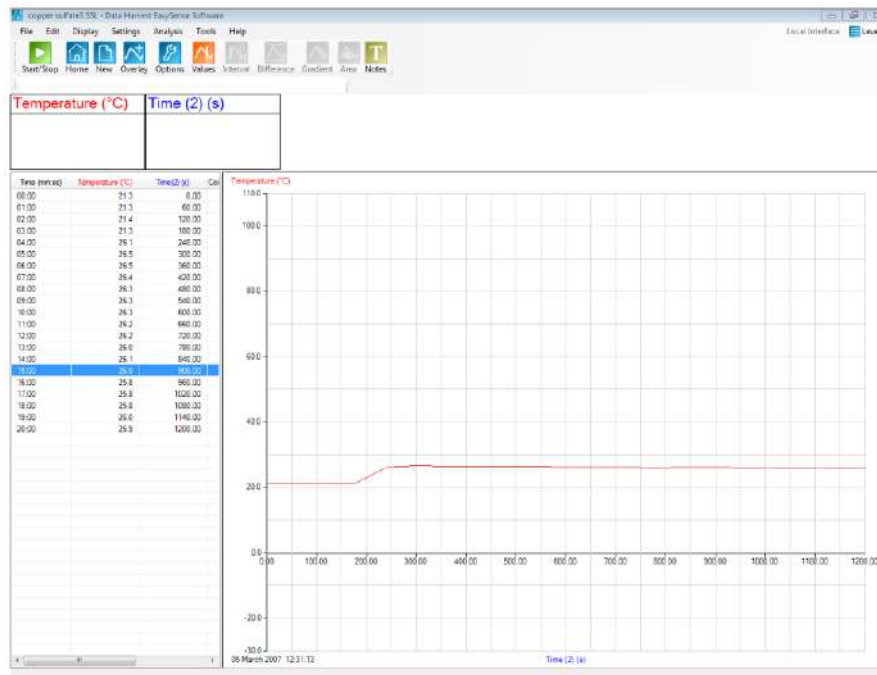


Fig 3.5 Graph of data with new time data column

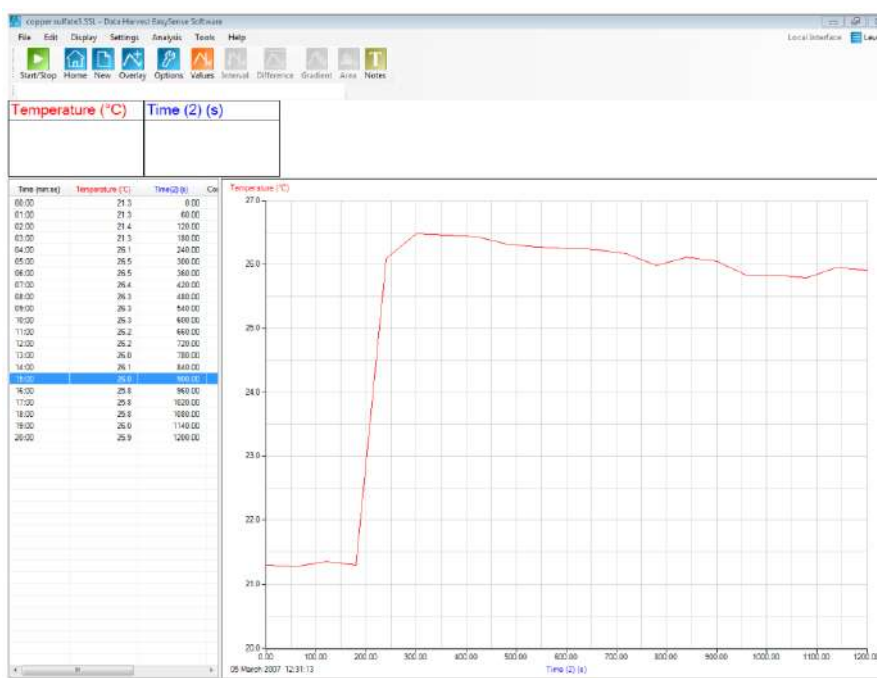


Fig 3.6 Plot of temperature against time

Add best fit lines to create  $T_0$  and find  $T_2$ .  $T_1$  is the maximum temperature shown in the data:

Tools > Best fit > Manual > Select y-axis (Temperature) > Select X-axis (Time(2)) > OK. Click on the graph where you want the line to start, drag the line out and click to terminate.

Add the  $T_0$  first, use the “jaggies” in the line to get it parallel to the x axis. When it is created the yellow  $y = mx + c$  data box will show  $y = 0.000x +$  (intercept of y axis), if it is parallel.

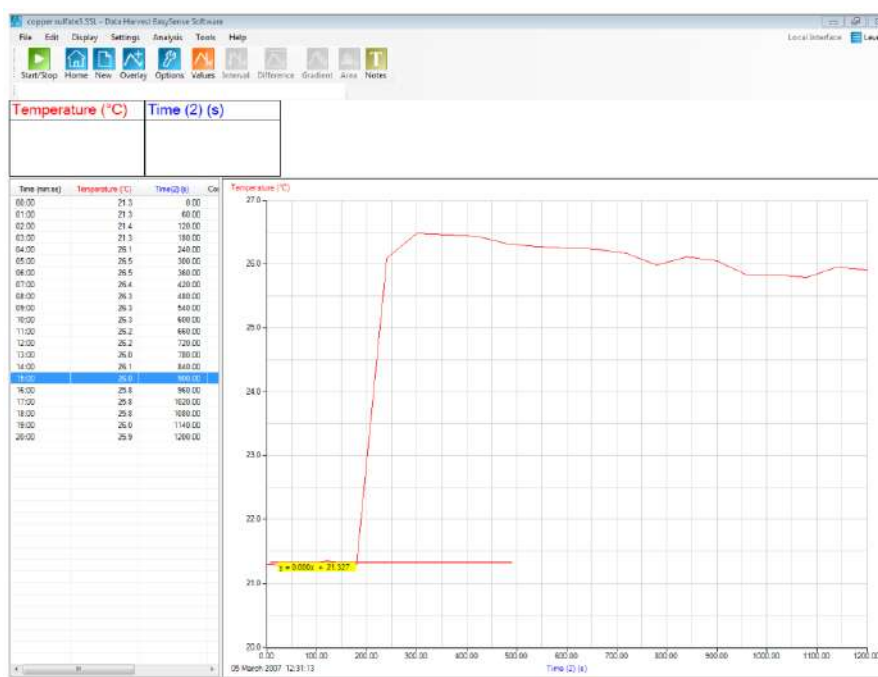


Fig 3.7 Best fit line created to find the base temperature



Fig 3.7 Best fit line through the falling temperature data

If the line does not look as if it is the best, best fit, click on either end of the best fit line and move it round until you are happy with the position.

To find  $T_0$  either

Use the  $y = mx + c$  value on the  $T_0$  best fit line.

Or, select Values and align the Time(2) vertical to the 180 s mark and align the horizontal line over the best fit line to see the  $T_0$  value in the red data box.



Fig 3.8 Using the Values tool to find the  $T_2$  value, align with the same Time(2) used for the  $T_0$  value and set the horizontal values line onto the upper best fit line.

The sample data give  $T_0 = 21.3$  and  $T_2 = 26.6$

So  $\Delta T = 26.6 - 21.3 = 5.3^\circ\text{C}$

## Analysing the data

Heat released by reaction = heat gained by the solution

1. Heat gained by the solution =  $M \times C \times \Delta T$
2.  $M$  = Mass of solution.
3.  $C$  = specific heat capacity, assumed to be  $4.18 \text{ J K}^{-1} \text{ g}^{-1}$
4.  $\Delta T$  = temperature change, as Kelvin

Use the values of  $T_0$  and  $T_2$  substituted into the calculation to find the energy transferred. Correct as necessary for joules to kilojoules.

Use the values obtained for both experiments to calculate the  $\Delta H_3$  in  $\text{J K}^{-1} \text{ g}^{-1}$

The joules value from our sample data will be  $5.6 \times 50 \times 4.18 = 1170 \text{ J}$  or  $1.17 \text{ kJ}$

### 3. To determine an enthalpy change indirectly

#### Conversion of anhydrous copper(II) sulfate into hydrated copper(II) sulfate

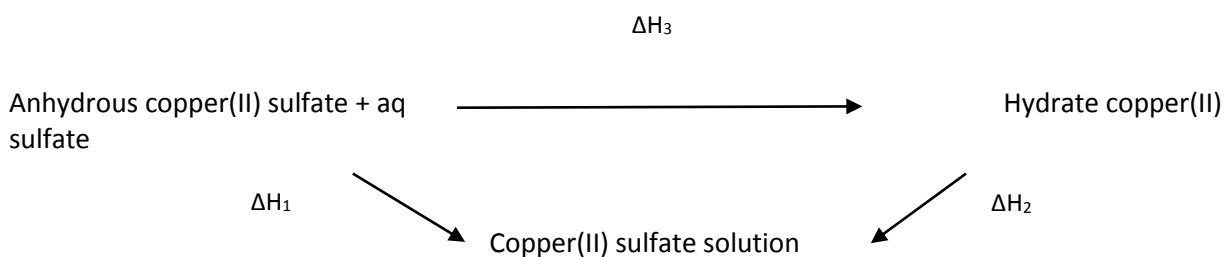
##### Practical skills AT a, d

Hess's law indicates that no matter what the route a reaction takes the energy change will be the same. In this practical you are to measure the energy change of anhydrous copper (II) sulfate to the hydrated copper (II) sulfate form.

This is not an energy change that can be measured directly as the water is added to the crystalline structure and is not available in a form or location that is possible to measure.

However we can hydrate to excess by dissolving the anhydrous form in water. If we then dissolve a same quantity of hydrated copper sulphate in a same volume of water we can use the energy changes of both to find the unknown value.

The Hess's law cycle for the change is described below



Hess's law tells us that:

$$\Delta H_1 = \Delta H_2 + \Delta H_3$$

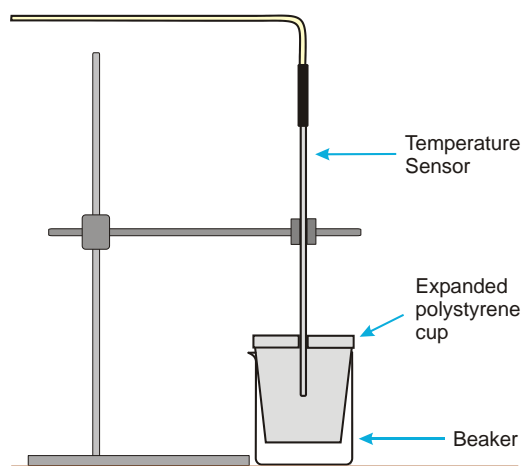
It follows that:

$$\Delta H_3 = \Delta H_1 + \Delta H_2$$

##### Assumptions made

1. If the reaction is exothermic, the heat evolved is only transferred to the solution.
2. If the reaction is endothermic, the heat is only absorbed from the solution.
3. The reaction takes place sufficiently rapidly for the maximum temperature change to be reached before the mixture begins to return to room temperature.
4. The reaction vessel does not gain or lose heat.
5. There is no heat exchange with the environment.
6. The specific heat capacity of the aqueous solution is taken to be that of water.

The experiment uses anhydrous copper(II) sulfate and hydrated copper(II) sulfate.



## Apparatus

1. Temperature sensor
2. 0.025 moles anhydrous copper(II) sulfate
3. 0.025 moles hydrated copper(II) sulfate
4. Polystyrene cup
5. Deionised water
6. 100 cm<sup>3</sup> beaker (polystyrene or well insulated)
7. Measuring cylinders
8. Accurate balance
9. Stirrer and magnetic flea or glass stirring rod
10. Retort stand, boss, clamps

## Set up

Check with your tutor for the method as there are two possible variations that will depend on the expected learning outcome of the practical. This will modify instruction 4 in the method.

1. Use EasyLog or
2. Use Graph and set the logger to record for 20 minutes and at a rate of 1 sample per minute.

Recording method	Time	Intersample	Total samples	Overlay
Graph	20 minutes	1 minute	20	On

## Method

1. Calculate the mass of the copper compound required and weigh it out. Make a record of the exact mass measured out. Take care to keep the anhydrous form as dry as possible at all times.
2. Set up the apparatus as shown in the diagram. Connect the Temperature sensor to the data logger.
3. Place 25 cm<sup>3</sup> of deionised water into the beaker.
4. Use EasyLog or Graph (see setup) and select Start. Let the data record for 4 minutes with the water being continuously stirred.
5. Add the anhydrous copper(II) sulfate rapidly to the water. Keep the water stirred.
6. Record data for at least 15 minutes.
7. Stop logging and Save the data.

- Repeat the data collection for hydrated copper(II) sulfate. One exception to the method is that the volume of water used should be 24 cm<sup>3</sup> to account for the water already present in the hydrated form of the copper compound.

## Results and analysis

Either

Use the Values tool to find the temperature at each minute and plot a graph on paper. Use the data for the first four minutes to create a best fit base temperature line and make a best fit line for the data after the addition of the compounds. Extend both lines to find  $T_0$  to find  $T_2$  and hence  $\Delta\theta$ .

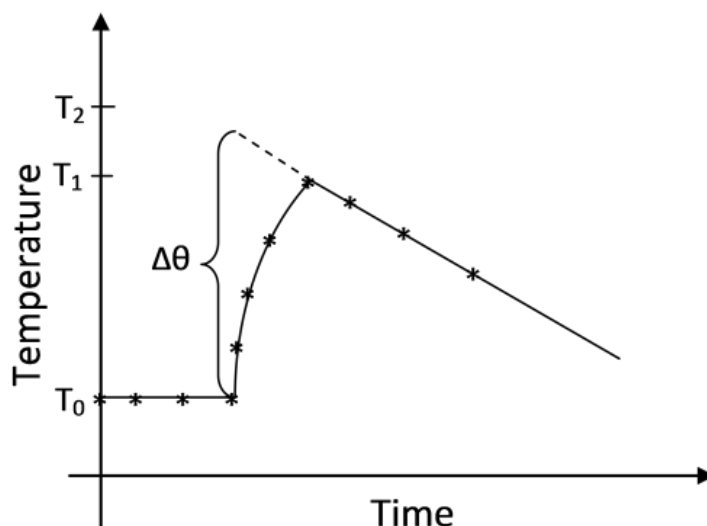


Fig 3.1 Finding the estimate of the maximum temperature rise.

Or

Use the tools within EasySense to find  $T_0$  and  $T_2$  and hence  $\Delta\theta$ .

Convert the time to a data channel.

- Use the Post log Function, Formula and select  $ax^2 + bt + c$ . Make  $a = 0$ ,  $b = 1$  and  $c = 0$ . Name the new data set Time(2) and set the units to (s).
- Use Display, X-Axis, Channel to convert to a channel vs. channel graph.
- Click on the x axis label to use the Time(2) channel and the y axis to be temperature.
- Use Best Fit lines to create the  $T_0$  line and the extrapolated cooling phase best fit line.
- Use Values to find  $T_0$  and  $T_2$ .
- Calculate  $\Delta\theta$ .

## Calculations

Heat released by reaction = heat gained by the solution

- Heat gained by the solution =  $M \times C \times \Delta T$
- $M$  = Mass of solution (mass of acid + mass of magnesium ribbon)
- $C$  = specific heat capacity, assumed to be  $4.18 \text{ J K}^{-1}\text{g}^{-1}$
- $\Delta T$  = temperature change

Use the values of  $T_{\text{start}}$  and  $T_{\text{final}}$  substituted into the calculation to find the energy transferred. Make sure the volume of the acid and magnesium actually used, are used, and not the suggested volumes and masses.

**Worked example**

In a similar experiment 100.5 cm<sup>3</sup> of acid were used, 4.2 g of magnesium ribbon added and a temperature increase of 5.2°C was measured from the graph:

Substituting the experimental data into the calculation

$$M \times C \times \Delta T$$

$$104.7 \times 4.18 \times 5.2 = 2275 \text{ J}$$

3. The atomic mass of Magnesium = 24.3

4. Moles of Magnesium in the reaction is  $0.500 \div 24.3 = 0.0206 \text{ mol}$

Therefore, the heat released per mole of magnesium =  $2275 \div 0.0206 = 110\,436 \text{ J mol}^{-1}$  or  $110.4 \text{ kJ mol}^{-1}$

## Teacher's notes

### 4. Hess's law: The reaction between sodium hydroxide and hydrochloric acid

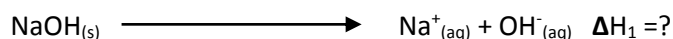
#### Practical skills AT a, d

If no thermo chemical data is available for a particular reaction or the reaction is considered to be too dangerous to make in one step, the enthalpy change can still be predicted by calculation. Hess found that whatever the route taken to make a product the enthalpy change was always the same, provided the changes are determined under the same conditions.

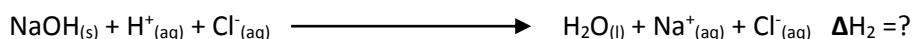
In this experiment three reactions are going to be monitored, the sum of the heats of reaction of two of the reactions should equal the heat of reaction of the third.

The reactions are:

1. Solid sodium hydroxide dissolves in water to form an aqueous solution of ions.



2. Solid sodium hydroxide reacts with aqueous hydrochloric acid to form water and an aqueous solution of sodium chloride.



3. Solutions of aqueous sodium hydroxide and hydrochloric acid react to form water and aqueous sodium chloride.



The objective of this practical is to confirm Hess's law of additivity.

Reaction 2 is the sum of the reactions 1 and 3, the  $\Delta H$  values of 1 + 3 should equal that of 2.

#### Apparatus

1. Temperature sensor
2. 100 cm<sup>3</sup> measuring cylinder
3. 250 cm<sup>3</sup> beaker
4. Expanded polystyrene cup
5. 50 cm<sup>3</sup> 1.0 mol dm<sup>-3</sup> Sodium hydroxide (NaOH)
6. 50 cm<sup>3</sup> 1.0 mol dm<sup>-3</sup> Hydrochloric acid (HCl)
7. 100 cm<sup>3</sup> 0.5 mol dm<sup>-3</sup> Hydrochloric acid (HCl)
8. 100 cm<sup>3</sup> Water
9. 2 x 4.0 g solid Sodium hydroxide (pellets) pre-weighed in a small bottle or beaker
10. Retort stand, boss and clamp
11. Accurate balance

#### Set up

Use EasyLog. If the students let the recording run for 5 minutes it will give plenty of time to record all the relevant information. When using EasyLog and Overlay the repeat time is linked to the time of the first recording. E.g. if the original recording lasted 5 minutes then all subsequent Overlay logs will also last 5 minutes.



## Hazard information

Sodium Hydroxide		Precautions	
Corrosive 0.5 M or higher	Irritant	Goggles and gloves should be worn	The solid hydroxide should not be allowed to come into contact with skin, if it does it should be washed away with plenty of running cold water

## Practical notes

Solid sodium hydroxide should be pre weighed for the students in small pots; to save time the exact mass of the sodium hydroxide could be indicated on the pot. The students need to use gloves and wear goggles when handling this material.

There have been several assumptions made in the experiment.

1. The heat capacity of all the liquids is that of water.
2. The density of all of the solutions is taken to be  $1.0 \text{ g / cm}^3$
3. The temperature of the solutions of sodium hydroxide and hydrochloric acid are the same when mixed. If the solutions have been made up the day before this is going to be true.

If expanded polystyrene cups cannot be found a small beaker fitted into a larger beaker will suffice. The gap between the beakers should be filled with an insulating material such as cotton waste or mineral wool.

## Analysis and results

The students are lead through the calculation in the work sheet.

### They will need to calculate:

1. The temperature change for each reaction
2. The energy trapped in the calorimeter through specific heat x mass x temperature change. This is defined on the student's sheet as  $Q = C_p \times m \times \Delta T$ . Specific heat is that of the water in the experiment and is assumed to be 4.18. This assumption is of course one source of error.
3. The value calculated for Q will be a positive value, placing a negative in front of the value will convert it to the  $\Delta H$  value.
4. Moles of NaOH are calculated from the mass used divided by the sum of the formula masses. Na is taken to be 22.98, Oxygen 15.99 and Hydrogen 1.00. NaOH is therefore determined as 39.97. Values from different data tables may vary according to number of decimals used and the reference atom used. This is another source of "error" in the final value.

**Moles** = Mass used / Molar mass

**Molarity** = Moles in solution x (volume of solution used / 1000)

**Mass in a "molar" solution** = molarity x molar mass.

**Example results (not from experiment) and analysis**

	Reaction 1	Reaction 2	Reaction 3
<b>1. Mass of NaOH</b>	2.0 g	2.0 g	(no solid mass, in solution)
<b>2. Mass of solution (total)</b>	100.0 g	2.0 g	2.0 g
<b>3. Final temperature</b>	27.0°C	33.8°C	29.1°C
<b>4. Start temperature</b>	22.0°C	22.2°C	22.3°C
<b>5. Change in temperature <math>\Delta t</math></b>	5.0	11.6	6.8
<b>6. Heat Q</b> $Q = C_p \times m \times \Delta t$	$4.18 \times 100 \times 5 =$ 2.09 kJ	$4.18 \times 100 \times 11.6 =$ 4.85 kJ	$4.18 \times 100 \times 6.8 =$ 2.84 kJ
<b>7. <math>\Delta H</math></b> $\Delta H = -Q$	-2.09 kJ	-4.85 kJ	-2.84 kJ
<b>8. Moles of NaOH</b>	0.05 mol	0.048 mol	0.05 mol
<b>9. <math>\Delta H / \text{mol}^{-1}</math></b>	-41.8 kJ mol <sup>-1</sup>	-101 kJ mol <sup>-1</sup>	-56.8 kJ mol <sup>-1</sup>
<b>10 Experimental Value</b>	(reaction 1 + reaction 3) = -98.6 kJ mol <sup>-1</sup>		
<b>11 Accepted value</b>	(reaction 2) = -101 kJ mol <sup>-1</sup>		
<b>12 Percent error</b>			

## 4. Hess's law: The reaction between sodium hydroxide and hydrochloric acid

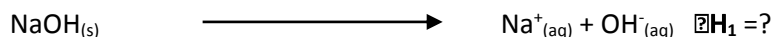
### Practical skills AT a, d

Hess's law states that the total enthalpy change of a reaction is independent of the route taken.

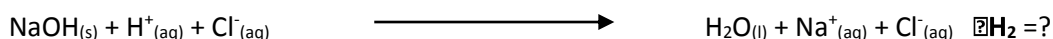
In this experiment three reactions are going to be monitored, the sum of the heats of reaction of two of the reactions should equal the heat of reaction of the third.

The reactions are:

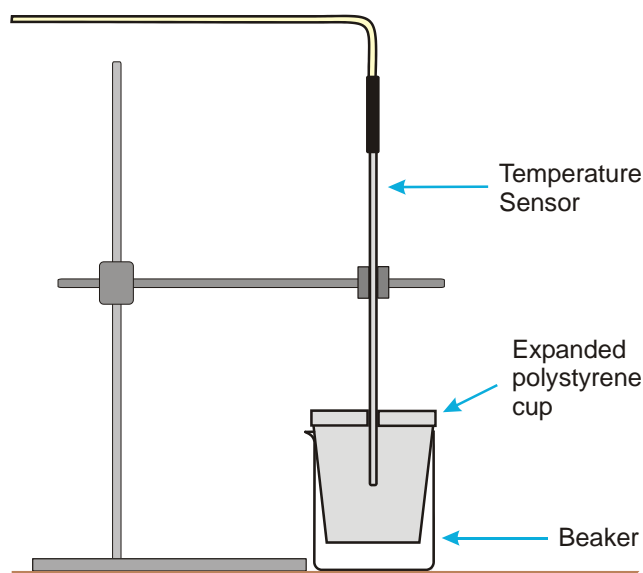
1. Solid sodium hydroxide dissolves in water to form an aqueous solution of ions.



2. Solid sodium hydroxide reacts with aqueous hydrochloric acid to form water and an aqueous solution of sodium chloride.



3. Solutions of aqueous sodium hydroxide and hydrochloric acid react to form water and aqueous sodium chloride.



### Apparatus

1. Temperature sensor
2. 100 cm<sup>3</sup> measuring cylinder
3. 250 cm<sup>3</sup> beaker
4. Expanded polystyrene cup
5. 50 cm<sup>3</sup> 1.0 mol dm<sup>-3</sup> Sodium Hydroxide (NaOH)
6. 50 cm<sup>3</sup> 1.0 mol dm<sup>-3</sup> Hydrochloric acid (HCl)
7. 100 cm<sup>3</sup> 0.5 mol dm<sup>-3</sup> Hydrochloric acid (HCl)
8. 100 cm<sup>3</sup> Water
9. 2 x 4.0 g solid Sodium hydroxide (pellets) pre-weighed in a small bottle or beaker
10. Retort stand, boss and clamp
11. Accurate balance

## Risk assessment

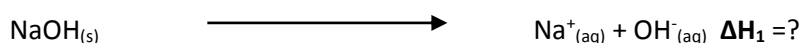
Sodium Hydroxide		Precautions	
Corrosive 0.5 M or higher	Irritant	Goggles and gloves should be worn	The solid hydroxide should not be allowed to come into contact with skin, if it does it should be washed away with plenty of running cold water

## Method

A simple calorimeter will need to be set up as shown. The inner cup is made of expanded polystyrene, if one of these is not available then a plastics drink cup surrounded by insulating wool should work as well.

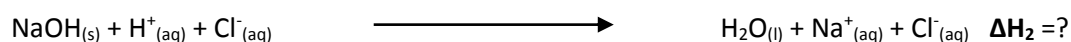
For the purposes of this experiment the heat loss into the air from the surface of the reactants is assumed to be negligible.

## Reaction 1



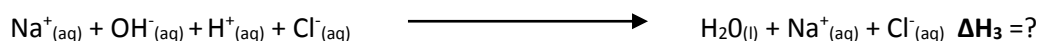
1. Measure out 100 cm<sup>3</sup> of water into the inner cup of the calorimeter.
2. Connect the Temperature sensor to the data logger. Position the sensor in the water; use a clamp to hold it in place. Make sure the sensor is not touching the walls of the cup, and is in the centre of the liquid.
3. Collect a pre weighed container of the solid sodium hydroxide. DO NOT LET THIS COME INTO CONTACT WITH YOUR SKIN, if it does, wash off with running cold water immediately. Any spillages must be reported.
4. Select EasyLog as the recording method.
5. Select Overlay (allows the data from all three experiments to be presented on the same graph).
6. Click on Start, wait for a few seconds to record the starting temperature, and then add the sodium hydroxide to the water. Use a stirring rod to keep the water moving in the cup.
7. Keep recording data for about 5 minutes (this will allow enough time for the data in the other reactions to be captured). Click on Stop to finish logging.
8. Dispose of the solution as instructed by your teacher, wash the cup and sensor thoroughly and dry ready for the next reaction.

## Reaction 2



1. Repeat the experiment using 100 cm<sup>3</sup> of 0.5 mol dm<sup>-3</sup> Hydrochloric acid instead of the water.

## Reaction 3



1. Repeat the experiment using 50 cm<sup>3</sup> of 1.0 mol dm<sup>-3</sup> Hydrochloric acid instead of the water and 50 cm<sup>3</sup> of 1.0 mol dm<sup>-3</sup> Sodium hydroxide solution instead of the solid sodium hydroxide.

## Analysis

- Each experiment uses the same volume of liquid, 100 cm<sup>3</sup>. The mass of the liquid will be assumed to be 1.0 g cm<sup>3</sup>.
- Calculate the temperature change for each experiment ( $T_{\text{final}} - T_{\text{start}} = \Delta T$ ).
- Calculate the heat of reaction Q for each reaction using the formula  $Q = C_p \times m \times \Delta T$ .
- $m$  = the mass of liquid used,
- $C_p = 4.18 \text{ J/g}^\circ\text{C}$  convert your answers to kJ.
- Find  $\Delta H$  ( $\Delta H = -Q$ ).
- Calculate the number of moles of NaOH used in each reaction. In experiments 1 + 2 this can be calculated directly from the mass used. In experiment 3 the molarity of the solution will need to be used.
- The combined  $\Delta H$  values of experiment 1 and 3 should equal the value of experiment 2.

Assume the value for experiment 2 to be the true value, calculate the error in this experiment.

**Moles** = Mass used  $\div$  Molar mass

**Molarity** = Moles in solution  $\times$  (volume of solution used  $\div$  1000)

Mass in a "molar" solution = Molarity  $\times$  molar mass.

MW of NaOH can be calculated using the following mass values.

- Na is taken to be 22.98
- Oxygen 15.99
- Hydrogen 1.00

	Reaction 1	Reaction 2	Reaction 3
1. Mass of NaOH	g	g	(no solid mass, in solution)
2. Mass of solution (total)	g	g	g
3. Final temperature	$^\circ\text{C}$	$^\circ\text{C}$	$^\circ\text{C}$
4. Start temperature	$^\circ\text{C}$	$^\circ\text{C}$	$^\circ\text{C}$
5. Change in temperature $\Delta t$			
6. Heat Q $Q = C_p \times m \times \Delta t$	kJ	kJ	kJ
7. $\Delta H$ $\Delta H = -Q$	kJ	kJ	kJ
8. Moles of NaOH	mol	mol	mol
9. $\Delta H/\text{mol}$	kJ mol <sup>-1</sup>	kJ mol <sup>-1</sup>	kJ mol <sup>-1</sup>
10. Experimental value (reaction 1 + reaction 3)	kJ mol <sup>-1</sup>		
11. Accepted value (reaction 2)	kJ mol <sup>-1</sup>		
12. Percentage error			

What are the sources of error? How would you control them?

## Teacher's notes

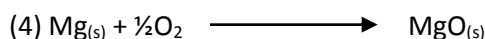
### 5. Heat of combustion: Magnesium and oxygen

#### Practical skill AT a, d

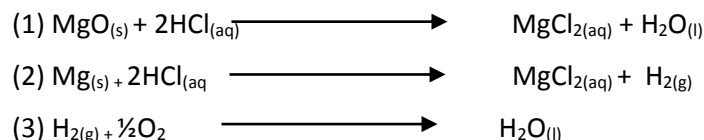
If no thermo chemical data is available for a particular reaction or the reaction is considered to be too dangerous to make in one step, the enthalpy change can still be predicted by calculation. Hess found that whatever the route taken to make a product the enthalpy change was always the same, provided the changes are determined under the same conditions.

In this investigation the heat of combustion of magnesium ribbon is to be found by producing magnesium oxide indirectly.

The reaction of magnesium and oxygen is:



By using other reactions with Mg the oxide MgO can be produced. The  $\Delta H$  of each of these other reactions, when added will give the  $\Delta H$  of reaction (4)



The  $\Delta H$  of reaction (3) is given in data books as -285.8 kJ. The  $\Delta H$  of reactions 1 and 2 will be derived by experiment.

#### Apparatus

1. Temperature sensor
2. 100 cm<sup>3</sup> measuring cylinder
3. 250 cm<sup>3</sup> beaker
4. Expanded polystyrene cup
5. Magnesium oxide (MgO)
6. Magnesium ribbon
7. 1 mol dm<sup>-3</sup> Hydrochloric acid (HCl)
8. Balance accurate to 0.1 g
9. Retort stand, boss and clamp

#### Risk assessment

Magnesium ribbon. Highly flammable. This needs to be carefully monitored. Follow local guidelines about storage, quantities, etc. Do not encourage burning of the magnesium. The light from burning magnesium is intense and can cause eye damage. Dry sand should be available for use as a fire extinguisher. Do not use or attempt to use water on burning magnesium.

The hydrochloric acid + magnesium reaction may produce an acid vapour. A lid for the apparatus is recommended.

#### Set up

Use EasyLog and select Overlay to collect all experiments on the same graph.

## Practical notes

It is best to have the magnesium pre-cut to sections that weigh about 0.5 g. They should be kept in a tin with a tight fitting lid. The pieces can then be weighed by the students to find the exact mass.

The accepted value for the  $\Delta H$  is -602 kJ/mol. Results from the investigation will vary but should easily be of the same magnitude. Results can be very close to the published figure, errors of less than 1% from published are possible.

## Analysis and results

The students are lead through the calculation in the work sheet. They will need to calculate:

1. The temperature change for each reaction.
2. The energy trapped in the calorimeter through specific heat x mass x temperature change. This is defined on the students sheet as  $Q = C_p \times m \times \Delta T$ . Specific heat is that of the water in the experiment and is assumed to be 4.18. This assumption is of course a source of error.
3. The value calculated for Q will be positive value, placing a negative in front of the value will convert it to the  $\Delta H$  value.
4. Moles of MgO and Mg are calculated from the mass used divided by the sum of the formula masses. Mg is taken to be 24.3 and MgO is 40.29. Values from different data tables may be different according to number of decimals used and the reference atom used. This is another source of 'error' in the final value.

Worked example	Reaction 1	Reaction 2
Volume of hydrochloric acid (cm <sup>3</sup> )	100	100
Final temperature (T <sub>2</sub> )	29.5	39.7
Starting temperature (T <sub>1</sub> )	22.1	22.3
Change in temperature $\Delta T = (T_2 - T_1)$	7.4	17.4
Mass of solid (g)	1.0	0.5
Energy $Q = C_p \times m \times \Delta t$	$1.18 \times 7.4 \times 101 = 3124 \text{ J}$ 3.124 kJ	$4.18 \times 17.4 \times 100.5 = 7309 \text{ J}$ 7.309 kJ
$\Delta H$	-3.124 kJ	-7.309 kJ
Moles	$1.0 \div 40.3 = 0.0248$ Moles MgO	$0.5 \div 24.3 = 0.0206$ Moles Mg
$\Delta H \text{ mol}^{-1}$	$-3.124 \div 0.0248 =$ $-125.97 \text{ kJ mol}^{-1}$ (value rounded up)	$-7.309 \div 0.0206 =$ $-354.80 \text{ kJ mol}^{-1}$
(1) $\text{MgCl}_{2(aq)} + \text{H}_2\text{O}_{(l)} \longrightarrow \text{MgO}_{(s)} + 2\text{HCl}_{(aq)}$		+125.97
(2) $\text{Mg}_{(s)} + 2\text{HCl}_{(aq)} \longrightarrow \text{MgCl}_{2(aq)} + \text{H}_{2(g)}$		-354.80
(3) $\text{H}_{2(g)} + \frac{1}{2}\text{O}_2 \longrightarrow \text{H}_2\text{O}_{(l)}$		-286.0
(4) $\text{Mg}_{(s)} + \frac{1}{2}\text{O}_2 \longrightarrow \text{MgO}_{(s)}$		(1) + (2) + (3) = (4) $+125.97 + (-354.80) + (-286.0) =$ $-515 \text{ kJ mol}^{-1}$
Note reaction (1) has been reversed to provide the energy data for the creation of MgO from MgCl <sub>2</sub> and H <sub>2</sub> O		
Published value is -603 kJ mol <sup>-1</sup>		
	Percentage error	14.6%

## 5. Heat of combustion: Magnesium and oxygen

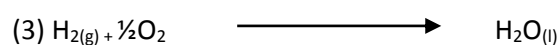
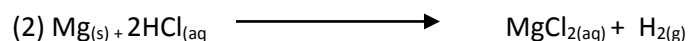
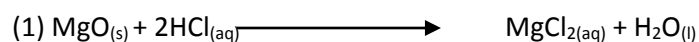
### Practical skill AT a, d

Hess's law informs us about the additivity of the heats of reaction. In this experiment you will use the principles of Hess's law to calculate the heat of a reaction that would be difficult to measure directly. The reaction of magnesium with oxygen produces large quantities of heat outside the range of most laboratory thermometers and calorimeters.

The reaction of magnesium and oxygen is:

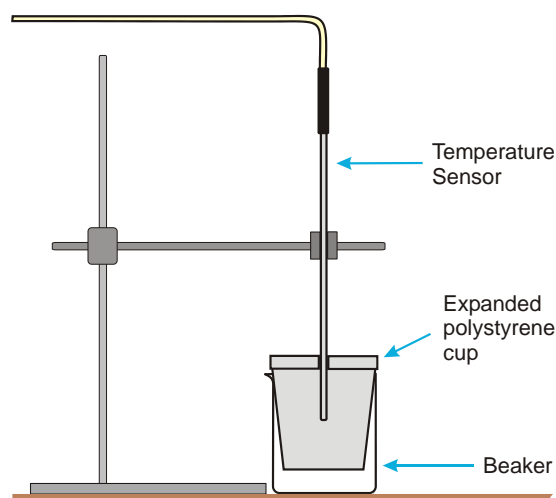


By using other reactions with Mg the oxide MgO can be produced. The  $\Delta H$  of each of these other reactions, when added will give the  $\Delta H$  of reaction (4)



The  $\Delta H$  of reaction (3) is given in data books as -285.8 kJ. The  $\Delta H$  of reactions 1 and 2 will be derived by experiment.

To calculate the heat of combustion of the reaction between magnesium and oxygen to make magnesium oxide



### Apparatus

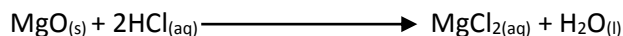
1. Temperature sensor
2. 100 cm<sup>3</sup> measuring cylinder
3. 250 cm<sup>3</sup> beaker
4. Expanded polystyrene cup
5. Magnesium oxide (MgO)
6. Magnesium ribbon
7. 1 mol dm<sup>-3</sup> Hydrochloric acid (HCl)
8. Balance accurate to 0.1 g
9. Retort stand, boss and clamp



## Method

Set up a simple calorimeter as shown. The inner cup is made of expanded polystyrene. If this is not available a plastic drinks cup can be used with the space between it and the beaker being filled with insulating material. The practical will be made up of measurements from 3 reactions. The third reaction (hydrogen + oxygen) will not be done but the data from the experiment is made available.

### Reaction 1

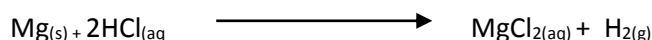


1. Place 100 cm<sup>3</sup> of 1.0 mol dm<sup>-3</sup> hydrochloric acid into the inner cup of the calorimeter.
2. Connect the Temperature sensor to the data logger. Position the Temperature sensor in the acid, making sure the tip of the sensor is not touching any of the sides of the cup.
3. Select EasyLog as the recording method.
4. Select Test Mode (Tools menu), monitor the temperature of the acid, when it is stable cancel Test Mode.
5. Using an accurate scale weigh out approximately 1.0 g of magnesium oxide and record the exact mass used.
6. Click on Start; let the recording run for a few seconds to record the starting temperature.
7. Add the magnesium oxide to the acid in the calorimeter and stir the solution.
8. Stop the recording when the temperature has shown an obvious decrease from its peak value. (You should not need to record for more than 5 minutes, typically 2.5 minutes will be enough).
9. At the end of the logging period use Values and note down the start temperature (Tstart) and the maximum temperature (Tmax) reached.

Hydrochloric acid and Magnesium oxide	
Start temperature (Tstart)	Maximum temperature (Tmax)

10. Select Overlay to allow the data for reaction 2 to be collected on the same graph.
11. Use Add Text to label the graph line as 'Reaction 1'. Save the data.

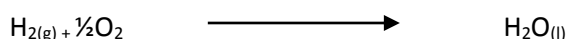
### Reaction 2



1. Repeat the experiment using 0.5 g of magnesium ribbon instead of the magnesium oxide.
2. Use Add Text to label the graph line as 'Reaction 2'. Save the data.

Hydrochloric acid and Magnesium ribbon	
Start temperature (Tstart)	Maximum temperature (Tmax)

### Reaction 3



Hydrogen is burnt in oxygen. The nature of the reaction means the data is supplied.

The  $\Delta H$  for the reaction is **-285.8 kJ**.

## Analysis of data

Step	What to do / calculate
1	Calculate the temperature change for each reaction ( $T_{\text{start}} - T_{\text{max}} = \Delta t$ )
2	Calculate the heat released, $Q$ , using $Q = C_p \times m \times \Delta t$ for each reaction. $C_p = 4.18 \text{ J/g}^\circ\text{C}$ , $m$ = the mass of liquid used (100 g)
3	Determine $\Delta H$ ( $\Delta H = -Q$ )
4	Calculate the number of moles of MgO and Mg used in each experiment.
5	Use your step 3 and step 4 results to calculate $\Delta H/\text{mol}$ for MgO and Mg
6	Calculate $\Delta H/\text{mol}$ Mg for reaction 4. Use your step 5 results and $\Delta H = -285.8 \text{ kJ}$ for reaction 4.

## Results and calculations table:

	Reaction 1	Reaction 2
Volume of hydrochloric acid ( $\text{cm}^3$ )		
Final temperature ( $T_2$ )		
Starting temperature ( $T_1$ )		
Change in temperature $\Delta T = (T_2 - T_1)$		
Mass of solid (g)		
Energy $Q = C_p \times m \times \Delta t$	= kJ	= kJ
$\Delta H$	kJ	kJ
Moles	= Moles MgO	= Moles Mg
$\Delta H \text{ mol}^{-1}$	= kJ $\text{mol}^{-1}$ (value rounded up)	= kJ $\text{mol}^{-1}$
(1) $\text{MgCl}_{2(\text{aq})} + \text{H}_2\text{O}_{(\text{l})} \longrightarrow$	$\text{MgO}_{(\text{s})} + 2\text{HCl}_{(\text{aq})}$	
(2) $\text{Mg}_{(\text{s})} + 2\text{HCl}_{(\text{aq})} \longrightarrow$	$\text{MgCl}_{2(\text{aq})} + \text{H}_{2(\text{g})}$	
(3) $\text{H}_{2(\text{g})} + \frac{1}{2}\text{O}_{2} \longrightarrow$	$\text{H}_2\text{O}_{(\text{l})}$	-285.8
(4) $\text{Mg}_{(\text{s})} + \frac{1}{2}\text{O}_{2} \longrightarrow$	$\text{MgO}_{(\text{s})}$	(1) + (2) + (3) = (4) = kJ $\text{mol}^{-1}$

## Teacher's notes

### 6. Acid, alkali titration using a burette

#### Practical skills AT a, c, d

This is a standard pH titration investigation that uses the EasySense software to record the volumes of acid / alkali added and the change in pH.

Titration is an activity that can prove troublesome for many students; their lack of practical skills becomes apparent as the practical progresses. Using the data logger takes some of the confusion away from the student. Experience has often shown that for a task of this complexity, that students will focus on getting one part right (recording burette volumes for example) and forget to take the pH reading.

The activity uses the “Asks for a Volume” function in SnapShot. The function prompts the student for the volume added after each pH reading has been taken. Hopefully the need to “snap” the data and the visual prompt for additional information will keep the student on task.

With the data recorded electronically analysis of the data will become easier and access to further tools of analysis becomes possible.

The activity can be seen as its own ends to means or it can be the foundation for studies using an automated titration system.

The method can easily be modified for any combination of solutions or measure of reaction e.g. temperature, conductivity.

#### Apparatus

1. pH sensor
2. 100 ml conical flask
3. Stirrer – glass rod or magnetic
4. Retort stand and clamp
5. 2.5 ml pipettes or syringe
6. 100 ml beaker
7. 20 cm<sup>3</sup> Sodium hydroxide (0.1 mol dm<sup>-3</sup> NaOH)
8. 20 cm<sup>3</sup> Hydrochloric acid (0.1 mol dm<sup>-3</sup> HCl)

**Note:** Solutions should all be at the same temperature

#### Set up

Recording method	Display	Pre-log Function
SnapShot	Table and graph	Titration, Asks for the Volume added

The volume the student is asked for will be the volume indicated on the burette after each addition.

#### Practical notes

There can be a danger that if the students wait for the instrument to stabilise and take a reading they are then waiting for the ‘correct result’.

The solutions can be purchased ready made to the concentrations given; the molarities are well controlled by most chemical suppliers and are probably more accurate than dilutions of strong stock to the same value.

Readings to within 0.5 of a pH unit will be more than acceptable at the introductory level of this investigation. The readings even at 0.5 of pH unit will be more accurate than values derived from universal indicator solutions or papers, indicators may be even more accurate, but to the naive user the colour change can be missed (or misinterpreted).

If the activity is conducted as a whole class experiment the students may well need a reminder of the fragility of the pH sensor. Suggestions that they should not be used for stirring and they should be left in the storage solution when not in use would be appropriate.

It would be sensible to have some storage solution at hand to replace any spillages of the solution. Use the recipe in the pH sensor manual.

The pH sensor can be calibrated to standard buffers solutions if high accuracy is required, the nature of the calibration may create a loss of accuracy at the extreme ends of the scale but will enhance mid-range readings.

Consider also the effect of temperature when deciding to calibrate the pH sensor, heat produced in the reaction can introduce a greater error than a suspect calibration. Please refer to the pH sensor manual for more details.

### Sample data

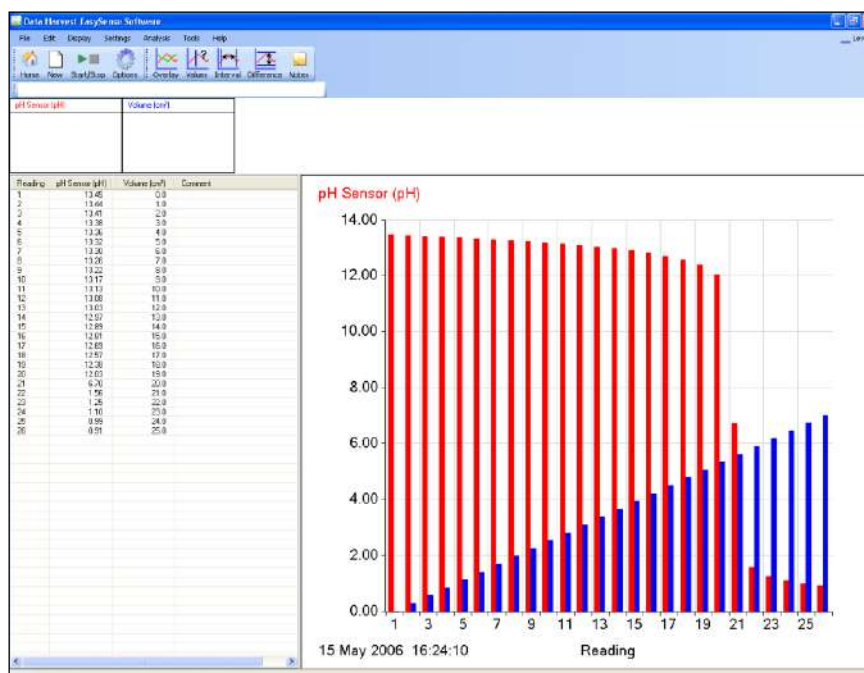


Fig 6.1 Data as collected, 1 cm<sup>3</sup> additions. Note how volume is incremental, in this example no attempt was made to refine the volume added as the end point was reached.

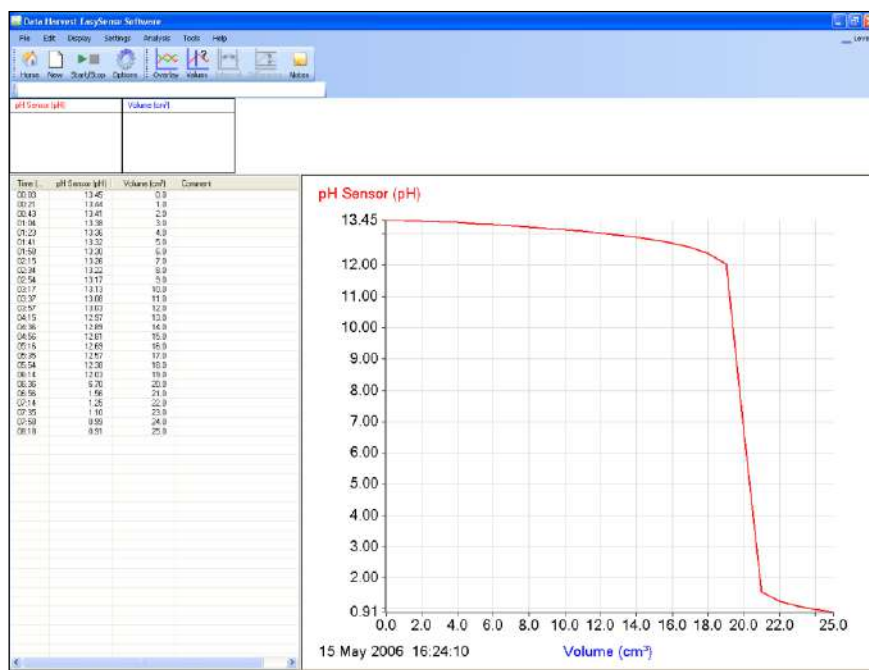


Fig 6.2 Axis changed to give pH vs. Volume, line used for the graph not bar. Notice in the table that reading number has gone and time appeared – it took 8 minutes to do this experiment!

## Analysis of data

With the data recorded electronically there is no real need to make the pH vs. Volume graph. Using Values will tell the observer both the pH and the volume at that pH.

If the data has been collected with small increments you could apply a first and second derivative analysis. When a first derivative function (**a dx/dt**) is applied to the pH data you will get a “spike” when the rate of change in pH is greatest. The peak of the derived spike is the “end point” of the reaction and gives a very accurate definition of the end point / point of neutralization.

If a second derivative function (**a dx/dt**) is applied to the first derivative data you will get a double spike with one peak above the x-axis and another below the x-axis. The intersect is the end point of the reaction and gives a very accurate definition of the end point / point of neutralization.

The **a dx/dt** function can be accessed by two routes,

1. As a Preset function: From the Tools menu select Post-log Function, Preset function, Titration, First derivative of pH.
2. As a Formula function: **a dx/dt**. This does the same work as the preset function but exposes the students to the math in a more obvious manner. From the Tools menu select Post-log Function, Formula, **a dx/dt**.
  - Follow the wizard, the student will need to indicate the channel that contained the pH data, the name of the new channel ( $\Delta\text{pH}$ ) and give the axis limits
  - A multiplier is also asked for as the value “a”, if pH is falling a will equal “-1” (or bigger number) this will be needed to convert the values to a positive, and to make them large enough to be seen. The exact value of the multiplier will subject o trial and error, it depend upon the strength of the reagents and the reaction. A useful starting value is -10 or +10

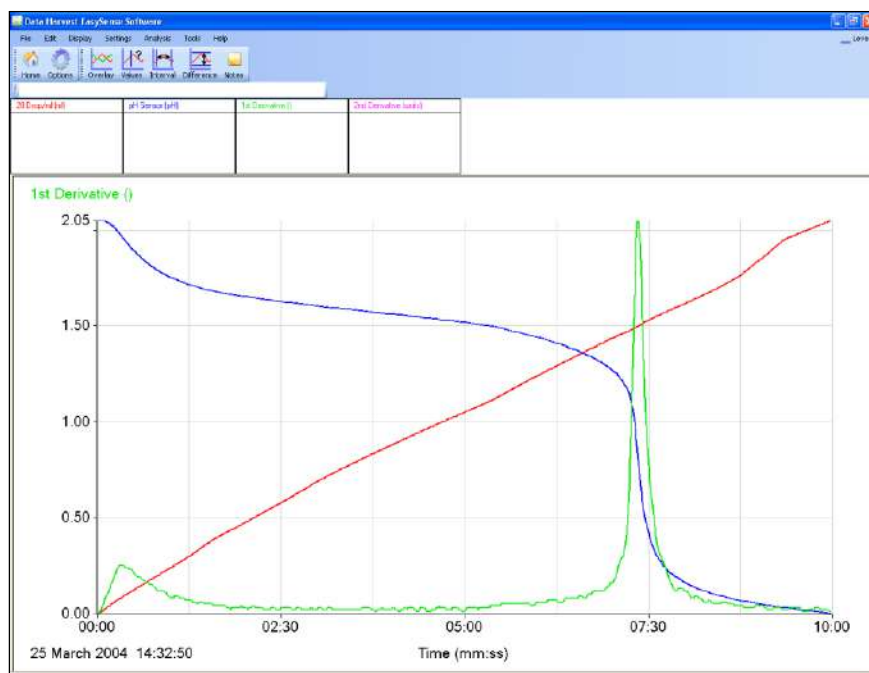


Fig 6.3 Application of 1<sup>st</sup> derivative to a titration of sodium bicarbonate with hydrochloric acid.

Sample data collected using a Drop counter. You can get very good results with a burette / pipette but you do need to increase the resolution of the addition regime i.e. use the accuracy of the burette to add  $0.1 \text{ cm}^3$  of titrant. The clarity of the end point is obvious

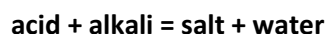


Fig 6.4 Application of second derivative to a titration of sodium bicarbonate with hydrochloric acid, note the intercept of the x-axis.

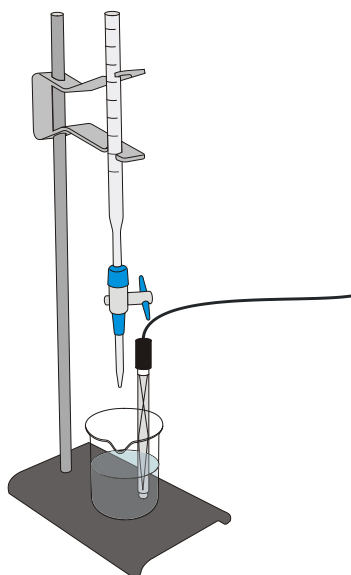
## 6. Acid, alkali titration using a burette

### Practical skill AT a, c, d

An acid will react with an alkali to produce a salt and water. The word equation for this reaction is:



In this investigation you will react hydrochloric acid (the acid) with sodium hydroxide (the alkali). They will form sodium chloride (a salt). The hydrochloric acid will be used up; this should mean that the amount of acid in the reaction will decrease. You will watch the reaction by measuring the change in pH as sodium hydroxide is added to the acid.



### Apparatus

1. pH sensor
2. Conical flask
3. Stirrer
4. Retort stand and clamp
5. 2.5 ml pipettes or syringe
6. 100 ml beaker
7. 20 cm<sup>3</sup> alkali solution - Sodium hydroxide (bench) (0.1 mol dm<sup>-3</sup> NaOH)
8. 20 cm<sup>3</sup> acid solution - Hydrochloric acid (bench) (0.1 mol dm<sup>-3</sup> HCl)

Note: Solutions should all be at the same temperature

### Risk assessment

Sodium hydroxide	Precautions	
Corrosive 0.5 M or higher Irritant	Goggles and gloves should be worn	Should not be allowed to come into contact with skin, if it does wash away with plenty of running cold water
		Clear spills immediately
Hydrochloric acid	Precautions	
Irritant 0.5 M or higher	Goggles and gloves should be worn	Should not be allowed to come into contact with skin, if it does wash away with plenty of running cold water
		Clear spills immediately

## Method

1. Connect the pH sensor to the data logger. Set up the apparatus as shown.
2. Set up the recording:

Recording method	Display	Pre-log Function
SnapShot	Table and graph	Titration, Asks for Volume added

3. Click on Start to begin logging.
4. Click in the graph area to record the pH value of the alkali solution in the flask. A prompt box will open and ask you for a value. Enter 0 (zero). This records the pH of the alkali before adding any acid (0 volume).
5. Using the burette add 2 cm<sup>3</sup> of acid into the flask. Gently swirl the solution, wait 10 seconds and click in the graph area to record the new pH value. Enter the volume of acid added, as indicated by the burette scale.
6. Repeat step 5, but as you get to where the volume of acid being added is close to the volume of alkali (about 15 cm<sup>3</sup>) change the volume of acid added each time to a smaller volume (0.5 or even 0.1 cm<sup>3</sup> depending on the resolution and accuracy of the burette). Don't be tempted to rush and use large additions if you want accuracy for later analysis.
7. Continue repeating until all the acid has been added then select Stop.

## Results and analysis

You will have a graph of Volume of acid added and the pH of the solution vs. Reading.

To plot volume against pH:

1. Save the data (in case you make a mistake and need to get back to the original data).
2. Select Options. Select the X-Axis tab and click on the Channel button, then OK.
3. Alter the graph to pH on the y-axis (vertical axis) and Volume on the x-Axis (horizontal).

Add a Title to the graph and then Save the results.

## Advanced analysis

You will need small steps in the data to be able to do this.

### Using first and second derivative

If a first derivative function (**a dx/dt**) is applied to the pH data you will get a 'spike' when the rate of change in pH is greatest. The point of the derived spike is the 'end point' of the reaction and gives a very accurate definition of the end point / point of neutralization.

*Note: **a dx/dt** means the difference between points x1 and x2 divided by the change in time that separates x1 and x2. D is Delta, which in science indicates a change between two defined points / times. It is often written in texts as d to get round the need to insert Δ as a symbol.*

The a dx/dt function can be accessed by two routes,

1. As a Preset function: From the Tools menu select Post-log Function, Preset function, Titration, First derivative of pH.
2. As a Formula function: This does the same work as the First derivative of pH but shows the underlying maths in a more obvious manner. From the Tools menu select Post-log Function, Formula, a dx/dt.



- You will need to indicate the channel that contained the pH data, the name of the new channel ( $\Delta\text{pH}$ ) and give the axis limits
- A multiplier is also asked for as the value “a”, if pH is falling a will equal “-1” (or bigger number) this will be needed to convert the values to a positive, and to make them large enough to be seen. The exact value of the multiplier will subject to trial and error. A useful starting value is -10 or +10

## Questions

1. When the solution is giving an acid reading (a low pH value) what is there a surplus of in the solution?
2. When the solution is giving an alkali reading (a high pH value) what is there a surplus of in the solution?
3. What is happening to the number of acid and alkaline particles when the solution reads neutral (pH 7.0)?
4. How much acid was needed to make the alkaline neutral? Why?
5. Was the change in pH the same with every volume you added?
6. Assume the molarity of the added solution was accurate; calculate the molar strength of the ‘unknown’.

## Teacher's notes

### 7. Acid base titration: Sodium carbonate with hydrochloric acid

#### Practical skills AT a, c, d

In this investigation the Drop counter is used to electronically measure the volume of hydrochloric acid titrated into a known volume of sodium bicarbonate solution. The experiment will use  $1 \text{ mol dm}^{-3}$  hydrochloric acid and  $0.5 \text{ mol dm}^{-3}$  sodium carbonate solutions.

The equation of the reaction,



It is a 1:2 reaction (that is 1 particle of  $\text{Na}_2\text{CO}_3$  reacts with 2 particles of  $\text{HCl}$ ). If the solutions are the same concentration the equivalence point of the reaction should be when double the volume of acid is run into the carbonate solution. In this investigation the solution of sodium carbonate is only half the strength of the acid used so equal volumes of the two solutions are required to reach the equivalence point. Pupils will use more acid than theory suggests making sure the end point is reached and the titration curve is extended beyond that point.

#### Apparatus

1. pH sensor
2. Drop / Bubble counter set to the correct volume range (see calibrating the Drop counter) with alignment adapter fitted
3. The drop counter reagent reservoir fitted with two stopcocks\* and tip.
4. 2 x 200 ml beakers
5. Magnetic stirrer and follower
6.  $20 \text{ cm}^3$  of  $0.5 \text{ mol dm}^{-3}$  Sodium carbonate ( $\text{Na}_2\text{CO}_3$ )
7.  $60 \text{ cm}^3$  of  $1.0 \text{ mol dm}^{-3}$  Hydrochloric acid ( $\text{HCl}$ )
8. Measuring cylinders (100 ml capacity).

\*The Drop counter reagent reservoir is fitted with two stopcocks. The upper stopcock is used to control the speed of the flow and the lower stopcock is the On / Off control. If a device with only one stopcock is used then students may find it difficult to regulate the flow to give discrete drops.

#### Set up

Recording method	Time	Intersample
Graph	10 minutes	1 s

#### Practical notes

If the pH of the water used to make up the solution of sodium carbonate is acid, the first 'plateau and step' may not be seen. If the water is made more alkaline then the titration curve will show two regions of buffering and two end points.

The simplest method of making the water alkaline is to add concentrated sodium hydroxide to the water until the pH of the water is 10. The sodium carbonate can then be added to this water to make the correct molar solution. When trialling this investigation we used 16.8 g of sodium carbonate added to  $100 \text{ cm}^3$  of the 'corrected' water to make the sodium carbonate solution ( $0.5 \text{ mol dm}^{-3}$ ). The acid used was  $1.0 \text{ mol dm}^{-3}$  stock solution. This gave a very good end point at twice the volume of the sodium carbonate which shows the 1:2 nature of the reaction.

### Calibrating the Drop counter

This investigation uses the Drop counter with one of its preset calibrated ranges e.g. 27 drops/cm<sup>3</sup> so the drops counted are automatically converted and displayed as volume in cm<sup>3</sup>.

If accuracy is not critical and you are using the reagent reservoir and tip supplied with a low viscosity liquid (like water) and the flow rate set to: -

- Fast e.g. 10 plus drops per second, use the **24 drops/cm<sup>3</sup>** range.
- Medium e.g. between 5 – 10 drops per second, use the **25 drops/cm<sup>3</sup>** range.
- Slow e.g. between 1.5 – 5 drops per second, use the **26 drops/cm<sup>3</sup>** range.
- Very Slow e.g. less than 1.5 drops per second, use the **27 drops/cm<sup>3</sup>** range

When used with a pH Sensor, the flow rate is best set very slow (less than 1.5 drops per second) to allow the pH sensor time to settle to a new reading after addition of the titrant.

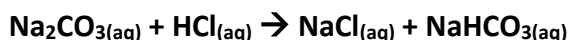
#### To calculate the number of drops in a cm<sup>3</sup>

1. Set up the reagent reservoir in the alignment adapter of the Drop / Bubble Counter. Close both stopcocks and fill the reservoir with the type of solution being used.
2. The first step is to adjust the flow rate. Place a beaker under the stopcock to catch the drops. Fully open the lower stopcock. Slowly turn the top stopcock round until it begins to produce drops and then finely adjust the drop rate. When the correct flow rate of drops is achieved close the lower stopcock to stop the flow. Now the 'flow rate' is set, do not adjust the top stopcock – leave in this position. Use the lower stopcock to turn the drops on and off.
3. Top up the reservoir. Place an accurate measuring container e.g. volumetric flask (10 mls or less) under the dropping tip. Open the lower stopcock fully and count the number of drops required to fill up to the volume mark on the measuring container. You can use the Drop / Bubble Counter to count the total number of drops (set to the Drop / bubble count range). Make sure you zero the Sensor before each run. Close the lower stopcock to stop the drops.
4. Divide the number of drops by the volume (in cm<sup>3</sup>) to get the drops per cm<sup>3</sup> value e.g. 272 drops fill a capacity of 10 ml = 27.2 drops/cm<sup>3</sup>. Top up the reservoir and repeat three times to get an average value.

### Results and analysis

The reaction is taking place in two steps:

**Step 1:** the end point at pH 8.3.



In the first step the sodium carbonate is reacting with the acid to produce sodium hydrogen carbonate. This reaction does not produce carbon dioxide (the student may observe that at this point no gas is produced).

**Step 2:** the end point at pH 3.7.



In the second step, the sodium hydrogen carbonate produced reacts with more acid to produce carbon dioxide and water.

## Sample data

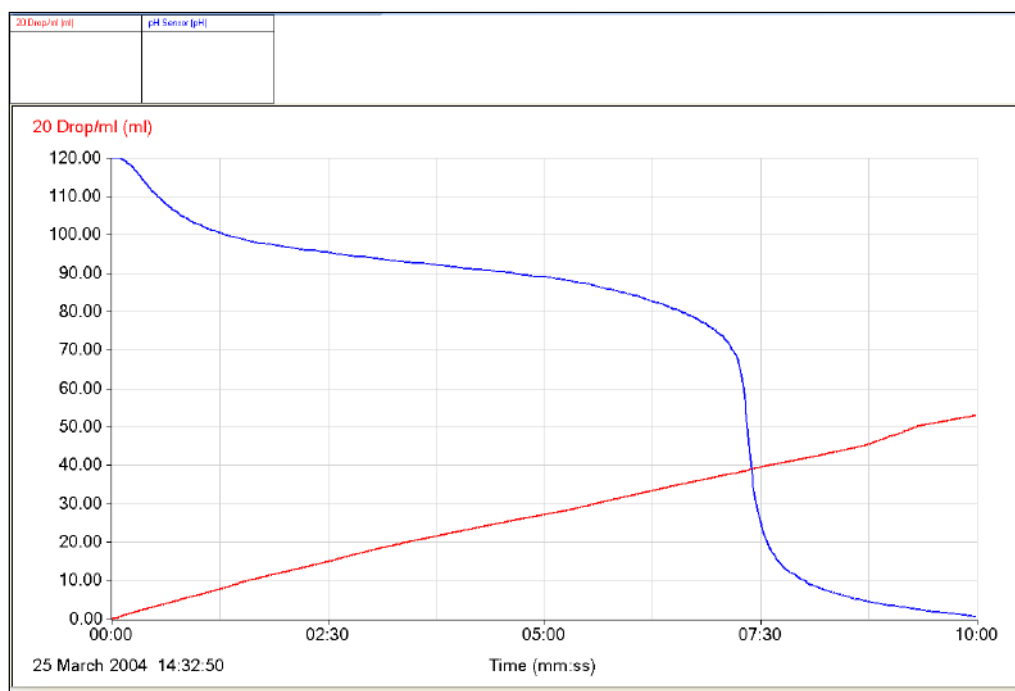


Fig 7.1 Titration of sodium carbonate with acid. Shows two end points, one at a pH of about 8.3 and a second at 3.7.

A first derivative (rate of change) will indicate more clearly the equivalence points. The accuracy of the result will still be influenced by the accuracy of the solutions. When plotted this data set reveals a peak at the point of maximum change of pH, this equals the end point. By using the Values tool and finding the peak 'rate of change' value this will give the pH at the end point.

### To create a first derivative curve:

From the Tools menu select Post-log Function. Choose the formula function a  $dx/dt$  and set the following parameters,

- x = pH sensor
- a = -1 (if you were titrating alkali into acid this value would be 1)
- Number of decimals = 4 (the derivative can produce very small numbers; with a few decimals the detail of the number is lost.
- Max = 1
- Min = 0
- Name = Rate of change

### Alternatively,

- From the Tools menu select Post-log Function, Preset function, Titration, First derivative of pH.
- Select channel as pH
- Name as DpH
- Units = pH/s
- Scale factor = -20

The calculation is exactly the same in both cases, in the latter case the math is hidden from the user

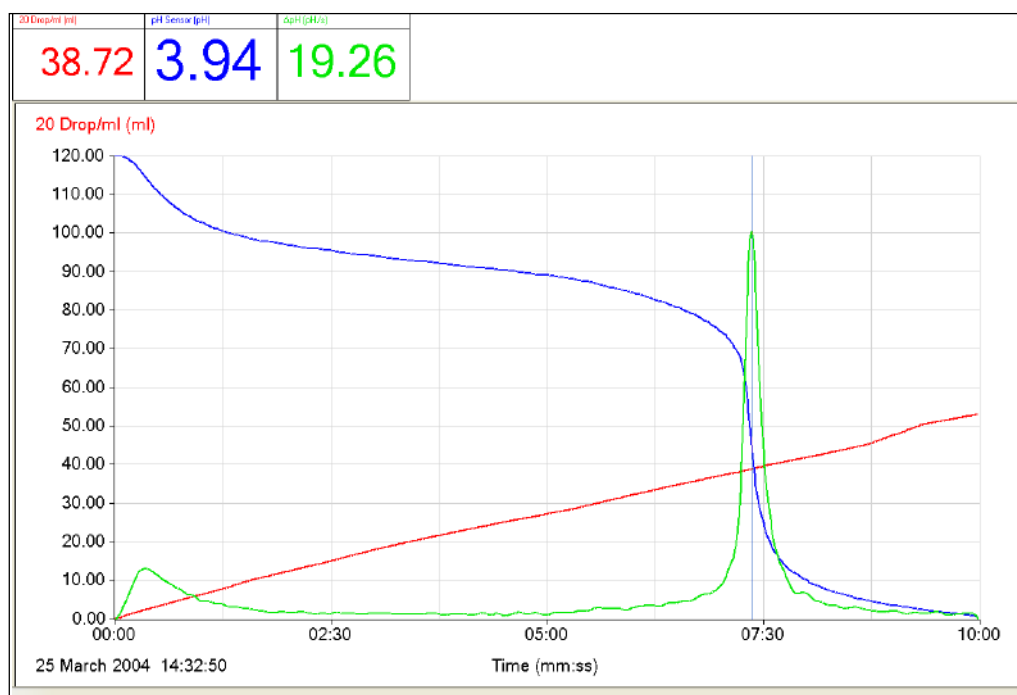


Fig 7.2 The pH data can be differentiated to create a data set of 'rate of change'. When the rate of change is plotted against pH the point of the peak produced will equal the pH at neutralisation.

A plot of rate of change vs. volume will show the volume of titrated fluid at neutralisation.

## 7. Acid base titration: Sodium carbonate with hydrochloric acid

### Practical skills AT a, c, d

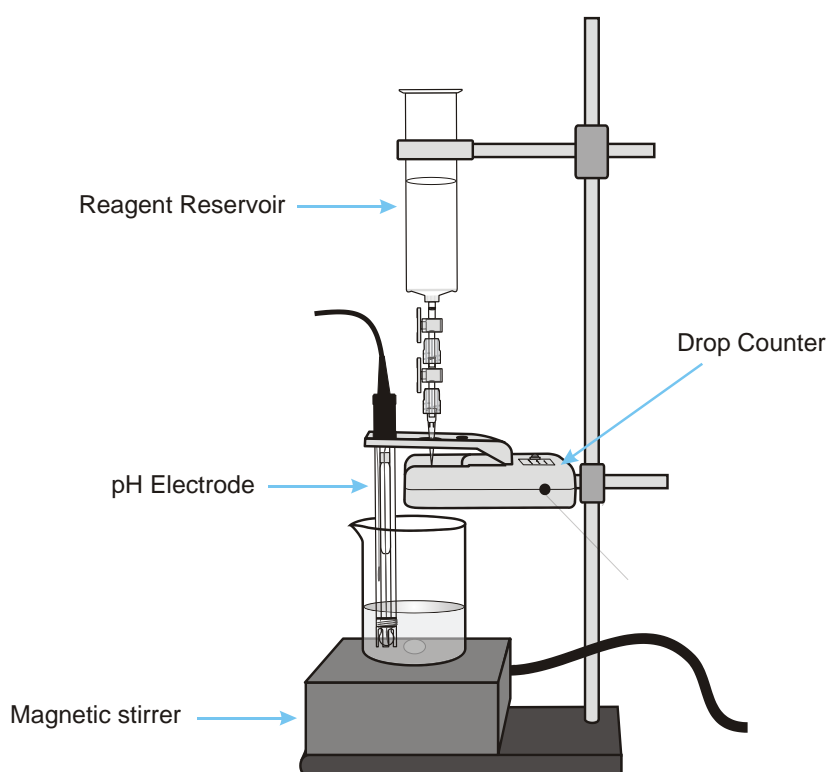
When you carry out a titration, you use an indicator to tell you when the end point of the reaction has been reached. The indicator is chosen to give a definite colour change to coincide with the equivalence point.

You can use a Drop counter to electronically measure the volume titrated and a pH sensor will monitor the changes in pH. The experiment will use  $1 \text{ mol dm}^{-3}$  hydrochloric acid and  $0.5 \text{ mol dm}^{-3}$  sodium carbonate solutions.

The equation of the reaction you will be following is,



It is a 1:2 reaction (that is 1 particle of  $\text{Na}_2\text{CO}_3$  reacts with 2 particles of  $\text{HCl}$ ). If the solutions are the same concentration the equivalence point of the reaction should be when double the volume of acid is run into the carbonate solution.



### Apparatus

1. pH sensor
2. Drop / Bubble counter with alignment adapter fitted.
3. The drop counter reagent reservoir fitted with two stopcocks and tip
4. 2 x 200 ml beakers
5. Magnetic stirrer and stir bar
6.  $20 \text{ cm}^3$  of  $0.5 \text{ mol dm}^{-3}$  Sodium carbonate ( $\text{Na}_2\text{CO}_3$ )
7.  $60 \text{ cm}^3$  of  $1.0 \text{ mol dm}^{-3}$  Hydrochloric acid ( $\text{HCl}$ )
8. Measuring cylinders (100 ml capacity)

## Method

1. Set up the apparatus as shown. Connect the pH sensor and Drop counter to the data logger.
2. Fill the reagent reservoir with the hydrochloric acid. Open both stopcocks to allow a small amount of HCl to pass through. Use the top stopcock to adjust the rate of flow e.g. to about 1 drop per second, leave in that position and close the lower stopcock. Pour the HCl from the beaker back into the reagent reservoir.
3. Pour 20 cm<sup>3</sup> of the sodium carbonate into another beaker and place under the reservoir. Check the solution covers the bulb end of the pH electrode. Add the magnetic stir bar and turn on the stirrer. Check the stir bar is free to rotate and is rotating slowly and evenly.
4. Press the button on the Drop Counter to set the counter back to **zero**.
5. Set up

Recording method	Time	Intersample
Graph	10 minutes	1 s

6. The label at the top of the y-axis for the Drop Counter will indicate which calibration range is currently selected e.g. 27 Volume for the 27drops/cm<sup>3</sup> range. If this is not correct change the range of the sensor.
7. Click on Start and open the lower stopcock to let the hydrochloric acid drip into the alkali. The LED on the Drop counter will blink as a drop passes through the infrared beam. Top up the acid in the reagent reservoir if necessary.
8. When you are satisfied that the titration has gone past the equivalence point close the lower stopcock and click on Stop to finish logging. Save the data.

## Results and analysis

The data will be displayed a Volume and pH vs. Time graph. To alter the display to a pH vs. Volume graph select Options from the toolbar, select the X-Axis tab and click on Channel. If necessary, click outside the graph area to alter the data channel displayed so that pH is on the y-axis (vertical) and Volume is on the x-axis (horizontal).

Use Values to find the end point (or point of neutralization), which is the maximum rate of pH change.

## Advanced

The a dx/dt function can be applied to the pH data to produce a first derivative curve. The point of the sharp peak produced will represent the end point of the titration.

From the Tools menu select Post-log Function. Choose the formula function a dx/dt and set the following parameters:

- x = pH sensor
- a = -1 (if you were titrating alkali into acid this value would be 1)
- Number of decimals = 4 (the derivative can produce very small numbers; with a few decimals the detail of the number is lost.
- Max = 1
- Min = 0
- Name = Rate of change

**Alternately,**

- From the Tools menu select Post-log Function, Preset function, Titration, First derivative of pH
- Select Channel as pH

- Name as  $\Delta\text{pH}$
- Units =  $\text{pH/s}$
- Scale factor = -20

A new data channel line will be drawn which shows a sharp peak when the pH changes most quickly. The point of this peak is the equivalence point.

## Questions

1. Explain the shape of the graph.
2. At what pH should an indicator change colour if it is used to indicate when:
  - All the carbonate ions have been converted to hydrogen carbonate ions?
  - All the carbonate ions have been converted to carbonic acid?



## Teacher's notes

### 8. Rate of reaction: Marble chips and hydrochloric acid

#### Practical skills AT a, d, l

When marble chips (calcium carbonate) react with an acid, they produce carbon dioxide gas, calcium chloride and water. The rate at which the carbon dioxide is produced provides a way of measuring the rate of the reaction.

In this experiment the carbon dioxide produced is bubbled through water, the bubbles are then counted electronically by a Bubble counter.

The equation for the reaction is,



This is a classic experiment used to demonstrate rates of reaction. Normally the time taken for the chips to disappear is used or the students are asked to quantify the rate by awarding 'stars' to indicate speed and vigour of the reaction.

The use of the Bubble counter allows a more quantitative approach to be taken and it becomes simple to relate particle size and temperature to rate. The production of the graph of the rate of reaction in real time enable the students to make (and see) the comparisons easily.

#### Apparatus

1. Drop / Bubble counter set to the Drop/Bubble Count range with the alignment adapter fitted
2. Retort stand and clamps
3. Reagent reservoir filled with water
4. 20 ml measuring cylinder
5. 200 ml conical flask
6. Bung to fit conical flask, with a single hole fitted with a glass or hard plastic delivery tube
7. Stopcock fitted to the tube from the conical flask's bung
8. Plastic delivery tubing (to fit glass or hard plastic tube)
9. Calcium carbonate ( $\text{CaCO}_3$ ) (Marble chips in 3 different grades)
10.  $1 \text{ mol dm}^{-3}$  Hydrochloric acid (HCl)
11. Balance
12. Syringe to test your set up

#### Set up

Recording method	Overlay
EasyLog	On

The data will continue to be logged until the user intervenes and stops the logging. The reaction as described will reach completion in about 1:30 hrs to 2:00 hrs.

#### Practical notes

Grade is the size of the marble chips; often the supplier will have given an average size of the chips within the grade. The average size could be used as the controlled variable when plotting size vs. rate

A preliminary experiment could be carried out to show that the gas produced is carbon dioxide. Collect the gas and test with limewater.

The bubbles are counted but there is no calibration of the bubble to volume. The size of the bubble formed will be affected by the size of the point where the bubble is forming, the pressures over the bubble chamber and the temperature.

Make sure the students understand the need to reset the counter to zero before each new run or the count becomes a cumulative count.

#### Sample data

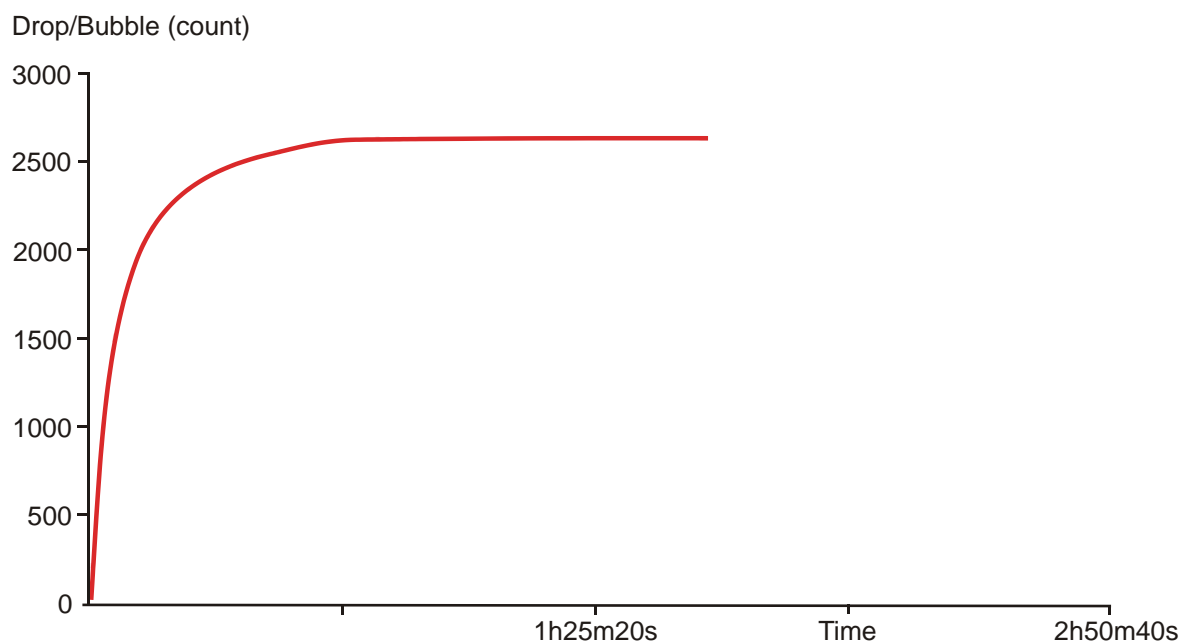


Fig 8.1 Plot of gas bubble production from marble chips in hydrochloric acid against time, left to go to completion.

## 8. Rate of reaction: Marble chips and hydrochloric acid

### Practical skills AT a, d, l

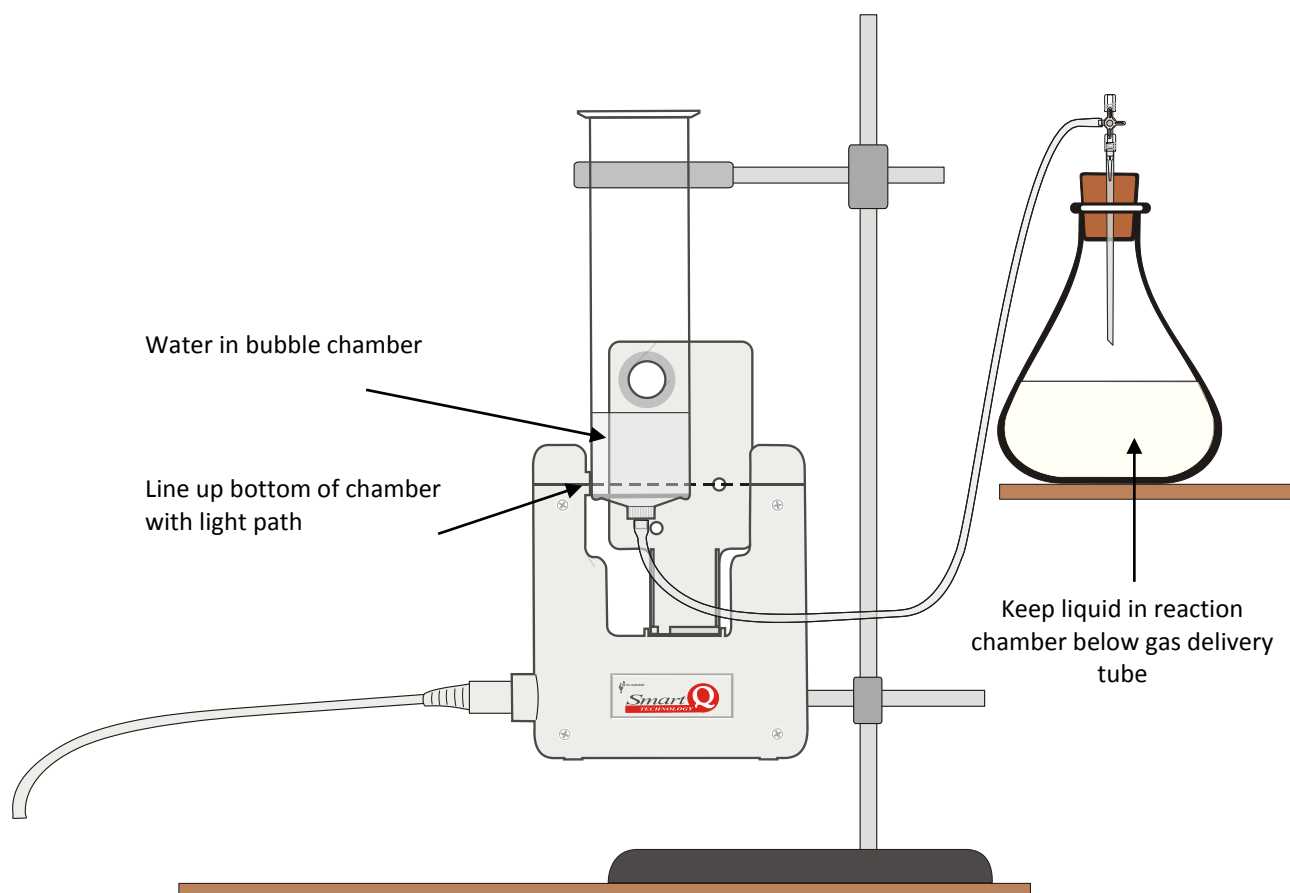
When marble chips (calcium carbonate) react with an acid they produce carbon dioxide gas, calcium chloride and water. The rate at which the carbon dioxide is produced provides a way of measuring the rate of the reaction.

In this experiment the carbon dioxide produced is bubbled through water. The bubbles are then counted electronically, as they rise through a column of water, by the Drop / Bubble counter.

The equation for the reaction is,



The equation informs us that for each calcium carbonate molecule that reacts with hydrochloric acid, 2 acid molecules are used up and one molecule of gas is produced. The measurement of the production of carbon dioxide is therefore a good measure of the rate of the reaction.



### Apparatus

1. Drop / Bubble counter set to the Drop/Bubble Count range with the alignment adapter fitted
2. Retort stand and clamps
3. Reagent reservoir filled with water
4. 20 ml measuring cylinder
5. 200 ml conical flask
6. Bung to fit conical flask, with a single hole fitted with a glass or hard plastic delivery tube

7. Stopcock fitted to the tube from the conical flask's bung
8. Plastic delivery tubing (to fit glass or hard plastic tube)
9. Calcium carbonate ( $\text{CaCO}_3$ ) (marble chips in 3 different grades)
10.  $1 \text{ mol dm}^{-3}$  Hydrochloric acid
11. Balance
12. Syringe to test your set up

## Method

1. Connect the Bubble counter to the data logger.
2. Set up the apparatus as shown. The reagent reservoir should be clamped between the receiver and emitter of the Bubble counter so the reservoir touches the emitter moulding. Adjust the reservoir vertically so the moulding ring at the bottom of the reservoir barrel is level with the lower edge of the emitter moulding (see diagram). Adjust the reservoir laterally so the reservoir is just touching the moulding of the large hole in the alignment plate.
3. Test your set up before beginning the experiment to check that as bubbles rise they will be detected by the Bubble counter e.g. pour some water into the reservoir, attach a syringe full of air to the plastic tube and gently push the syringe plunger in so the air produces a stream of bubbles. If the LED does not respond adjust the reagent reservoir slightly and try again.
4. Set the recording method as EasyLog.
5. Weigh out 3 g of marble chips (make a record of the actual mass used).
6. Place  $20 \text{ cm}^3$  of the hydrochloric acid into the conical flask. Add the marble chips to the acid, swirl the flask to mix the contents.
7. Place the bung into the neck of the conical flask. Open the stopcock to allow any bubbles created by the displacement of air in the tube to be released.
8. Press the button on the Bubble counter to set the counter to **zero**.
9. Click on Start, the LED on the Drop counter will blink as a bubble passes through the infrared beam.
10. Click on the Stop icon when you want to finish. Save the data.
11. Empty the conical flask. Select Overlay and repeat the experiment from step 5 using a different grade of marble chip. Make sure you reset the Bubble counter to zero.

## Results and analysis

You will have a graph of Bubble count vs. Time.

Calculate the rate of reaction either using values taken from the graph or by selecting Gradient to find the rate as count /sec. Use the first part of the results to find the rate over the linear section of the graph, this will usually be in the region of 1 - 2 minutes.

Plot on paper a graph of rate vs. grade size of the marble chips (with grade on the horizontal x-axis and rate on the vertical y-axis).

## Questions

1. Describe the shape of the graph.
2. How would you identify the end point of the reaction?
3. Why was the rate of reaction calculated at the beginning of the reaction?
4. What is the relationship between grade and rate of reaction?
5. How is the grade of the marble chips related to the surface area of the marble chips?

6. What is the relationship between surface area and rate of reaction?
7. If all of the marble chips were dissolved how much carbon dioxide was produced?

### **Extension**

1. What is the relationship between the mass of the marble chips and the rate of reaction?
2. What is the relationship between the temperature of the acid and the rate of reaction?
3. What is the relationship between the concentration of the acid and the rate of reaction?

## Teacher's notes

### 9. Rate of reaction: Light transmittance through a reaction mixture of hydrochloric acid and sodium thiosulfate

#### Practical skills AT a, d, e, l

This investigation is about rates of reaction, it can easily be extended into a set of investigations that study the factors affecting rates. The thiosulfate reaction is popular for rate investigations because it produces a coloured, opaque product. The appearance of the product over time gives a rate.

The rate timings are normally produced by timing how long it takes for a cross drawn on paper to become obscured by the yellow opaque product. Although this works well it is limited for several reasons e.g.

- The rate is simply the end point divided by the time taken.
- The interpretation of the end point is very open.
- There is no measurement of the latency of the reaction.

Using a Colorimeter allows the end point to become more defined, e.g. the time taken to reach 90% transmission. This improves the rate data and improves the quality of the trend lines graphed from the data. Using a data logger to record the output from a Colorimeter allows the whole reaction to be recorded.

#### Risk assessment

Sulphur dioxide is produced in the reaction so good ventilation is required. A fume cupboard is advised for the finished reactants (using open sinks in the laboratory to dispose of reactants can release significant quantities of  $\text{SO}_2$  into the room).

1 mol  $\text{dm}^{-3}$  Hydrochloric acid is an irritant. Eye protection should be used.

#### Apparatus

1. Colorimeter set to Transmittance range with the blue filter
2. Hydrochloric acid 1 mol  $\text{dm}^{-3}$
3. Sodium thiosulphate solution of 40 g per litre (0.15 mol  $\text{dm}^{-3}$ )
4. 5 and 10 ml syringes
5. At least 2 cuvettes per group

#### Set up

Recording method	Time	Intersample time	Overlay
Graph	5 minutes	1 second	On

#### Practical notes

Care needs to be taken that the acid does not come into contact with the thiosulphate solution.

The cuvettes hold 4.0  $\text{cm}^3$  of solution; it should be possible for the students to add chemicals into the cuvettes while they are in place in the Colorimeter.

Try to encourage a routine that places the biggest solution into the apparatus last, this mixes the solutions in the cuvette and gives a more consistent start time. The cuvettes need to be cleaned out promptly after

the reaction has finished, the colloidal sulphur produced by the reaction will stick to the surface of the cuvettes if left.

The set up will allow a student or group to complete a full investigation in a one hour lab session.

Suggest volumes for a simple rate / concentration investigation.

Volume of water (cm <sup>3</sup> )	Volume of 1 mol dm <sup>-3</sup> hydrochloric acid (cm <sup>3</sup> )	Volume of thiosulfate (cm <sup>3</sup> )	Total Volume (cm <sup>3</sup> )
0.0	0.5	3.5	4.0
0.5	0.5	3.0	4.0
1.0	0.5	2.5	4.0
1.5	0.5	2.0	4.0
2.0	0.5	1.5	4.0
2.5	0.5	1.0	4.0
3.0	0.5	0.5	4.0

### Sample data

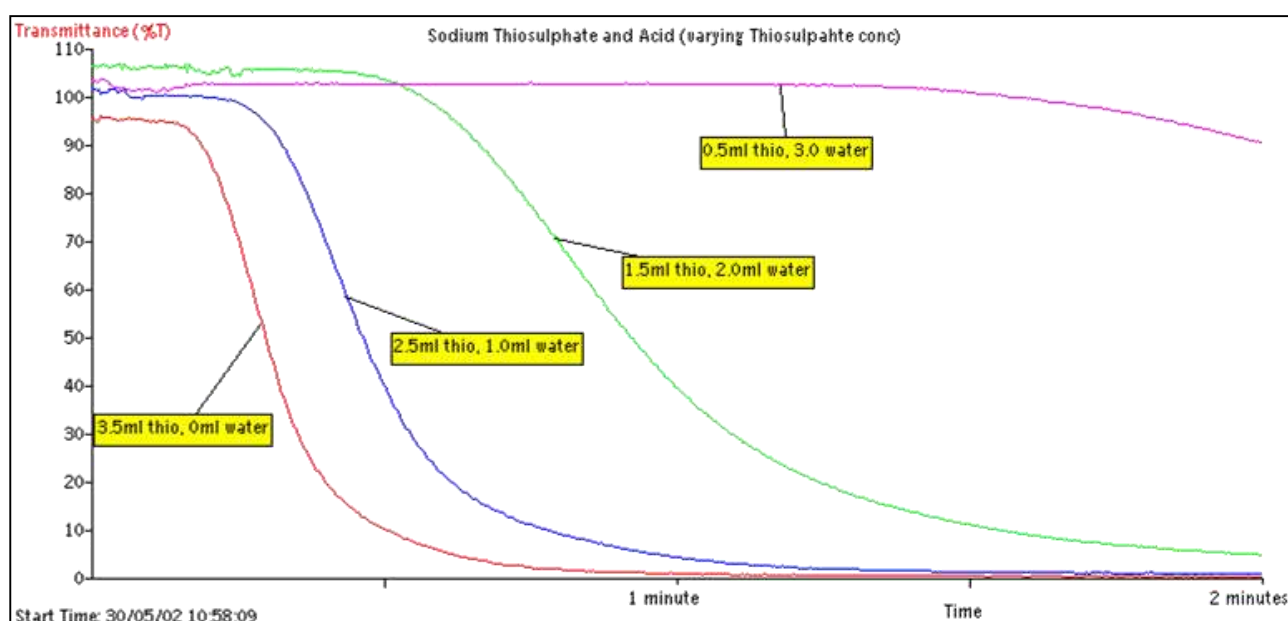


Fig 9.1 An example of a concentration of thiosulfate investigation. Note how the first appearance of the colloidal sulfur becomes slower as the thiosulfate is diluted.

To determine a rate the students should take an arbitrary transmission value that is present in all the results they collected and find how long it took each experiment to reach this light value, this is the nominal rate. A plot of rate vs. concentration of the thiosulfate / temperature will show the relationship between rate and the controlled variable.

To produce a better rate plot the time value to reach x% transmittance should be plotted as  $1/t$  vs. the controlled variable.

## Extension work

### 1. Effect of increasing temperature.

To provide different temperatures:-

- The sodium thiosulfate stock can be divided and placed into water baths of different temperatures.
- The students can warm the thiosulphate using their own water bath and bunsen burner.
- The syringe for the thiosulfate can be filled with the volume to be used and placed into a water bath for 2 to 3 minutes to reach the correct temperature.
- There is always going to be cooling in the transfer to the Colorimeter and once the cuvette is in the Colorimeter. In practice the error created appears to be standardised and the effect of temperature is easily seen.

### 2. Effect of changing the concentration of acid.

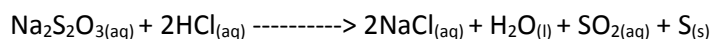


## 9. Rate of reaction: Light transmittance through a reaction mixture of hydrochloric acid and sodium thiosulfate

### Practical skills AT a, d, e, l

When  $0.15 \text{ mol dm}^{-3}$  sodium thiosulfate and hydrochloric acid are mixed together they react to form sulfur and the mixture goes cloudy. In this investigation a Colorimeter is used to monitor the change in transmittance of the reaction mixture as the turbidity (cloudiness) increases.

The reaction for the experiment is shown below,



Once a base rate of reaction has been established, other variables such as temperature and concentration of the acid can be studied.

### Apparatus

1. Colorimeter set to Transmittance range with the blue filter and two cuvettes
2. Hydrochloric acid  $1 \text{ mol dm}^{-3}$
3. Sodium thiosulphate solution (40 g per litre) ( $0.15 \text{ mol dm}^{-3}$ )
4. 5 and 10 ml syringes

### Risk assessment

Hydrochloric acid (HCl): Wear eye protection and nitrile gloves.

Sulphur dioxide fumes evolved in reaction and at disposal, avoid inhalation. Ensure good ventilation.

### Method

1. Connect the Colorimeter to the data logger. Place the blue filter supplied in the front slot of the Colorimeter.
2. Set up the recording:

Recording method	Time	Intersample time	Overlay
Graph	5 minutes	1 second	On

3. Create a control cuvette for calibrating the Colorimeter by adding equal volumes of water and hydrochloric acid into a cuvette.
4. Place the control cuvette into the Colorimeter. Make sure the ribbed faces of the cuvette are to the sides of the Colorimeter and close the lid.
5. Select Test Mode (Tools menu) and use the control knob on the Colorimeter to give a transmittance reading of 100%. Stop Test Mode and remove the cuvette.
6. Place the water and hydrochloric acid (as indicated in the first line of the table below) into a clean cuvette (do not add the thiosulfate).

Volume of water (cm <sup>3</sup> )	Volume of 1 mol dm <sup>-3</sup> hydrochloric acid (cm <sup>3</sup> )	Volume of thiosulphate (cm <sup>3</sup> )	Total Volume (cm <sup>3</sup> )
0.0	0.5	3.5	4.0
0.5	0.5	3.0	4.0
1.0	0.5	2.5	4.0
1.5	0.5	2.0	4.0
2.0	0.5	1.5	4.0
2.5	0.5	1.0	4.0
3.0	0.5	0.5	4.0

- Place the cuvette in the Colorimeter. Click on the Start icon to begin logging and immediately add the thiosulphate solution to the cuvette. Close the lid.
- When the logging has finished, remove the cuvette and rinse (to stop the sulphur formed sticking to the cuvette).
- Use Add Text to label the graph line with the concentration of the thiosulphate.
- Check that Overlay is selected.
- Repeat stages 6 – 9 using the other concentrations of thiosulphate (as shown in the table). Make sure the cuvette is dried between uses.
- Add a Title to the graph and then Save the results.

## Results and analysis

The rate of reaction in this experiment may be inferred in a number of ways. Use Values to find:

- The average gradient of the trace during e.g. the first minute.
- The time taken for the light level to fall to an arbitrary transmission value.
- The time taken for the light level to fall to half the initial value.
- Create a graph showing the rate of reaction against concentration of sodium thiosulphate.

## Questions

- How does the rate of reaction vary with the initial concentration of sodium thiosulphate? Suggest a reason.
- How does the shape of the graphs tell you that the reaction has finished?
- Devise an experiment to show that the reaction is not changed by the amount of acid in the reaction mix.
- What would be the effect of temperature on the reaction?

## Extension

- What factors increase the rate of this reaction?
- In another variation of this investigation try varying the molarity of the acid (0.5 and 1 mol dm<sup>-3</sup>) or the starting temperature (30, 40, 50 and 60°C) of the reactants.

## Teacher's notes

### 10. Thiosulfate and acid, following the rate of reaction

#### Practical skills AT a, d, e, l

This investigation is about rates of reaction, it can easily be extended into a set of investigations that study the factors affecting rates.

The thiosulfate reaction is popular for rate investigations because it produces a coloured, opaque product. The appearance of the product over time gives a rate.

The rate timings, for the thiosulfate reaction, are normally produced by timing how long it takes for a cross drawn on paper to become obscured by the yellow opaque product. Although this works well it is limited for several reasons e.g.

- The rate is simply the end point divided by the time taken.
- The interpretation of the end point is very open.
- There is no measurement of the latency of the reaction.

Using a colorimeter allows the end point to become more defined, e.g. the time taken to reach 90% transmission. This improves the rate data and improves the quality of the trend lines graphed from the data. Using a data logger to record the output from a colorimeter allows the whole reaction to be recorded.

This version of the practical uses a Light level sensor, set to transmission range, to create a colorimeter.

The student's sheet describes a classic practical protocol with the students measuring and mixing solutions, there is no reason why a more prepared protocol cannot be used, the colorimeter is only the device for measurement, it should not intrude into the practical.

#### Risk assessment

Sulphur dioxide is produced in the reaction so good ventilation is required. A fume cupboard is advised for the finished reactants (using open sinks in the laboratory to dispose of reactants can release significant quantities of SO<sub>2</sub> into the room).

1 mol dm<sup>-3</sup> Hydrochloric acid is an irritant. Eye protection should be used.

#### Apparatus

1. Light level sensor set to the Transmission range
2. A blue filter (optional, offers more discrimination in light detection)
3. Hydrochloric acid 1 mol dm<sup>-3</sup>
4. Sodium thiosulfate solution of 40 g per litre (0.15 mol dm<sup>-3</sup>)
5. 5 and 10 ml syringes
6. At least 2 boiling tubes or test tubes per group

#### Set up

Recording method	Time	Intersample time	Overlay
Graph	5 minutes	1 second	On

Note: Graph offers a recording time of 2 or 5 minutes, the weaker thiosulfate solutions need closer to 5 minutes, the stronger solutions finish below a minute. You cannot mix time intervals. You could use 2 minutes and use a range of mixes that fit better into the time span.

#### Suggested volumes / concentrations to use

Volume of 1 mol dm <sup>-3</sup> hydrochloric acid (cm <sup>3</sup> )	Volume of water (cm <sup>3</sup> )	Volume of thiosulfate (cm <sup>3</sup> )	Total Volume (cm <sup>3</sup> )
5.0	0.0	35.0	40.0
5.0	5.0	30.0	40.0
5.0	10.0	25.0	40.0
5.0	15.0	20.0	40.0
5.0	20.0	15.0	40.0
5.0	25.0	10.0	40.0
5.0	30.0	5.0	40.0

#### Practical notes

You will need to provide the students with one of the simple colorimeters illustrated and the appropriate diagram.

Care needs to be taken that the acid does not come into contact with the thiosulfate solution.

You will need to scale up or down the volumes of each solution to match the apparatus. The table in the student notes and this teacher's sheet are for a 40 cm<sup>3</sup> volume, which is about a half full boiling tube.

Try to encourage a routine that places the biggest solution into the apparatus last, this mixes the solutions in the tubes and gives a more consistent start time. The tubes need to be cleaned out promptly after the reaction has finished, the colloidal sulphur produced by the reaction will stick to the surface of the glassware if left.

The set up will allow a student or group to complete a full investigation in a one hour lab session.

## Sample data and analysis

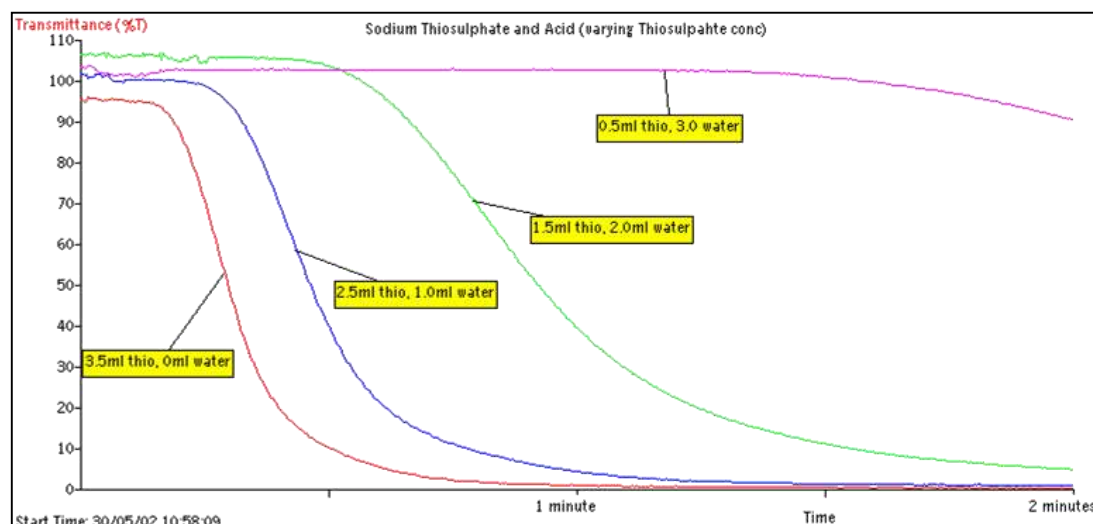


Fig 10.1 An example of a concentration of thiosulfate investigation, The data was collected in a standard colorimeter using 4 cm<sup>3</sup> cuvettes. You should expect very similar results from the apparatus described.

Note how the first appearance of the colloidal sulphur becomes slower as the thiosulphate is diluted.

To determine a rate the students should take an arbitrary transmission value that is present in all the results they collected and find how long it took each experiment to reach this light value, this is the nominal rate. A plot of rate vs. concentration of the thiosulphate / temperature will show the relationship between rate and the controlled variable.

To produce a better rate plot the time value to reach x% transmission should be plotted as 1/t vs. the controlled variable.

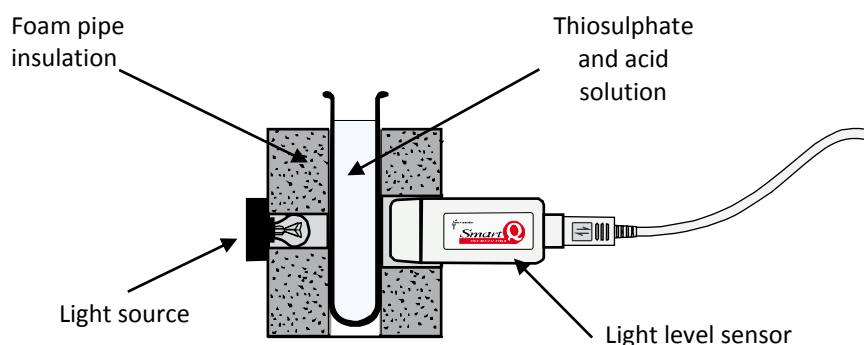
## Extension work

### 1. Effect of increasing temperature.

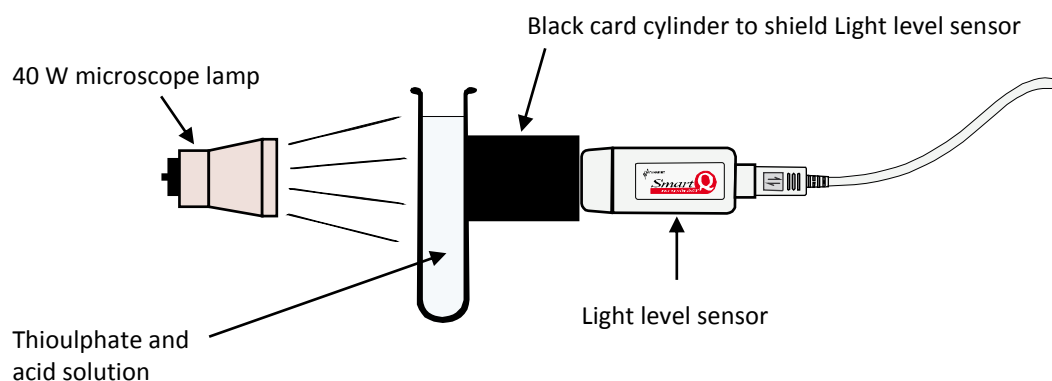
To provide different temperatures:-

- The sodium thiosulfate stock can be divided and placed into water baths of different temperatures.
- The students can warm the thiosulfate using their own water bath and bunsen burner.
- The syringe for the thiosulfate can be filled with the volume to be used and placed into a water bath for 2 to 3 minutes to reach the correct temperature.
- There is always going to be cooling in the container. In practice the error created appears to be standardised and the effect of temperature is easily seen.

### 2. Effect of changing the concentration of acid.

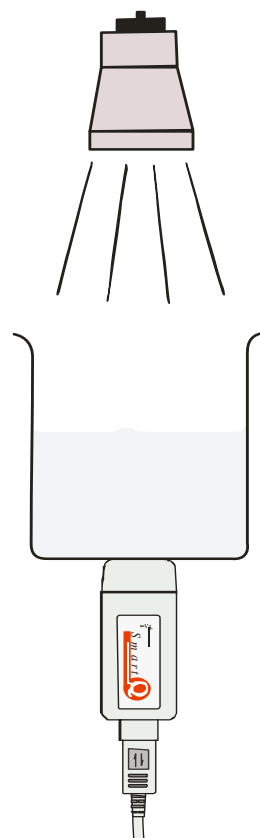
**Example apparatus using a Light sensor to create a simple colorimeter**

**Alternative 1:** The foam pipe insulation used is readily available in DIY centres. The version for large (22mm) pipes fits most standard boiling tubes and the version for small (15mm) pipes fits most standard test tubes. If the foam is cut square a base can be glued on and a self-standing unit can be achieved. The light source may not have to be placed into the foam, this will depend upon the intensity of the light source. Use a small torch bulb or a white LED.

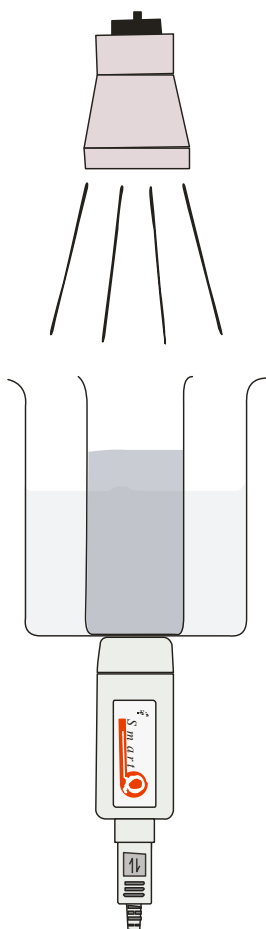


**Alternative 2:** This alternative is a simple set up in terms of preparation. It only requires a piece of light proof card to ensure the only light entering the sensor has come from the test tube. The downside is that you will need more retort stands to support and align everything. The shape of the tube will create a lens that will focus the light. Watch out for small changes in position having a bigger than expected effect on light intensities. You will really want to check light intensity on the sensor at each run for qualitative work.

**Alternative 3:** This adopts a larger scale of apparatus. You are shining light down through a beaker, clear water cup etc. onto a Light sensor. The beaker can be clamped or supported by a tripod (in which case you may need a sturdy card of hardboard support with a centre hole for light. If top light in the lab space is good you may be able to dispense with the additional light. If the additional light is not to be used, consider a light proof sleeve to surround the beaker to reduce changes in light intensity by shadows, light from sun altering the room brightness, etc. A top light usually overwhelms such differences. Make sure the sensor touches the base of the beaker, but does not support the beaker. Adjust light intensity by moving the top light.



**Alternative 4:**



This is a more sophisticated reaction vessel. The method of collecting the light changes is the same as alternative 3.

What we do here is take a larger beaker and using glass glue stick a smaller glass pot inside the beaker. Typically a glass specimen bottle or a redundant screw top culture pot. Preference is for the culture pot as they are more robust. A beaker of 150 ml capacity (squat form) has the same height as the inserted tube (in most cases). You can use aluminium foil to cover the inner vessel if you wish to restrict light.

The glass glue is quite robust and will withstand hand washing and scrubbing well.

Advantages of this set up is that you can use the space between the beaker and the inserted pot to act as water bath and gain control over the temperature of the reaction.

## 10. Thiosulphate and acid, following the rate of reaction

### Practical skills AT a, d, e, l

This investigation is about rates of reaction, a rate of reaction is a change in the concentration of a reactant (or product) over a period of time. Rate of reaction = change in concentration / change in time.

Understanding of rates enables chemists to make predictions and control reactions. The thiosulfate reaction is popular for rate investigations because it produces a coloured, opaque product. The appearance of the product over time gives a rate.

The rate timings are normally produced by timing how long it takes for a cross drawn on paper to become obscured by the yellow opaque product. Although this works well it is limited for several reasons e.g.

- The rate is simply the end point divided by the time taken.
- The interpretation of the end point is very open.
- There is no measurement of the latency of the reaction.

Using a colorimeter allows the end point to become more defined, e.g. the time taken to reach 90% transmission. This improves the rate data and improves the quality of the trend lines graphed from the data. Using a data logger to record the output from a colorimeter allows the whole reaction to be recorded.

The Light level sensor should be positioned to be half way up the liquid volume in the tube.

### Apparatus

1. Light level sensor set to the Transmission range
2. Hydrochloric acid 1 mol dm<sup>-3</sup>
3. Sodium thiosulfate solution of 40 g per litre (0.15 mol dm<sup>-3</sup>)
4. 5 and 10 ml syringes
5. At least 2 test tubes or boiling tubes
6. Apparatus for simple colorimeter
7. Boiling tubes
8. Water bath
9. Retort stand and clamp
10. Test tube rack

### Hazard info and control measures

Sulphur dioxide is produced in the reaction so good ventilation is required.

1 mol dm<sup>-3</sup> Hydrochloric acid is an irritant. Eye protection should be used.

### Method

1. Connect the Light level sensor to the data logger.
2. The Light level sensor should be placed directly opposite the light source, which should be half way up the reaction mixture in the tube being used. Black paper tube or foam insulation is used to exclude ambient light.
3. Set the recording time

Recording method	Time	Intersample time	Overlay
Graph	5 minutes	1 second	On



4. Select Test Mode (Tools menu).
5. Place a boiling tube of water where the experiment tube will be placed, with the light source turned on. Move the light source and / or Light sensor to get the biggest light level. Make sure the sensor is not being over illuminated.
6. When you are happy with the layout, fix the apparatus so it cannot be moved.
7. Swap the boiling tube with the one the experiment will take place in.
8. Add to the boiling tube the solutions as shown in the table, add the acid, then the water then the thiosulfate. You may have to give a quick stir when the thiosulfate is less than half the total volume to give a good mix.

Volume of 1 mol dm <sup>-3</sup> hydrochloric acid (cm <sup>3</sup> )	Volume of water (cm <sup>3</sup> )	Volume of thiosulfate (cm <sup>3</sup> )	Total Volume (cm <sup>3</sup> )
5.0	0.0	35.0	40.0
5.0	5.0	30.0	40.0
5.0	10.0	25.0	40.0
5.0	15.0	20.0	40.0
5.0	20.0	15.0	40.0
5.0	25.0	10.0	40.0
5.0	30.0	5.0	40.0

9. As soon as you have added the thiosulfate (and finished the stir), click on Start to begin logging.
10. Leave the set-up and do not disturb any part of the apparatus.
11. After 5 minutes logging will stop. Save the data (you will be doing many repeats and you do not want to lose any results)
12. Dispose of the contents of the boiling tube, this will usually be to a place told to you by your teacher, not just down the sink!
13. Check Overlay is on before starting the next mixture / run.
14. Repeat the experiment using the other mixtures in the table at the beginning of the instructions.

## Results and analysis

The rate of reaction in this experiment may be inferred in a number of ways. Use Values to find:

- The average gradient of the trace during e.g. the first minute.
- The time taken for the light level to fall to an arbitrary transmission value.
- The time taken for the light level to fall to half the initial value.

Use any of the above values to create a rate value (change per unit time)

Create a graph showing the rate of reaction against concentration of sodium thiosulfate.

Calculate the moles of sodium thiosulfate in the reaction mixture, and then the concentration. Plot a graph of concentration against 1/rate.

## Questions

1. How does the rate of reaction vary with the initial concentration of sodium thiosulfate? Suggest a reason.
2. How does the shape of the graphs tell you that the reaction has finished?
3. Devise an experiment to show that the reaction is not changed by the amount of acid in the reaction mix.
4. What would be the effect of temperature on the reaction?

## Extension

1. What factors increase the rate of this reaction?
2. In another variation of this investigation try varying the molarity of the acid (0.5 and 1 mol dm<sup>-3</sup>) or the starting temperature (30, 40, 50 and 60°C) of the reactants.

## Teacher's notes

### 11. A kinetic study to determine the order of a reaction (iodine clock)

#### Practical skills AT a, e, d, l

The iodine clock reaction has several variations; this one uses potassium iodate and sodium sulphite. The reaction produces a sudden blue black colour. The reaction is often a favourite for the showman chemist, with careful preparation you can pace the talk around the reaction to make the colour appear on demand.

The method outlined in this worksheet uses a data logger and Light level sensor to act as the impartial observer.

The practical is devised around a 200 ml capacity beaker as this was found to be a good compromise for dilutions and the need to clamp easily.

The Light sensor is simply pushed up against the base of the beaker. The change of light intensity as the reaction produces the blue black is obvious, the variance in light levels entering the sensor due to changes in class light levels does not have to be controlled.

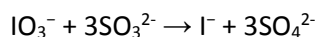
A definition of when to decide the colour has developed needs to be agreed upon for the analysis and data extraction.

#### Chemistry

The practical uses an alternative variation of the clock reaction. It uses a solution of potassium iodate ( $\text{IO}_3^-$ ) to which an acidified solution (with sulfuric acid) of sodium bisulfite ( $\text{NaHSO}_3$ ) is added.

The iodide ion is generated by the following slow reaction between the iodate and bisulfite:

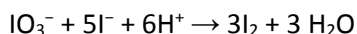
#### Stage 1



This is the rate determining step.

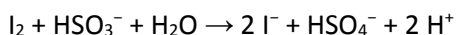
The iodate in excess will oxidize the iodide generated above to form iodine:

#### Stage 2



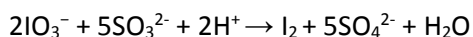
However, the iodine is reduced immediately back to iodide by the bisulfite:

#### Stage 3



When the bisulfite is fully consumed, the iodine will survive (i.e., no reduction by the bisulfite) to form the dark blue complex with starch.

#### Overall



Iodine is only liberated when the acid is added. It is therefore possible to determine the effect of the acid on the initial rate of the reaction by timing how long it takes for the iodine to be produced. The presence of the iodine is shown by the addition of starch and the creation of the characteristic dark ink blue iodine starch complex.

All factors remain constant with the exception of the acid concentration. This includes the method of adding and mixing the reagents and the timing start. In the trial the reagents were mixed in the beaker in situ above the Light sensor. Timing was started at the beginning of the pour of the second reagent.

Temperature has an effect and can be determined by repeating the reaction at three different temperatures, on ice, at room temperature and hot water bath.

### Risk assessment

Assume all of the reagents are toxic, corrosive and flammable. It is also the schools / teachers responsibility to undertake a similar assessment before presenting the practical to the students.

The reaction can evolve sulphur dioxide, make sure the room is well ventilated.

Potassium iodate is damaging to the eyes, eye protection should be used.

### Apparatus

What you supply and how you supply it to the students will depend on the focus of the practical. This is the list created from notes made during testing of the practical method.

1. Light level sensor with 1,000 lx range
2. Potassium iodate (V) solution ( $3.5 \text{ g dm}^{-3}$ ). Each student will need approx.  $200 \text{ cm}^3$ .
3. Sodium sulfite solution ( $5.0 \text{ g dm}^{-3}$ ). Each student will need approx.  $200 \text{ cm}^3$ .
4.  $0.1 \text{ mol dm}^{-3}$  sulfuric acid. Each student will need approx.  $500 \text{ cm}^3$
5. 1 -2% starch solution
6. Distilled, deionised water
7.  $250 \text{ cm}^3$  tall form beaker
8.  $100 \text{ cm}^3$  measuring cylinder
9.  $2 \times 10 \text{ cm}^3$  measuring cylinder
10. 5 and  $10 \text{ cm}^3$  graduated syringes
11. Retort stand, boss and clamp

### Set up

Either EasyLog or after trialling:

Recording method	Time	Intersample
Graph	10 minutes*	1 second

\*insert the time you have found most acceptable from your pre-trials.

### Practical notes

How the practical is conducted will depend on the focus of the practical work.

If the focus is to show the rate and how a rate order is determined then the use of syringes to measure the quantities may be acceptable to allow the pace of the practical work to be maintained. If the focus is practical skills then the correct use of a measuring cylinder may make them the preferred apparatus.

Use a  $250 \text{ cm}^3$  capacity beaker. This will let the data logger and Light sensor be used at a very simple level. Students should be able to get the  $2 \times 100 \text{ cm}^3$  solutions easily into the beaker. If you try to reduce the volumes down you start having to use odd fractional volume measurements or re test for timings to blue black.

The table suggests 6 dilutions and to have repeats of each dilution. Pragmatism will need to be employed, unless you are lucky the time required will exceed the allocation of time in most schools. Testing all the recommended dilutions will tax the time skills of most students.

It should be possible to pool data from groups; the times are well defined for each dilution. Poor practical skills will become apparent. A suggested route is to get each practical group to do 3 dilutions across the time periods and pool the data, but arrange the division so that groups do not do successive dilutions and that dilutions have more than two groups working on them.

e.g.

Experiment	1	2	3	4	5	6
Group 1	X		X		X	
Group 2		X		X		X
Group 3	X				X	X
Group 4		X	X	X		

Each group does 3 dilutions, each dilution gets 6 times (2 x 3 repeats)

If simple distilled water is used you will get a systematic error that will potentially offset the slope of the graph depending upon the additional ions in the water and how they interfere with the reaction.

### Solution 1

15 cm<sup>3</sup> of the potassium iodate made up to 100 cm<sup>3</sup>, ideally with deionised water. The iodate does not seem to dissolve quickly.

### Solution 2

15 cm<sup>3</sup> of the sulphite solution. And acid and water in the proportion in the table below to make up 100 cm<sup>3</sup>.

Experiment	1	2	3	4	5	6
Acid volume	35	45	55	65	75	85
Water volume	50	40	30	20	10	0
Sulfite	15	15	15	15	15	15
Total volume	100	100	100	100	100	100

Tip: Add the sulphite and acid and make up to 100!

## Results and analysis

Sample data collected on an iPad, PC software will display the data in similar form.

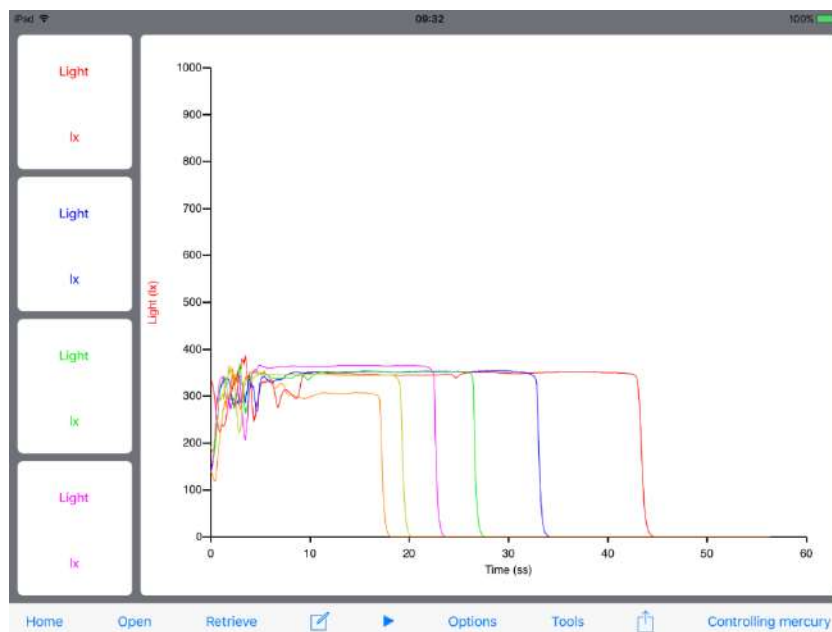


Fig 11.1 Example data. Note the erratic data at the beginning of each of the recordings; this is the change in light due to the addition of the second reagent and from the experimenter moving around in front of the apparatus. This has no effect on the results as we are only interested in ( $t_{\text{start}} > t_{\text{end}}$ ).

Volume of acid	35	45	55	65	75	85
Log/volume						
Time (t)						
1/t						
Log(1÷t)						

Again depending on the focus of the learning, using a spreadsheet may be appropriate.

Students will need to calculate the values for the table. Rules on rounding and significant figures should be followed (3 sig figs).

Data from the example on Excel (data as calculated no rounding or sig fig allowances).

A	B	C	D	E	F
Volume of acid	log/volume	Time (s)	1/t	log(1/t)	
35	1.544068044	43.14	0.02318	-1.63488	
45	1.653212514	32.88	0.030414	-1.51693	
55	1.740362689	26.46	0.037793	-1.42259	
65	1.812913357	22.56	0.044326	-1.35334	
75	1.875061263	19.8	0.050505	-1.29667	
85	1.929418926	17.1	0.05848	-1.233	

Fig 11.2 Sample spreadsheet to show treatment of data

Plot the data as  $\log(1 \div t)$  vs.  $\log(\text{volume of acid})$ .

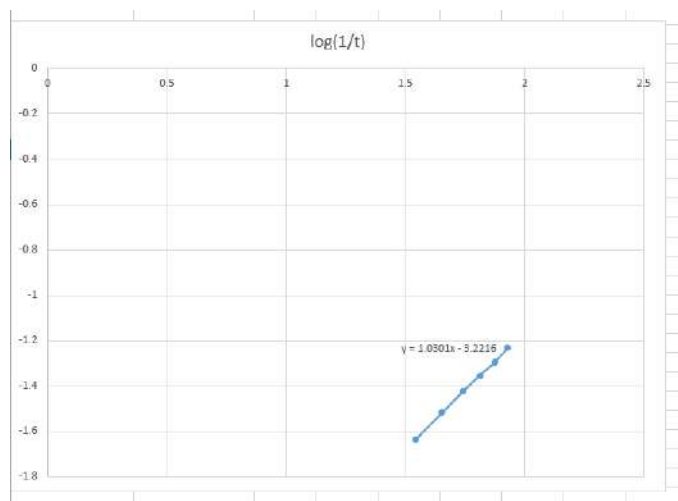


Fig 11.3 Plot the data as  $\log(1/t)$  vs.  $\log(\text{volume of acid})$ . The sample data shows a good straight line, the gradient of the slope is 1.03 which is within an expected range of 0.85 to 1.15.

The concentrations have been kept constant with each trial, with the exception of the acid. The rate equation for this reaction simplifies down to:

$$\text{rate} = k[H^+]^z$$

$z$  is the rate order with respect to the hydrogen ion concentration.

If we convert to logs we can write:

$$\log(\text{rate}) = z \log[H^+] + \text{constant}$$

With the event being measured fixed, i.e. the appearance of the blue black colour, the rate can be expressed as:

$$\text{rate} = \frac{1}{t}$$

When we conduct the experiment the total volume remains constant, this alters the concentration of the hydrogen ion present by dilution of the changing volume of acid in each trial. Therefore the  $[H^+]$  can be described by the volume of sulfuric acid added.

With a bit of substitution the rate expression becomes;

$$\log\left(\frac{1}{t}\right) = z \log(\text{volume of acid}) + \text{constant}$$

A plot of  $\log(1/t)$  on the y axis against  $\log(\text{volume of acid})$  on the x axis should give a straight line with a gradient of  $z$ . The graph is in the form of  $y=mx + c$  so the gradient  $m$  is equal to  $z$ .

## Extension

Repeat the work but change the temperature to see how it affects the rate.

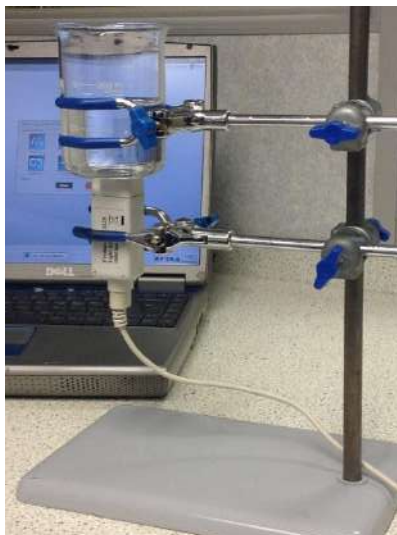
## 11. A kinetic study to determine the order of a reaction (iodine clock)

### Practical skills AT a, d, e, l

The iodine clock reaction has several variations, this one uses potassium iodate and sodium sulfite. The reaction produces a sudden blue black colour.

The method outlined in this worksheet uses a data logger and Light level sensor.

The exercise is to investigate the reaction of iodate(V) ions with sulfite ions in an acidic solution. The rate order with respect to hydrogen ions will be determined.



The Light sensor is simply pushed up against the base of the beaker. The beaker is clamped into position to support the mass of the beaker and experiment solutions. The change of light intensity as the reaction produces the blue black is obvious, the variance in light levels entering the sensor due to changes in class light levels does not have to be controlled.

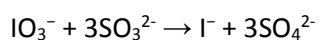
### Chemistry

The practical uses an alternative variation of the clock reaction.

It uses a solution of potassium iodate ( $\text{IO}_3^-$ ) to which an acidified solution (with sulfuric acid) of sodium bisulfite ( $\text{NaHSO}_3$ ) is added.

The iodide ion is generated by the following slow reaction between the iodate and bisulfite:

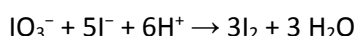
#### Stage 1



This is the rate determining step.

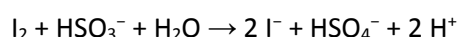
The iodate in excess will oxidize the iodide generated to form iodine:

#### Stage 2



However, the iodine is reduced immediately back to iodide by the bisulfite:

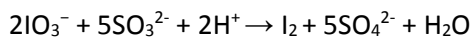
#### Stage 3



When the bisulfite is fully consumed, the iodine will survive (i.e., no reduction by the bisulfite) to form the dark blue complex with starch.



## Overall



Iodine is only liberated when the acid is added. It is therefore possible to determine the effect of the acid on the initial rate of the reaction by timing how long it takes for the iodine to be produced. The presence of the iodine is shown by the addition of starch and the creation of the characteristic dark ink blue iodine starch complex.

All factors remain constant with the exception of the acid concentration. This includes the method of adding and mixing the reagents and the timing start, for example timing is started at the beginning of the pour of the second reagent.

## Apparatus

What you are supplied with will depend on the focus of the practical.

1. Light level sensor set to the 1,000 lx range
2. Approx. 200 cm<sup>3</sup> Potassium iodate (V) solution (3.5 g dm<sup>-3</sup>)
3. Approx. 200 cm<sup>3</sup> Sodium sulfite solution (5.0 g dm<sup>-3</sup>)
4. Approx. 500 cm<sup>3</sup> 0.1 mol dm<sup>-3</sup> Sulfuric acid
5. 1 -2% starch solution
6. Distilled, Deionised water
7. 250 cm<sup>3</sup> tall form beaker
8. 100 cm<sup>3</sup> measuring cylinder
9. 2 x 10 cm<sup>3</sup> measuring cylinder
10. 5 and 10 cm<sup>3</sup> graduated syringes
11. Pipettes
12. Retort stand, boss and clamp

## Hazard information

**The reaction can evolve sulphur dioxide, make sure the room is well ventilated.**

Potassium iodate is damaging to the eyes, eye protection should be used.

## Method

1. Set up the apparatus as shown. Connect the Light sensor to the data logger. The Light sensor needs to be clamped securely. The beaker should just rest on the sensor, the clamp is to hold the position and to take the weight of the beaker and its contents. Make sure all is level. Check the beaker can hold 200 cm<sup>3</sup>.
2. Place 15 cm<sup>3</sup> of the potassium iodate(V) solution into a 100 cm<sup>3</sup> measuring cylinder. Make up the volume to 100 cm<sup>3</sup> with deionised water.
3. Place 15 cm<sup>3</sup> of the sodium sulphite solution into a second 100 cm<sup>3</sup> measuring cylinder. Add 35 cm<sup>3</sup> of the 0.1 mol dm<sup>-3</sup> sulfuric acid, then make up to 100 cm<sup>3</sup> total volume.
4. Clamp the beaker above the Light sensor.
5. Select EasyLog as the recording method.
6. Add 1 or 2 pipettes of starch solution.
7. Add one of the solutions to the beaker and Start logging. Immediately add the other solution.
8. Let the recording run for 5 seconds (approx.) after the colour change.

## Sample data

You should get a recording that looks similar to the screenshot below.

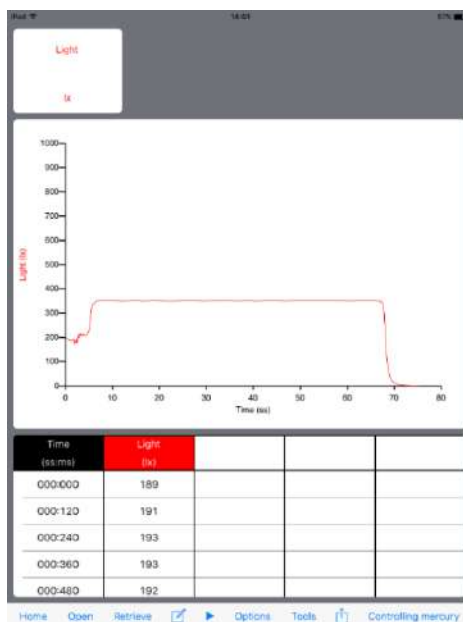


Fig 11.1 Example of data from a single run. Note the erratic data at the beginning is from adding the second solution and the shading of the sensor as you work close to it.

- Once the first run is complete, clean the beaker and prepare for the next run. Use the table below to modify the sulphite solution.

	run					
Acid volume cm <sup>3</sup>	35	45	55	65	75	85
Water volume cm <sup>3</sup>	50	40	30	20	10	0
Sulphite cm <sup>3</sup>	15	15	15	15	15	15
Total volume cm <sup>3</sup>	100	100	100	100	100	100

- Make sure Overlay is on and repeat until all concentration have been tested.
- If time allows do multiple repeats for each acid concentration / volume.

## Results and analysis

Use the Interval tool to find the time to go blue black. And enter the time value into a results table.

Calculate the other values in the results table

Volume of acid	35	45	55	65	75	85
log/volume						
Time (t)						
1/t						
Log(1/t)						

Plot the data as  $\log(1/t)$  vs.  $\log(\text{volume of acid})$

- The sample data should give a good straight line
- Find the gradient of the slope

The concentrations have been kept constant with each trial, with the exception of the acid. The rate equation for this reaction simplifies down to:

$$\text{rate} = k[H^+]^z$$

$z$  is the rate order with respect to the hydrogen ion concentration.

If we convert to logs we can write:

$$\log(\text{rate}) = z \log[H^+] + \text{constant}$$

With the event being measured fixed, i.e. the appearance of the blue black colour, the rate can be expressed as:

$$\text{rate} = \frac{1}{t}$$

When we conduct the experiment the total volume remains constant, this alters the concentration of the hydrogen ion present by dilution of the changing volume of acid in each trial. Therefore the  $[H^+]$  can be described by the volume of sulfuric acid added.

With a bit of substitution the rate expression becomes;

$$\log\left(\frac{1}{t}\right) = z \log(\text{volume of acid}) + \text{constant}$$

A plot of  $\log(1/t)$  on the y axis against  $\log(\text{volume of acid})$  on the x axis should give a straight line with a gradient of  $z$ . The graph is in the form of  $y=mx + c$  so the gradient  $m$  is equal to  $z$ .

## Extension

Repeat the work but change the temperature to see how it affects the rate.

## Teacher's notes

### 12. A kinetic study to determine the order of a reaction (iodination of propanone)

#### Hydrochloric acid catalyst

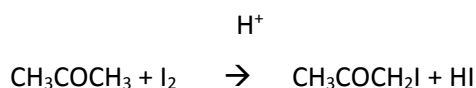
##### Practical skills AT a, d, e, l

There are several methods to the basic reaction. The variation is in the ratios of the solutions used to match the apparatus and the source of the  $\text{H}^+$  ions.

This version uses a Colorimeter measuring in absorbance and using  $4\text{ cm}^3$  disposable cuvettes. Solutions and suggested volumes have been tailored to the cuvette size. Hydrochloric acid provides the acid catalyst.

The concentrations used give a reasonable time for class use and to allow repeats.

The aim of the practical is to determine the rate equation for the iodination of propanone.



The iodopropanone created is colourless so the reaction can be monitored by measuring the rate of loss of colour. A Colorimeter attached to a data logger is used to monitor the change in light intensity.

Absorbance is directly linked to concentration.

#### Apparatus

What you supply and how you supply the apparatus to the students will depend on the focus of the practical. This is the list created from notes made during testing of the practical method.

1. Colorimeter set to the Absorbance range
2. A blue filter and  $4\text{ cm}^3$  cuvettes
3. Iodine solution as KI solution diluted to  $0.02\text{ mol dm}^{-3}$
4. Propanone  $2.0\text{ mol dm}^{-3}$
5. Distilled, deionised water
6. Hydrochloric acid  $1.0\text{ mol dm}^{-3}$
7.  $100\text{ cm}^3$  beakers
8.  $5$  and  $10\text{ cm}^3$  graduated syringes or pipettes

#### Set up

Either EasyLog or after trialling:

Recording method	Time	Intersample time
Graph	5 minutes*	1 second

\*insert the time you have found most acceptable from your pre-trials.

## Risk assessment

It is the responsibility of the student to carry out and be responsible for their own risk assessment before conducting the practical. You should verify this has been undertaken. Assume all of the reagents are toxic, corrosive and flammable. It is also the schools / teachers responsibility to undertake a similar assessment before presenting the practical to the students.

Iodopropane is noted as a lachrymator, i.e. it produces tears. At the concentrations being produced it should have no effect.

## Practical notes

How the practical is conducted will depend on the focus of the practical work.

There are several variations on the quantity and concentration of the solutions used. The hydrochloric acid is frequently swapped for sulfuric acid.

It should be possible with the suggested solutions to do repeats, although the data is fairly robust a student with good practical skill will get the all the data required with a single run for each concentration. It should be possible to pool data.

If simple distilled water is used you will get a systematic error that will potentially offset the slope of the graph depending upon the additional ions in the water and how they interfere with the reaction.

1% KI solution is 1g iodine in 1 litre KI giving a  $0.078 \text{ mol dm}^{-3}$  solution. A 1:4 further dilution gives a  $0.019 \text{ mol dm}^{-3}$  solution.

Propanone has a MW of 58, if you are using volume measurements you need to correct for density which is 0.791. Mass x density = volume. E.g. 29 g propanone will have a volume of  $29 \times 0.791 = 22.93 \text{ cm}^3$ .

Propanone in its stock form is a powerful solvent of most plastics, it will certainly dissolve the cuvettes. Make sure students are aware of this, nail varnish, plastic cases of phones, watches are at risk.

The experiments the students should do are:

Experiment	Volume I <sub>2</sub> solution cm <sup>3</sup>	Volume Water cm <sup>3</sup>	Volume propanone cm <sup>3</sup>	Volume HCl cm <sup>3</sup>
1	0.5	0.0	2.0	1.0
2	0.25	0.25	2.0	1.0
3	0.5	1.0	1.0	1.0
4	0.5	0.5	2.0	0.5

- Experiment 1 is the standard
- Experiment 2 halves the iodine
- Experiment 3 halves the propanone
- Experiment 4 halves the acid.

The analysis uses the rate of the change of colour as the measure of the rate of the reaction. This means that the exact time of the start of each experiment is not critical. It should as a matter of good practice be controlled.

The iodine is added last. If the cuvette with propanone, water, acid is placed in the Colorimeter it is possible to start data collection and using a pre-loaded syringe "shoot" the iodine in to mix the reaction mixture. Or after you have added the iodine suck the reaction mix back into the syringe and immediately eject back into the cuvette.

Alternatively if caps for the cuvettes are available add the iodine invert the cuvette once or twice to mix and add to the chamber of the Colorimeter.

## Results and analysis

### Sample data

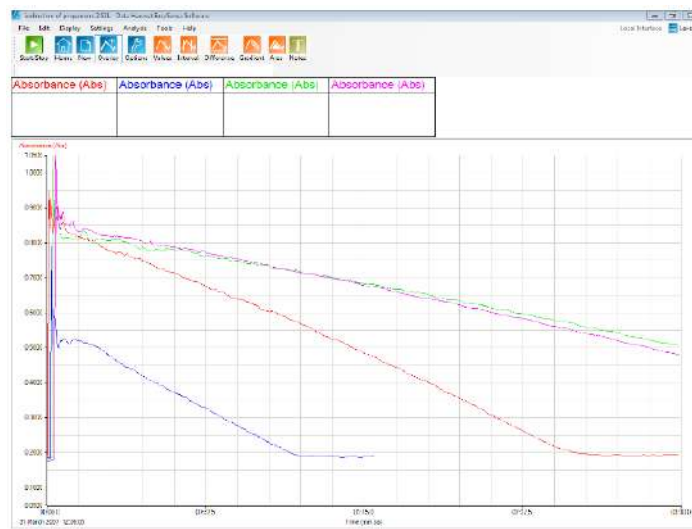


Fig 12.1 Example of a complete set of data. Note the erratic data at the beginning of each of the recordings, this is the change in light due to the addition of the iodine, this has no significance as we are interested in the rate.

The rate can be deduced in several ways.

1. The simple arithmetical treatment of change / time for the graph.
2. Best Fit line use to draw the line from “start” to “end”
3. On the iPad software a user defined gradient section tool is available.

The following screen shots show the best fit line being used. Use Tools, Best Fit and Manual draw. When using the Best fit tool, select the appropriate Y – Axis to get the line the same colour as the data.



Fig 12.2 Best fit lines added to the data.

The gradient can be read directly from the yellow information boxes. You may have to alter the length of the lines to ensure the yellow data boxes do not overlap.

In the sample data:

Gradient 1 = 0.004

Gradient 2 = 0.004

Gradient 3 = 0.002

Gradient 4 = 0.002

Comparing experiment 1 to experiment 2 the concentration of the iodine was halved and the rate was unchanged so the rate order is = 0

Comparing experiment 1 to experiment 3 the concentration of the propanone is halved and the rate is halved so rate order = 1

Comparing experiment 1 to experiment 4 the concentration of the acid is halved and the rate is halved so rate order = 1

So rate =  $k[\text{propanone}][\text{HCl}]$

The Colorimeter does not go to Absorbance = zero. You can use the gradient of the slope to find the time of intercept.

E.g. the maximum absorbance for the standard curve was 0.947, the gradient as shown by the fit line is 0.004x so the time for the curve to reach zero would be  $0.947 \div 0.004 = 236.75$  seconds. We can do this as the change of colour intensity is linear.

Now we know how long it took for all the iodine to be used we can attempt to calculate a value of  $k$  for the reaction.

If we calculate the original number of moles in the reaction for each concentration, e.g.

Concentration of iodine = number of moles of iodine / total volume of reaction mix.

$$= \frac{0.0005 \times 0.019}{0.0035} = 2.714 \times 10^{-3} \text{ mol dm}^{-3}$$

Repeat for propanone and acid.

Now calculate the rate:

$$= 2.714 \times 10^{-3} \text{ mol dm}^{-3} \div 237 = 1.145 \times 10^{-5} \text{ mol dm}^{-3} \text{ s}^{-1}$$

$$\text{Therefore } k = \frac{\text{rate}}{[\text{propanone}][\text{H}]}$$

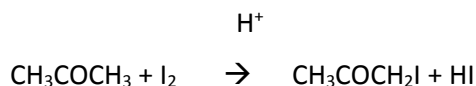
Using the results from the experiments above we achieved a value of  $3.072 \times 10^{-5}$

## 12. A kinetic study to determine the order of a reaction (iodination of propanone)

### Hydrochloric acid catalyst

#### Practical skills AT a, d, e, I

The aim of the practical is to determine the rate equation for the iodination of propanone.



The reaction is catalysed by acid.

The iodopropanone created is colourless so the reaction can be monitored by measuring the rate of loss of colour. A colorimeter attached to a data logger is used to monitor the change in light intensity.

### Apparatus

1. Colorimeter set to Absorbance range
2. A blue filter and 4 cm<sup>3</sup> cuvettes with lids
3. Iodine solution as KI solution diluted to 0.02 mol dm<sup>-3</sup>
4. Propanone 2.0 mol dm<sup>-3</sup>
5. Distilled, deionised water
6. Hydrochloric acid 1.0 mol dm<sup>-3</sup>
7. 100 cm<sup>3</sup> beakers
8. 5 and 10 cm<sup>3</sup> graduated syringes or pipettes

### Risk assessment

Iodopropane is noted as a lachrymator, i.e. it produces tears. At the concentrations being produced it should have no effect. Protective eyewear should be worn.

### Method

1. Collect together all the solutions required, Check you understand the concentrations and volumes and how you are going to measure out the volumes for the experiment runs.
2. Connect the Colorimeter to the logger.
3. Make up a cuvette of 0.5 cm<sup>3</sup> iodine and 3 cm<sup>3</sup> of water, this is the calibration standard.
4. Place the standard into the Colorimeter and use it to set the colorimeter to read its maximum value on the absorbance range with a blue filter in place.
5. Set the recording to EasyLog mode.
6. Transfer 2.0 cm<sup>3</sup> of the propanone and 1.0 cm<sup>3</sup> of the hydrochloric acid to a clean cuvette. Add the iodine, invert the cuvette to mix the contents and quickly place the cuvette into the Colorimeter and start recording.
7. Keep recording (at least) until the readings remain constant. Ideally you need to continue for longer. A total recording of at least 5 minutes is ideal.
8. Stop the recording, and select Overlay. Repeat with successive cuvettes made up as indicated in the following table:

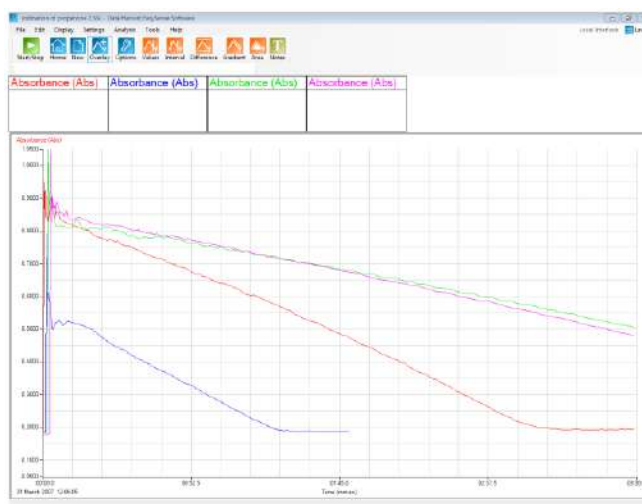


Experiment	Volume I <sub>2</sub> solution cm <sup>3</sup>	Volume Water cm <sup>3</sup>	Volume Propanone cm <sup>3</sup>	Volume HCl cm <sup>3</sup>
1	0.5	0.0	2.0	1.0
2	0.25	0.25	2.0	1.0
3	0.5	1.0	1.0	1.0
4	0.5	0.5	2.0	0.5

Experiment 1 is the standard, Experiment 2 halves the iodine, Experiment 3 halves the propanone, Experiment 4 halves the acid

## Results and analysis

You need to find the rate for each run and from the rate data deduce the rate order. Example of the data collected appears.



Note the erratic data at the beginning of each of the recordings, this is the change in light due to the addition of the iodine, this has no significance as we are interested in the rate.

The rate can be deduced in several ways.

4. The simple arithmetical treatment of change / time for the graph.
5. Best fit line use to draw the line from "start" to "end"
6. On the iPad software a user defined gradient section tool is available.

The Colorimeter does not go to zero; you can use the gradient of the slope to find the time of intercept.

E.g. In an experiment the maximum absorbance for the standard curve was 0.947, the gradient was calculated to be 0.004x. The time for the curve to reach zero would be  $0.947 \div 0.004 = 236.75$  seconds.

Now we know how long it took for all the iodine to be used we can attempt to calculate a value of  $k$  for the reaction.

You need to calculate the original number of moles in the reaction for each concentration, e.g.

Concentration of iodine = number of moles of iodine / total volume of reaction mix.

$$= \frac{\text{volume iodine solution used} \times \text{molar concentration of iodine solution}}{\text{total volume of cuvette}}$$

Repeat for propanone and acid.

Now calculate the rate:  $= \frac{\text{moles of iodine at start} - \text{moles of iodine at end}}{\text{time}}$

$$\text{Therefore } k = \frac{\text{rate}}{[\text{propanone}][\text{H}]}$$

## Teacher's notes

### 13. A kinetic study to determine the order of a reaction (iodination of propanone)

#### Sulfuric acid catalyst

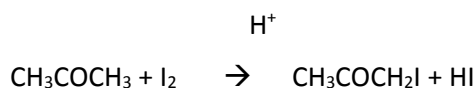
##### Practical skills AT a, d, e, I

There are several methods for the basic reaction. The variation is in the ratios of the solutions used to match the apparatus and the source of the  $\text{H}^+$  ions.

This version uses a Colorimeter measuring in absorbance and using  $4\text{ cm}^3$  disposable cuvettes. Solutions and suggested volumes have been tailored to the cuvette size. Sulfuric acid provides the acid catalyst.

The concentrations used give a reasonable time for class use and to allow repeats.

The aim of the practical is to determine the rate equation for the iodination of propanone.



The iodopropanone created is colourless so the reaction can be monitored by measuring the rate of loss of colour. A Colorimeter attached to a data logger is used to monitor the change in light intensity.

Absorbance is directly linked to concentration.

#### Apparatus

What you supply and how you supply the apparatus to the students will depend on the focus of the practical. This is the list created from notes made during testing of the practical method.

1. Colorimeter set to the Absorbance range
2. A blue filter and  $4\text{ cm}^3$  cuvettes
3. Iodine solution as KI solution diluted to  $0.02\text{ mol dm}^{-3}$
4. Propanone  $1.0\text{ mol dm}^{-3}$
5. Distilled, deionised water
6. Sulfuric acid  $1.0\text{ mol dm}^{-3}$
7.  $100\text{ cm}^3$  beakers
8.  $5$  and  $10\text{ cm}^3$  graduated syringes or pipettes

#### Set up

Use EasyLog to record the data.

#### Hazard information

It is the responsibility of the student to carry out and be responsible for their own risk assessment before conducting the practical. You should verify this has been undertaken. Assume all of the reagents are toxic, corrosive and flammable. It is also the schools / teachers responsibility to undertake a similar assessment before presenting the practical to the students.

Iodopropane is noted as a lachrymator, i.e. it produces tears. At the concentrations being produced it should have no effect.

## Practical notes

How the practical is conducted will depend on the focus of the practical work.

It should be possible with the suggested solutions to do repeats, although the data is fairly robust and student with good practical skill will get the data required with a single run for each concentration. It should be possible to pool the data from several groups.

If simple distilled water is used you will get a systematic error that will potentially offset the slope of the graph depending upon the additional ions in the water and how they interfere with the reaction.

1% KI solution is 1 g iodine in 1 litre KI giving a  $0.078 \text{ mol dm}^{-3}$  solution. A 1:4 further dilution gives a  $0.019 \text{ mol dm}^{-3}$  solution.

The propanone has a MW of 58, if you are using volume measurements you need to correct for density which is 0.791. Mass  $\times$  density = volume. E.g. 29 g propanone will have a volume of  $29 \times 0.791 = 22.93 \text{ cm}^3$ .

Propanone in its stock form is a powerful solvent of most plastics; it will certainly dissolve the cuvettes. Make sure students are aware of this, nail varnish, plastic cases of phones, watches are at risk.

The experiments the students should do are:

Experiment	Volume I <sub>2</sub> solution cm <sup>3</sup>	Volume Water cm <sup>3</sup>	Volume propanone cm <sup>3</sup>	Volume sulfuric acid cm <sup>3</sup>
1	1.0	1.5	0.7	0.7
2	1.0	0.7	1.5	0.7
3	1.0	0.7	0.7	1.5
4	0.5	2.0	0.7	0.7

Volume in each cuvette is  $3.9 \text{ cm}^3$

Note: Pragmatism is applied, the 0.7 volumes should be 0.75 to be half 1.5. The reality of being able to measure out to  $0.05 \text{ cm}^3$  with school apparatus leads to the suggestion of  $0.7 \text{ cm}^3$ . If you believe you have the apparatus and the skill to measure  $0.75 \text{ cm}^3$  then alter the table.

- Experiment 1 is the standard
- Experiment 2 doubles the propanone
- Experiment 3 doubles the acid
- Experiment 4 halves the iodine.

The analysis uses the rate of the change of colour as the measure of the rate of the reaction. This means that the exact time of the start of each experiment is not critical. It should as a matter of good practice be controlled.

The iodine is added last. If the cuvette with propanone, water, acid is placed in the colorimeter it is possible to start data collection and using a pre-loaded syringe "shoot" the iodine in to mix the reaction mixture. Or after you have added the iodine suck the reaction mix back into the syringe and immediately eject back into the cuvette.

Alternatively if caps for the cuvettes are available add the iodine invert the cuvette once or twice to mix and add to the chamber of the colorimeter.

## Results and analysis

### Sample data

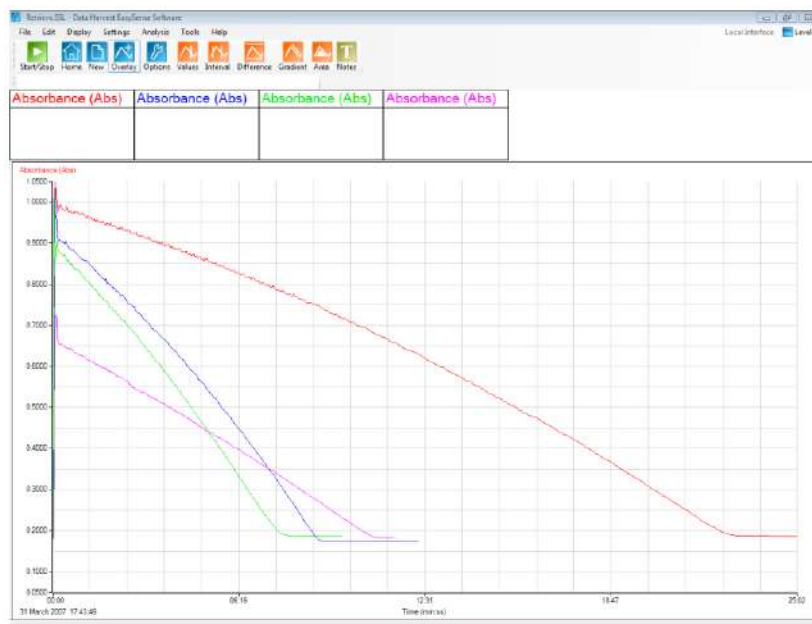


Fig 13.1 Example data for a full set of runs. Note the erratic data at the beginning of each of the recordings, this is the change in light due to the addition of the iodine, this has no significance as we are interested in the rate.

The rate can be deduced in several ways.

1. The simple arithmetical treatment of change / time for the graph.
2. Best fit line use to draw the line from “start” to “end”
3. On the iPad software a user defined gradient section tool is available.

In the sample data:

Gradient 1 = 0.0006

Gradient 2 = 0.0014

Gradient 3 = 0.0012

Gradient 4 = 0.0007

Comparing experiment 1 to experiment 2 the concentration of the propanone was halved and the rate was unchanged so the rate order is = 0

Comparing experiment 2 to experiment 1 the concentration of propanone in experiment 1 is halved and the rate is halved so rate order = 1.

Comparing experiment 3 to experiment 1 the concentration of acid in experiment 1 is halved and the rate is halved so rate order = 1.

Comparing experiment 4 to experiment 1 the concentration of iodine in experiment 4 is halved and the rate is the same so rate order = 0.

$$\text{So rate} = k[\text{propanone}][\text{H}_2\text{SO}_4]$$

The Colorimeter does not go to Absorbance = zero. You can use the gradient of the slope to find the time of intercept.

E.g. the maximum absorbance for the standard curve was 0.947, the gradient as shown by the fit line is 0.004x so the time for the curve to reach zero would be  $0.947 \div 0.004 = 236.75$  seconds. We can do this as the change of colour intensity is linear.

Now we know how long it took for all the iodine to be used we can attempt to calculate a value of  $k$  for the reaction.

If we calculate the original number of moles in the reaction for each concentration, e.g.

Concentration of iodine = number of moles of iodine / total volume of reaction mix.

$$= \frac{0.0005 \times 0.019}{0.0035} = 2.714 \times 10^{-3} \text{ mol dm}^{-3}$$

Repeat for propanone and acid.

Now calculate the rate:

$$= 2.714 \times 10^{-3} \text{ mol dm}^{-3} / 237 = 1.145 \times 10^{-5} \text{ mol dm}^{-3} \text{ s}^{-1}$$

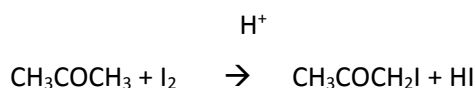
$$\text{Therefore } k = \frac{\text{rate}}{[\text{propanone}][H]}$$

## 13. A kinetic study to determine the order of a reaction (iodination of propanone)

### Sulfuric acid catalyst

#### Practical skills AT a, d, e, I

The aim of the practical is to determine the rate equation for the iodination of propanone.



The reaction is catalysed by acid.

The iodopropanone created is colourless so the reaction can be monitored by measuring the rate of loss of colour. A Colorimeter attached to a data logger is used to monitor the change in light intensity and uses 4 cm<sup>3</sup> disposable cuvettes.

Absorbance is directly linked to concentration.

### Apparatus

What is supplied and how will depend on the focus of the practical.

1. Colorimeter set to the Absorbance range
2. A blue filter and 4 cm<sup>3</sup> cuvettes with lids
3. Iodine solution as KI solution diluted to 0.02 mol dm<sup>-3</sup>.
4. Propanone 1.0 mol dm<sup>-3</sup>
5. Distilled, deionised water
6. Sulfuric acid 1.0 mol dm<sup>-3</sup>
7. 100 cm<sup>3</sup> beakers
8. 5 and 10 cm<sup>3</sup> graduated syringes or pipettes

### Risk assessment

Iodopropane is noted as a lachrymator, i.e. it produces tears. At the concentrations being produced it should have no tear making effect. It is damaging to the eye protective eyewear must be worn

### Method

1. Collect together all the solutions required, check you understand the concentrations and volumes and how you are going to measure out the volumes for the experiment runs.
2. Connect the Colorimeter to the data logger.
3. Make up a cuvette of 1.0 cm<sup>3</sup> iodine and 2.9 cm<sup>3</sup> of water, this is the calibration standard.
4. Place the standard into the Colorimeter and use it to set the colorimeter to read its maximum value on the absorbance range with a blue filter in place.
5. Set to record in EasyLog mode.
6. Transfer 2.0 cm<sup>3</sup> of the propanone and 1.0 cm<sup>3</sup> of the hydrochloric acid to a clean cuvette.
7. Add the iodine, invert the cuvette to mix the contents and quickly place into the Colorimeter and Start recording.

8. Keep recording (at least) until the readings remain constant. Ideally you need to continue for longer. A total recording of at least 5 minutes is ideal.
9. Stop the recording.
10. Select Overlay and repeat with successive cuvettes made up as indicated in the following table.

Experiment	Volume I <sub>2</sub> solution cm <sup>3</sup>	Volume Water cm <sup>3</sup>	Volume Propanone cm <sup>3</sup>	Volume Sulfuric acid cm <sup>3</sup>
1	1.0	1.5	0.7	0.7
2	1.0	0.7	1.5	0.7
3	1.0	0.7	0.7	1.5
4	0.5	2.0	0.7	0.7

- Experiment 1 is the standard
- Experiment 2 doubles the propanone
- Experiment 3 doubles the acid
- Experiment 4 halves the iodine.

## Results and analysis

You need to find the rate for each run and from the rate data deduce the rate order.

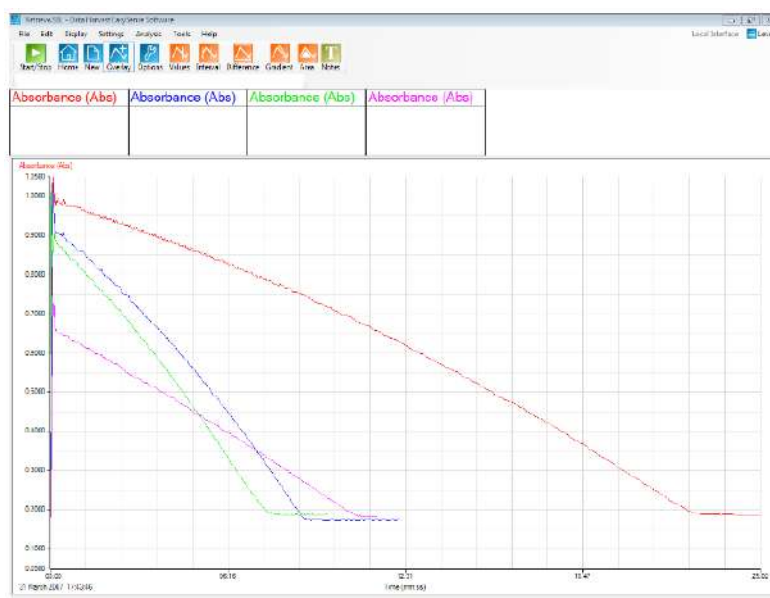


Fig 13.1 Sample of how the data collected could appear. Note the erratic data at the beginning of each of the recordings, this is the change in light due to the addition of the iodine, this has no significance as we are interested in the rate.

The rate can be deduced in several ways.

1. The simple arithmetical treatment of change / time for the graph.
2. On the iPad software a user defined gradient section tool is available.

The Colorimeter does not go to zero, you can use the gradient of the slope to find the time of intercept.

E.g. In an experiment the maximum absorbance for the standard curve was 0.947, the gradient was calculated to be 0.004x. The time for the curve to reach zero would be  $0.947 \div 0.004 = 236.75$  seconds.

Now we know how long it took for all the iodine to be used we can attempt to calculate a value of  $k$  for the reaction.

You need to calculate the original number of moles in the reaction for each concentration, e.g.

Concentration of iodine = number of moles of iodine / total volume of reaction mix.

$$= \frac{\text{volume iodine solution used} \times \text{molar concentration of iodine solution}}{\text{total volume of cuvette}}$$

Repeat for propanone and acid.

Now calculate the rate:

$$= \frac{\text{moles of iodine at start} - \text{moles of iodine at end}}{\text{time}}$$

$$\text{Therefore } k = \frac{\text{rate}}{[\text{propanone}][H]}$$



# PHYSICS

## CONTENTS

Teacher's notes: 1. Investigating interference – single slit diffraction .....	5
1. Investigating interference – single slit diffraction.....	9
Teacher's notes: 2. Investigating interference – Young's double slit experiment .....	15
2. Investigating interference – Young's double slit experiment.....	20
Teachers' notes: 3. Boyle's law ( $P + V$ ) .....	26
3. Boyle's law ( $P + V$ ).....	30
Teacher's notes: 4. Temperature volume relationship in a gas (Charles' law, Gay-Lussac's law) .....	33
4. Temperature volume relationship in a gas (Charles' law, Gay-Lussac's law).....	40
Teacher's notes: 5. SHM: Simple harmonic motion in a spring mass system (using a Motion sensor) .....	45
5. SHM: Simple harmonic motion in a spring mass system (using a Motion sensor) .....	49
Teacher's notes: 6. SHM: Simple harmonic motion in a spring mass system (using Force and Motion sensors).....	55
6. SHM: Simple harmonic motion in a spring mass system (using Force and Motion sensors) .....	59
Teacher's notes: 7. SHM: Simple harmonic motion in a spring mass system (using Force and Rotary Motion sensors).....	64
7. SHM: Simple harmonic motion in a spring mass system (using Force and Rotary Motion sensors) .....	69
Teacher's notes: 8. Period of an oscillating spring mass system.....	76
8. Period of an oscillating spring mass system .....	81
Teacher's notes: 9. Relationship between period and the length of the pendulum (using a Motion sensor) .....	85
9. Relationship between period and the length of the pendulum (using a Motion sensor).....	90
Teacher's notes: 9a. Relationship between period and the length of the pendulum (using a Rotary Motion sensor) .....	94
9a. Relationship between period and length of the pendulum (using a Rotary Motion sensor) .....	99
Teacher's notes: 9b. Relationship between period and length of the pendulum (using a Light gate) .....	103
9b. Relationship between period and length of the pendulum (using a Light gate).....	106
Teacher's notes: 10. Determination of 'g' via a plot of $2h/t$ vs. $t$ (using two Light gates) .....	109
10. Determination of 'g' via a plot of $2h/t$ vs. $t$ (using two Light gates).....	113
Teacher's notes: 11. Acceleration due to gravity – by free fall (using a falling ball).....	115
11. Acceleration due to gravity – by free fall (using a falling ball) .....	120
Teacher's notes: 12. Time constant for a capacitor - resistor circuit.....	124
12. Time constant for a capacitor - resistor circuit .....	132
Teacher's notes: 13. Charge stored on a capacitor .....	136
13. Charge stored on a capacitor .....	139
Teacher's notes: 14. Energy stored in a capacitor .....	142
14. Energy stored in a capacitor .....	147
Teacher's notes: 15. Interference in sound waves (using SnapShot).....	151
15. Interference in sound waves (using SnapShot) .....	154

Teacher's notes: 16. Interference in sound waves (with Motion sensor).....	159
16. Interference in sound waves (with Motion sensor) .....	163
Teacher's notes: 17. EMF and internal resistance.....	168
17. EMF and internal resistance .....	174
Teacher's notes: 18. How does the resistance of a wire depend upon its length? .....	177
18. How does the resistance of a wire depend upon its length? .....	179
Teacher's notes: 20. Magnetic field and angle.....	181
19. Magnetic field and angle .....	183

## Physics

The table below lists the practical worksheets (in order) in the physics section. For each practical there is a student worksheet and a teachers' guidance. Practical skills are indicated from the guidance given by the examination boards.

Practical name	Sensors	Practical skills
1. Investigating interference – single slit diffraction	Light level, Rotary Motion	a, b, j, k, i
2. Investigating interference – Young's double slit experiment	Light level, Rotary Motion	a, b, j, k, i
3. Boyle's law ( $P + V$ )	Pressure (0-700 kPa)	a, b, k
4. Temperature volume relationship in a gas (Charles' law, Gay-Lussac's law)	Temperature, Rotary Motion	a, b, k
5. SHM: Simple harmonic motion in a spring mass system (using a Motion sensor)	Motion	a, b, c, k
6. SHM: Simple harmonic motion in a spring mass system (using Force and Motion sensors)	Force, Motion	a, b, c, k
7. SHM: Simple harmonic motion in a spring mass system (using Force and Rotary Motion sensors)	Force, Rotary Motion	a, b, c, k
8. Period of an oscillating spring mass system	Motion	a, b, c, k
9. Relationship between period and the length of the pendulum (using a Motion sensor)	Motion	a, b, c, k
9a. Relationship between period and length of the pendulum (using a Rotary Motion sensor)	Rotary Motion	a, b, c, k
9b. Relationship between period and length of the pendulum (using a Light gate)	Light gate	a, b, c, d, k
10. Determination of 'g' via a plot of $2h/t$ vs. $t$ (using two Light gates)	Light gates	a, b, c, d, k
11. Acceleration due to gravity – by free fall (using a falling ball)	Motion	a, b, k
12. Time constant for a capacitor - resistor circuit	Voltage ( $\pm 12$ or $20$ V)	a, b, c, f, g, k
13. Charge stored on a capacitor	Voltage ( $\pm 12$ or $20$ V), Current ( $\pm 100$ mA or $\pm 1$ A)	a, b, c, f, g, k
14. Energy stored in a capacitor	Voltage ( $\pm 12$ or $20$ V), Current ( $\pm 100$ mA)	a, b, c, f, g, k
15. Interference in sound waves (using SnapShot)	Sound	a, b, c, h, i, k, l
16. Interference in sound waves (using a Motion sensor)	Sound, Motion	a, b, c, h, i, k, l

17. EMF and internal resistance	Voltage ( $\pm 12$ or $20$ V), Current ( $\pm 100$ mA)	a, b, f, k
18. How does the resistance of a wire depend upon its length?	Voltage ( $\pm 12$ or $20$ V), Current ( $\pm 1$ A)	a, b, e, f, g, k
19. Magnetic field and angle	Magnetic Field ( $\pm 10$ mT), Accelerometer Low g	a, b, f, k

**Apparatus and Techniques.** Skills identified in physics where data logging, data loggers or sensors should be considered.

- AT a – Use appropriate analogue apparatus to record a range of measurements (to include length/distance, temperature, pressure, force, angles, volume) and to interpolate between scale markings
- AT b - Use appropriate digital instruments, including electric multimeters, to obtain a range of measurements (to include time, current, voltage, resistance, mass)
- AT c - Use methods to increase accuracy of measurements, such as timing over multiple oscillations, or use of fiducial marker, set square or plumb line
- AT d - Use stopwatch or light gates for timing
- AT e - Use calipers and micrometers for small distances, using digital or vernier scales
- AT f - Correctly construct circuits from circuit diagrams using DC power supplies, cells, and a range of circuit components, including those where polarity is important
- AT g – Design, construct and check circuits using DC power supplies, cells, and a range of circuit components
- AT h - Use signal generator and oscilloscope, including volts/division and time-base.
- AT i - Generate and measure waves, using microphone and loudspeaker, or ripple tank, or vibration transducer, or microwave/radio wave source
- AT j - Use a laser or light source to investigate characteristics of light, including interference and diffraction
- AT k - Use ICT such as computer modelling, or data logger with a variety of sensors to collect data, or use software to process data
- AT l – Use ionising radiation, including detectors

## Teacher's notes

### 1. Investigating interference – single slit diffraction

#### Practical skills AT a, b, j, k, i

When light passes through a narrow opening it spreads out, i.e. it diffracts. The effect is greater for narrower openings. It is very important in the design of telescopes for astronomy, and in cameras. The image of a distant star should be a point. Interference produces a diffraction pattern of rings with a central disk. The size of the disk needs to be as small as possible for high resolution. In practice this is one of the reasons that mirrors and objective lenses in astronomical telescopes have a large diameter.

By using a data logger for the measurement of the fringes you can collect information about the intensity of the light vs. distance as well as the more normal distance between fringes data. This will reveal another level of information.

1. Light waves spread round corners – diffraction.
2. In narrow slits diffraction causes an interference pattern when light is shone through them.
3. The spacing for the dark fringes is given by the formula:

$$\Delta x = \frac{n\lambda \times d}{b}$$

4. The spacing for the first bright fringe is given by the formula:

$$\Delta x = \frac{1.43\lambda \times d}{b}$$

Key:-

$\Delta x$  = distance of the fringes from the middle of the central fringe

$\lambda$  = wavelength of the light

$d$  = distance between the slits and the fringe pattern

$b$  = slit width

$n$  = number of the fringe from the centre. 0 = the central fringe

#### Apparatus

1. A data logger capable of fast logging
2. Light level sensor (0 – 1,000 Lux Fast range)
3. Rotary Motion sensor set to the Linear distance range
4. Linear Rack attachment for the Rotary Motion sensor
5. Laser – Class 2, 1 mW, wavelength 645 – 665 nm (i.e. of a known visible wavelength)
6. Slits A to E on the Data Harvest slide.
7. Metre rule or, preferably, 3 – 5 m metal tape
8. Sticky tape
9. Blu-Tack or equivalent
10. 1 - 2 clamp stands with bosses and clamps

## Risk assessment

When using a laser safety precautions should be rigidly observed.

1. The laser beam should not be viewed by looking directly into the beam or a regularly reflected beam.
2. It must not be shone into the face of another person.
3. Ensure that you are aware of any local safety regulations with respect to the use of lasers.
4. The laser is Class 2, which means that if it is shone into the eye of someone, the blinking reflex will should normally close the eye before permanent damage is done.

## Set up

Recording method	Time	Intersample time
Graph	20 s	5 ms

This will give 20 seconds of recording time, you should be able to get at least one very good sweep across the fringes in this time. With practice you will find you can do a “there and back” sweep in the time available.

## Practical notes

The fringes can be lined up with the Light sensor using a white card, placed alongside the light guide.

Blackout is not necessary. However, low levels of lighting are preferable. Place the apparatus away from direct light and it may be better to shade the Light sensor with a tube of black paper.

There is some vertical movement on the rack. It is advisable to hold the rack close to the Light sensor, and pull it through the fringes making sure that the Light Sensor passes through the middle of each bright fringe.

The ambient light level should not change significantly during a sequence of readings.

The intensity of the fringes falls off very rapidly as you go out from the central maximum. The values as a percentage of the intensity of the central maximum are given in the table below:

Table 1.0 Maxima and % intensity of main and side fringes.

Number of maximum	Intensity as % of intensity of central maximum
0	100
1	4.7
2	1.7
3	0.8

From this table it is quite clear that the Light sensor is unlikely to be able to measure the light levels of the second and third maxima.

## Sample results and analysis

Distance  $d = 1.0 \text{ m}$  Slit width =  $0.06 \text{ mm}$

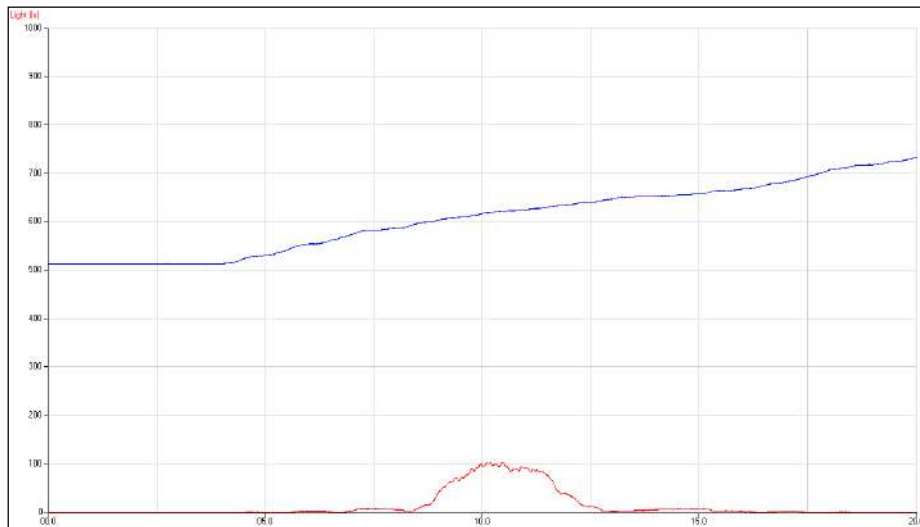


Fig 1.1 The screen showing the raw data

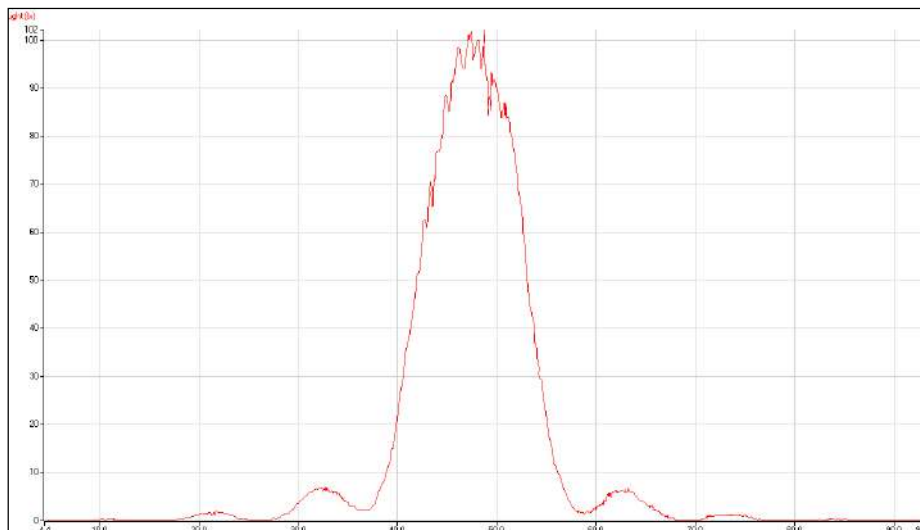


Fig 1.2. Light level scaled to fill the screen showing the first maxima on either side of the central fringe.

Measuring the intensity of the light clearly shows that the greatest amount of light passes through the centre of the slit, only light at the margins is bent, and this is much less. Measurements of the peaks can easily be made using Values.

### Bright fringe

Slit No	Reading	Reading	Interval	$\Delta x$	$\Delta x$	d	b	Lambda $\lambda$
	First fringe L1	First fringe L2	L1 - L2 mm	mm	m	m	m	m
D	62.9	32.5	30.4	15.2	0.0152	1	0.00006	6.37762E-07

Make sure the students use the correct units for distances, this is common source of error in student calculations.

The value obtained for  $\lambda$  is well within the expected errors for the experiment.

$$\left( \lambda = \frac{b \times \Delta x}{1.43d} \right)$$

### Errors

1. The biggest errors in this experiment are likely to be in the slit width 'b'. The stated error by the manufacturers is in the range  $\pm 4.5\%$  to  $\pm 11\%$ . The smallest error is for the largest value of b.
2. When measuring the values of the readings of the maxima there is an error of about  $\pm 0.5$  to 1 mm which will produce an error of between 2.5% and 5 % depending on the length of the interval measured.
3. It should be possible to measure the distance 'd' to within  $\pm 5$  mm. The error here will therefore be less than 0.5%.
4. The wavelength of the laser is stated to be in the range of 645 to 665 nm. This is a spread of about 3%. If we assume a wavelength of 655 nm, we will introduce an error of  $\pm 1.5\%$ .

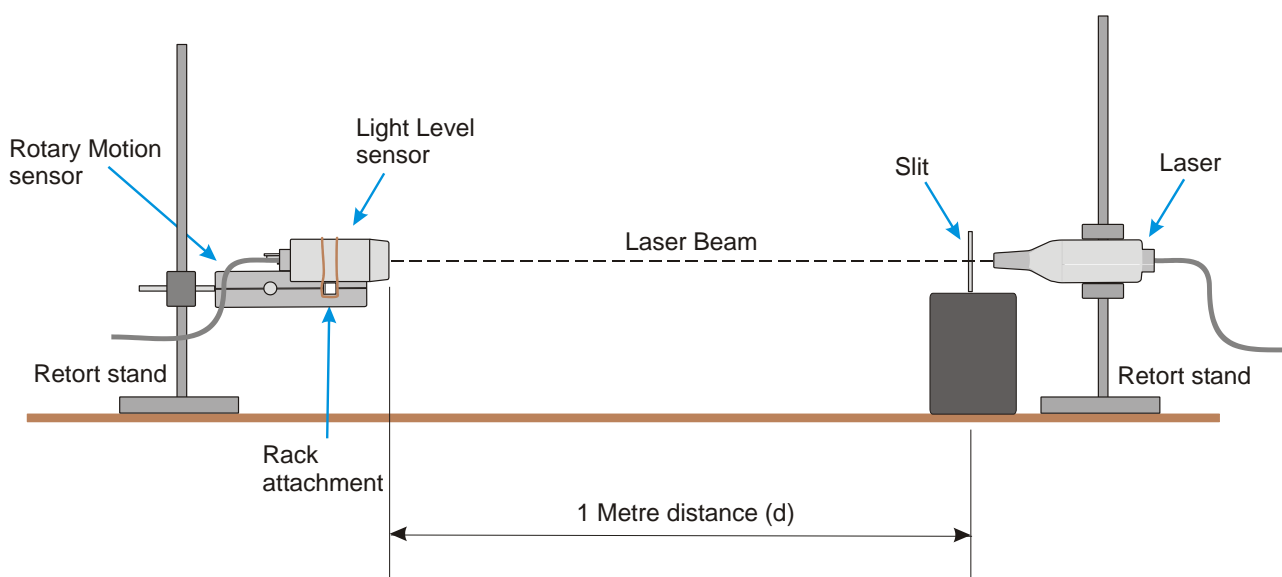


## 1. Investigating interference – single slit diffraction

### Practical skills AT a, b, j, k, i

When light passes through a narrow opening it spreads out, i.e. it diffracts. The effect is greater for narrower openings. It is very important in the design of telescopes for astronomy, and in cameras. The image of a distant star should be a point. Interference produces a diffraction pattern of rings with a central disk. The size of the disk needs to be as small as possible for high resolution. In practice this is one of the reasons that mirrors and objective lenses in astronomical telescopes have a large diameter.

In this experiment you are going to measure the distance between the fringes formed when a laser beam is shone on one slit, and from that information calculate the wavelength of the laser light.



### Apparatus

1. A data logger capable of fast logging
2. Light Level sensor (0 – 1,000 Lux Fast range)
3. Rotary Motion sensor with Linear Rack attachment
4. Laser – Class 2, 1 mW, wavelength 645 – 665 nm
5. Slits A to E on the optical slide
6. Metre rule or, preferably, 3 – 5 m metal tape
7. Sticky tape
8. Blu-Tack or equivalent
9. 1 - 2 clamp stands with bosses and clamps

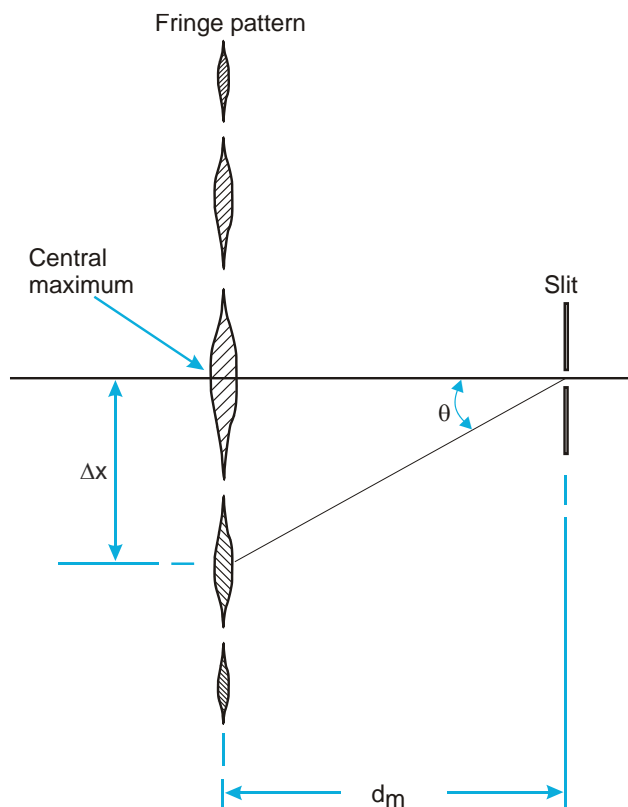
### Risk assessment

When using a laser safety precautions should be rigidly observed.

1. The laser beam should not be viewed by looking directly into the beam or a regularly reflected beam.

2. It must not be shone into the face of another person.
3. Ensure that you are aware of any local safety regulations with respect to the use of lasers.
4. The laser is a Class 2 laser, which means that if it is shone into the eye of someone, the blinking reflex will normally close the eye before permanent damage is done.

### Fringe pattern for a single slit diffraction of light



The shaded areas represent bright fringes.

Key:-

$\Delta x$  = distance of the fringes from the middle of the central fringe

$\lambda$  = wavelength of the light

$d$  = distance between the slits and the fringe pattern

$b$  = slit width

$n$  = number of fringes from the centre. 0 = the central fringe

### Risk assessment

- The laser must never be viewed directly with the eye.
- The beam must never be pointed at a person's face.
- The beam must never be viewed after direct reflection from a shiny surface or mirror.

## Method

Set up the apparatus as shown. You will need to take care in aligning everything correctly.

1. Connect the Light level sensor, Rotary Motion sensor and Laser to the data logger.
2. The Rotary Motion Sensor is arranged so that the rack is horizontal with the teeth facing sideways.
3. The Light level sensor is mounted on the rack of the Rotary Motion sensor with the clamp provided. Mount it so that the longest length of the sensor is vertical.
4. Mount the slits so they are vertical, on a suitable block. Blu-Tack or plasticine may be used for this purpose.
5. Place the Rotary Motion sensor so that the distance  $d$  is 1 metre (i.e. from the slit to the Light sensor).
6. Place the laser immediately behind slit E, and switch on the laser. Adjust the height of the laser so that fringes are at the same height as the end of the Light sensor. The fringe pattern should appear as a horizontal line of large dots. If the fringe pattern is not horizontal, move the slits in their mounting so that they are vertical. A white card placed next to the Light sensor will help.
7. If the logger is not used for a short time it will go to 'sleep mode' and the laser will switch off. Pressing one of the buttons on the logger will 'wake' up the logger and the laser can then be switched back on.
8. Check that you can move the light guide across the fringe pattern with a smooth movement, by moving the rack backwards and forwards.
9. There is some vertical movement on the rack. It is advisable to hold the rack close to the Light sensor, and pull it through the fringes making sure that the Light sensor passes through the middle of each bright fringe.
10. Measure the value  $d$ . It makes the calculations easier if you arrange  $d$  to be exactly 1 metre.
11. Set up the data recording:

Recording Method	Time	Intersample time
Graph	20 s	5 ms

12. Zero the Rotary Motion sensor when the Light sensor is at the end of a set of fringes.
13. Click on Start and move the light guide smoothly through the fringes. During the 20 seconds of the data recording time you should move the sensor slowly through the fringe pattern.
14. Check the curves you have obtained and save the file if they are satisfactory.
15. Repeat twice more for the same slit.
16. Note down the slit letter and slit width ' $b$ '.
17. You may repeat the experiment with the other slits if you have time.

You should have collected a set of results similar to the sample shown below. It may take several attempts to get the feel of moving the sensor and keeping it on the line of fringes.

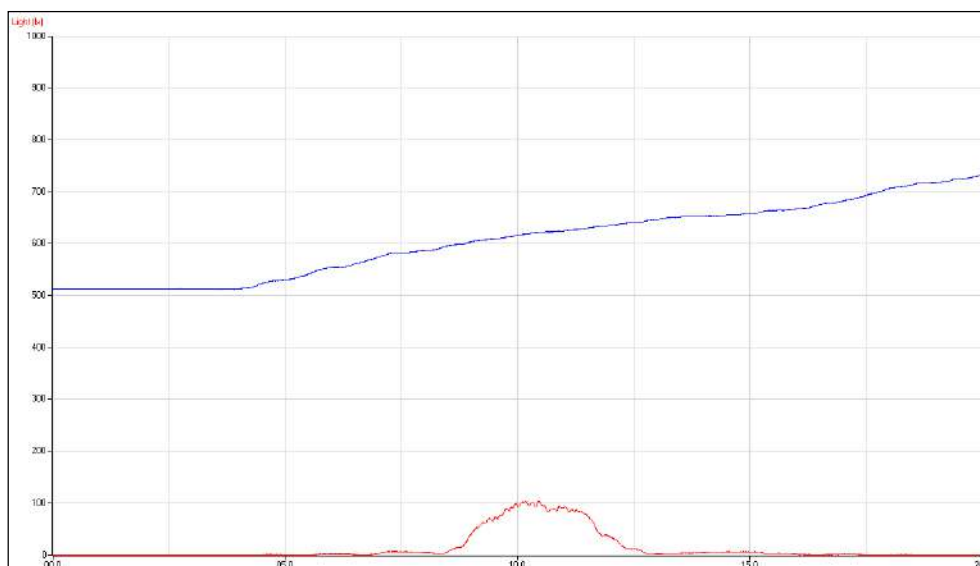


Fig 1.1 Example of data as collected.

## Theory

Calculating the wavelength

From the diagram above showing the pattern of fringes from a single slit we can see that for small values of  $\theta$ : -

$$\sin \theta = \tan \theta = \frac{\Delta x}{d}$$

The wavelength of the light can be calculated from the fringe separation as follows: -

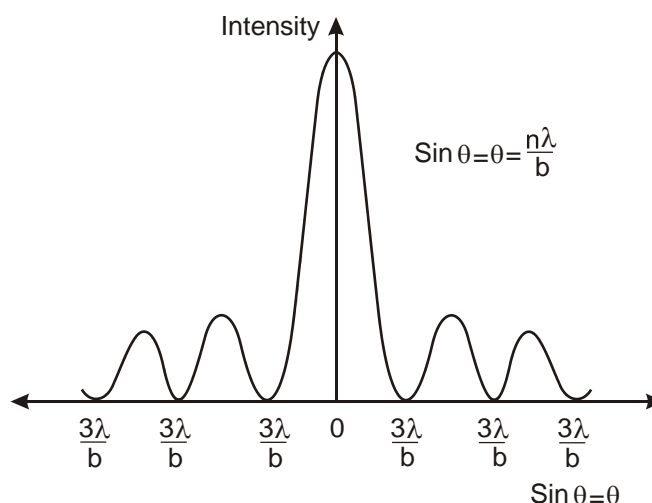


Fig 1.2 The angular positions of the minima produced in the fringe pattern.

For the first minimum:

$$\sin \theta = \frac{\lambda}{b} = \frac{\Delta x}{d}$$

$$\therefore \lambda = \frac{\Delta x \times b}{d}$$

The values for the maxima are: -

Number of maximum	Value of $\sin\theta = \theta$
0	0
1	$1.43 \lambda/b$
2	$2.46 \lambda/b$
3	$3.47 \lambda/b$

For the first maximum 
$$\lambda = \frac{b \sin \theta}{1.43}$$

Substituting for  $\sin\theta$  
$$\lambda = \frac{b \times \Delta x}{1.43d}$$

**Note:** You will use the first maximum rather than the first minimum because the values of  $\Delta x$  will be nearly 50% bigger and errors will be reduced significantly. In addition, the centre of a bright maximum is easier to judge on the light vs. distance graph.

## Results and analysis

Note down the following values: -

Slit width  $b = \dots\dots\dots\text{m}$

Distance from slit to Light sensor  $d = \dots\dots\dots\text{m}$

You will have obtained graphs of light level and distance (Linear Rack) against time. Use Options, Sensor Settings to scale the graphs.

The analysis of the results will involve the following steps: -

### Generate a Light level vs. Distance graph (X – Y plot)

1. Calculating  $\Delta x$  (the fringe spacing) from the Light level vs. Distance graph. If you are doing several sets of results, If you are using several slits or lasers of differing wavelengths this is achieved most effectively using a spreadsheet program such as Excel into which you can enter new values.
2. Calculate the wavelength of the laser light.

### Generate a Light level vs. Distance (linear) graph, as an X – Y plot

1. In Options click on the X –Axis tab.
2. Select Channel. Click on Finish.
3. The graph will now display an X – Y plot. Click in the space between the axis and the edge of the graphing area to make the X axis Linear distance and the Y axis Light.
4. Use Zoom or Autoscale to scale the graph as needed.
5. Use Smooth from the Tools menu to smooth the curve if necessary, you may have to smooth both Light and linear rack.

**Calculating  $\Delta x$  from the Light level vs. Distance X – Y graph**

1. Click on Values and place the cursor on the maximum of the first fringe on one side of the central fringe. Read the distance reading  $L_1$ , and enter the value in the table below.
2. Move the cursor to the maximum of the first fringe on the other side of the central maximum, and read the value of distance  $L_2$ . Enter the value into the table below.
3. Complete the interval column where Interval =  $L_2 - L_1$
4. The values of  $L_1$  and  $L_2$  are magnitude only; do not include any minus signs.
5. Fringe width  $\Delta x = \text{Interval} \div 2$ .

Calculate the wavelength of the light

Calculate the wavelength using the formula shown in the theory section, and below.

$$\lambda = \frac{b \times \Delta x}{1.43d}$$

**Note:** These calculations are most effectively achieved using a spreadsheet program such as Excel.

**Results table**

Slit No.	Reading $L_1$ mm	Reading $L_2$ mm	Interval $L_1 - L_2$ mm	$\Delta x (L_1 - L_2)/2$ mm	$\Delta x$ m	d m	b m	$\lambda$ m

**Questions**

1. List the sources of error in the experiment, and estimate the total error in the final value you have obtained for the wavelength of the laser.
2. Compare the diffraction pattern for a single slit with that of the pattern for two slits. How are they similar and different?
3. A diffraction pattern is obtained on a screen using a laser producing light of wavelength 589 nm (Sodium D2) and a single slit of width 0.01 mm. The screen is placed 2 m from the slit.

**Calculate:**

- a. The angular position of the first minimum.
- b. The angular width of the central maximum.
- c. The width of the central maximum on the screen.
- d. The distance of the second minimum from the middle of the central maximum.

**Extension**

Investigate the relationship between the slit width 'b', and the fringe width  $\Delta x$ .

## Teacher's notes

### 2. Investigating interference – Young's double slit experiment

#### Practical skills AT a, b, j, k, i

Thomas Young's experiment in 1801 provided experimental evidence for the wave nature of light. The corpuscular (particle) theory of light had held sway for about 150 years since Newton suggested it in the 17th century. He demonstrated that when light from a single source was shone through two narrow slits close together, the light from the two slits interfered and produced a pattern of light and dark lines or fringes. This experiment can only be explained if light acts as a wave.

The bright fringes are caused by constructive interference between the light from the two slits, and the dark fringes are caused by destructive interference.

We now know that light exhibits both wave and particle properties. It consists of packets of energy i.e. particles called photons. In the twentieth century, a repetition of Young's experiment, using single photons showed that even individual photons have wave properties as well as particle properties.

The laser beam passes through the double slit. The two slits act as coherent sources of light. As a result of single slit diffraction the beams spread out and interfere with one another and produce a series of fringes, in the form of large, blurred, dots of light.

1. The bright fringes are caused by constructive interference and the dark fringes by destructive interference.
2. The fringe width  $\Delta x$  is inversely proportional to the slit separation 's'.
3. The formula for Young's slits is:

$$\Delta x = \frac{d\lambda}{s}$$

$$\therefore \lambda = \frac{s \times \Delta x}{d}$$

Key:

- $\lambda$  = wavelength of the light
- $\Delta x$  = fringe width, i.e. the distance between successive bright fringes, OR successive dark fringes.
- $s$  = slit separation, the distance between the centres of the slits.
- $d$  = the distance from the fringe pattern to the slits. In this case the distance between the sensor and the slits.

#### Apparatus

1. A data logger capable of fast logging
2. Light Level sensor – 1,000 Lux Fast range
3. Rotary Motion sensor set to the linear distance range
4. Rotary Motion Linear Rack attachment.
5. Laser – Class 2 , 1 mW, wavelength 645 – 665 nm
6. Slits F to J on the laser optical slide

7. Metre rule or, preferably, 3 - 5 m metal tape
8. Sticky tape
9. Blu-Tack or equivalent
10. 1 - 2 clamp stands with bosses and clamps

## Risk assessment

When using a laser safety precautions should be rigidly observed.

- The laser beam should not be viewed by looking directly into the beam or a regularly reflected beam.
- It must not be shone into the face of another person.
- Ensure that you are aware of any local safety regulations with respect to the use of lasers.
- The laser supplied is a Class 2 laser which means that if it is shone into the eye of someone, the blinking reflex will normally close the eye before permanent damage is done.

## Set up

Recording Method	Time	Intersample time
Graph	20 s	5 ms

The logger needs to set to record in fast mode to increase the accuracy of the data collection. The disadvantage for the students with this type of logging is that do not see the results until the recording has completed.

## Practical notes

The Light level sensor is attached to the rack of the Rotary Motion Sensor with the clip provided in the accessory pack. Strong rubber bands can also be used.

The actual sensor in the Light sensor is a rectangle of about 2 mm by 3 mm. Position the Light sensor so that the long side of the sensor rectangle is vertical. You can experiment with making a slit from card or paper to go over the sensor; this will ensure that only the light from a single fringe is on the sensor at any one time. With distances of 1.0m between the slits and sensor the sensor should be able to be left unadulterated.

The fringes can be lined up with the Light sensor using a card, placed alongside the Light sensor.

There is some vertical movement on the rack. It is advisable to hold the rack close to the Light sensor, and pull it through the fringes making sure that the Light sensor passes through the middle of each bright fringe. If necessary manipulate the rack to keep the sensor running across the fringes.

The laser beam is an oval close to the laser. Clamp the laser so that the longest beam diameter is parallel to the slits.

Blackout is not necessary. However, low levels of lighting are needed. Place the apparatus away from direct light and it may be better to shade the light sensor and light guide with a tube of black paper.

The ambient light level should not change significantly during a sequence of readings.

Set the slit - sensor distance to 1 metre to make the mathematics easier.

It is advisable to write down all distances in metres from the start to avoid confusion.



### Sample results and analysis

Results were obtained using slits F to J on the optical slide, and a value of ' $d$ ' = 0.97 m. Sample graphs are for slits J.

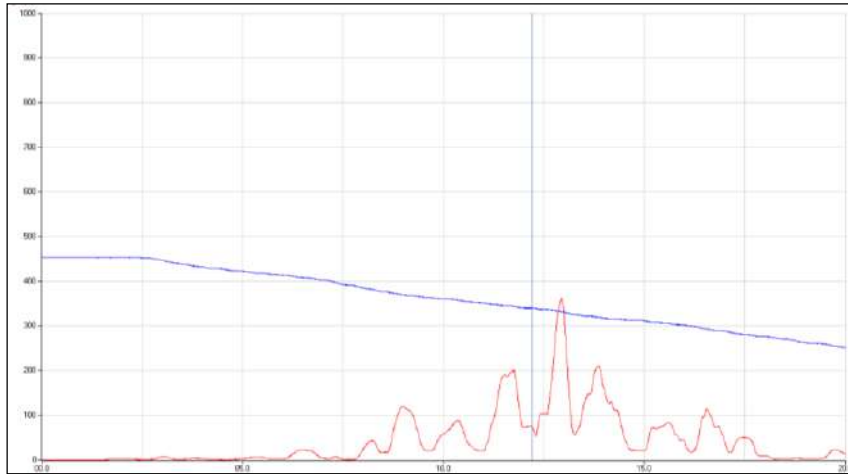


Fig 2.1 The data as displayed after collection

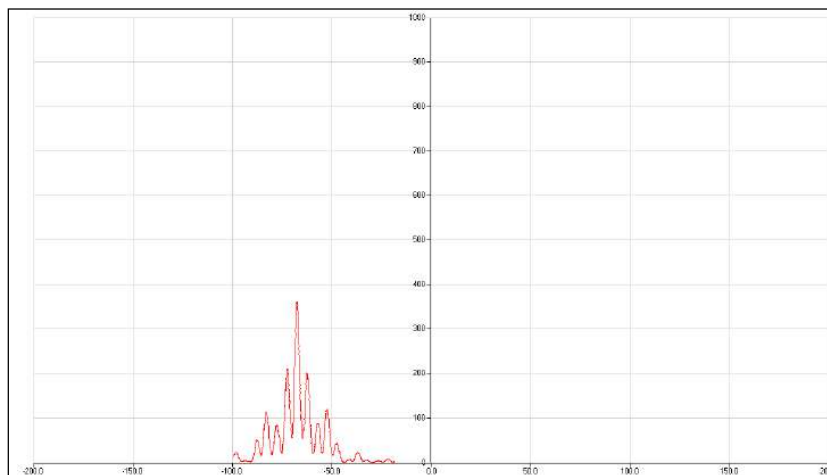


Fig 2.2 The data after scaling and generating the X – Y graph of Light level versus Distance

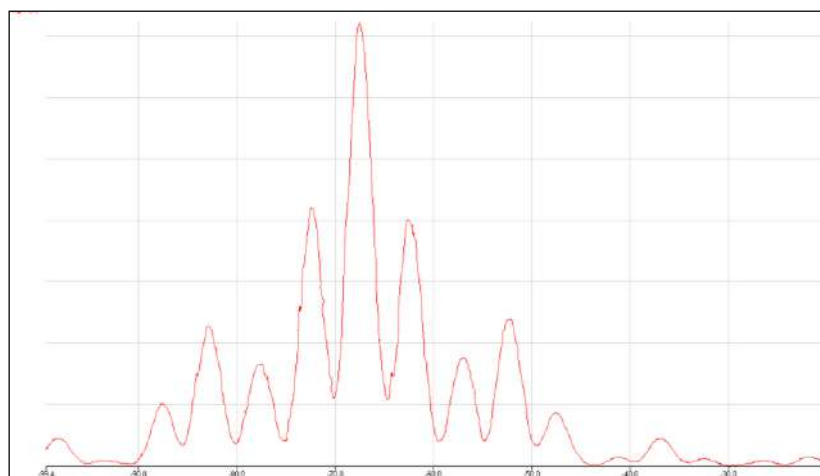


Fig 2.3 The data after using Autoscale and Smoothing on the Linear rack data

The Values tool can be used to find the peak of the light fringes. Alternatively, you could use the Interval tool to find the distance separating the fringes.

Table 05.1 The table shows the data for the Data Harvest optical slide's slits analysed in Excel.

Slit	Slit sep'n s	1/s	Reading 1st fringe	Reading last fringe	Interval	No of fringes	Delta x
F	0.000051	19607.84	0.0082	0.1291	0.1209	10	0.01209
G	0.000061	16393.44	0.0188	0.1189	0.1001	10	0.01001
H	0.000076	13157.89	0.0159	0.0899	0.074	9	0.008222
I	0.000102	9803.922	0.0271	0.0766	0.0495	8	0.006188
J	0.000122	8196.721	0.037	0.0983	0.0613	12	0.005108

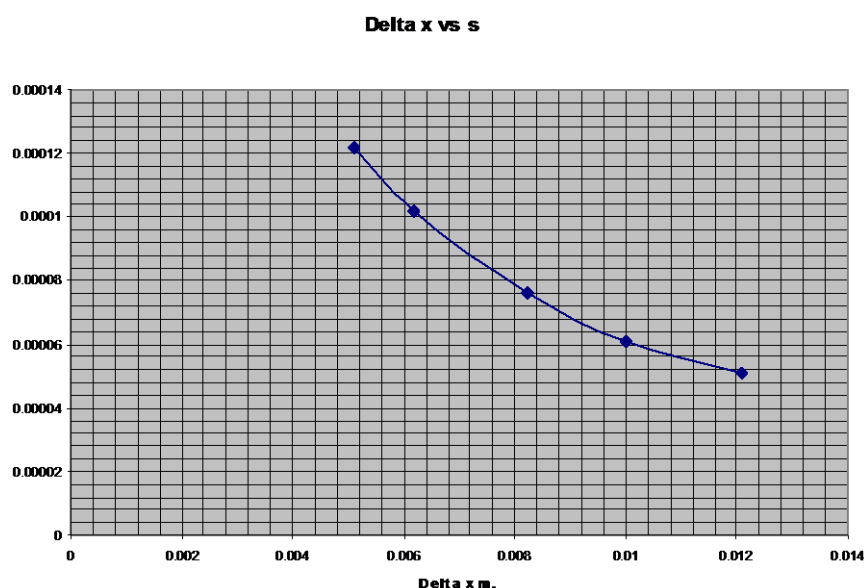


Fig 2.4 This graph clearly shows that fringe width  $\Delta x$  increases as the slit width decreases.

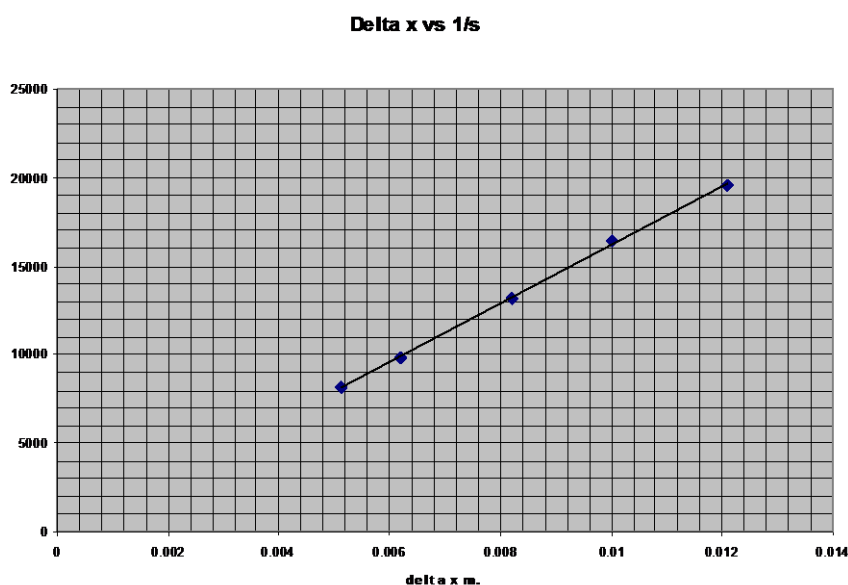


Fig 2.5 The graph is a straight line through the origin showing that:  $\Delta x \propto \frac{1}{s}$

## Errors

1. The biggest errors in this experiment are likely to be in the slit separation 's'.

The stated error by the manufacturers is in the range  $\pm 2.5\%$  to  $\pm 6\%$ . The smallest error is for the largest value of s.

2. When measuring the values of the readings of the maxima there is an error of about  $\pm 1$  mm which will produce an error of between 1 and 2% depending on the length of the interval measured.
3. It should be possible to measure the distance 'd' to within  $\pm 5$  mm. The error here will therefore be less than 0.5%.
4. The wavelength of the laser is stated to be in the range of 645 to 665 nm. This is a spread of about 3%. If we assume a wavelength of 655 nm we will introduce an error of  $\pm 1.5\%$ .

## 2. Investigating interference – Young's double slit experiment

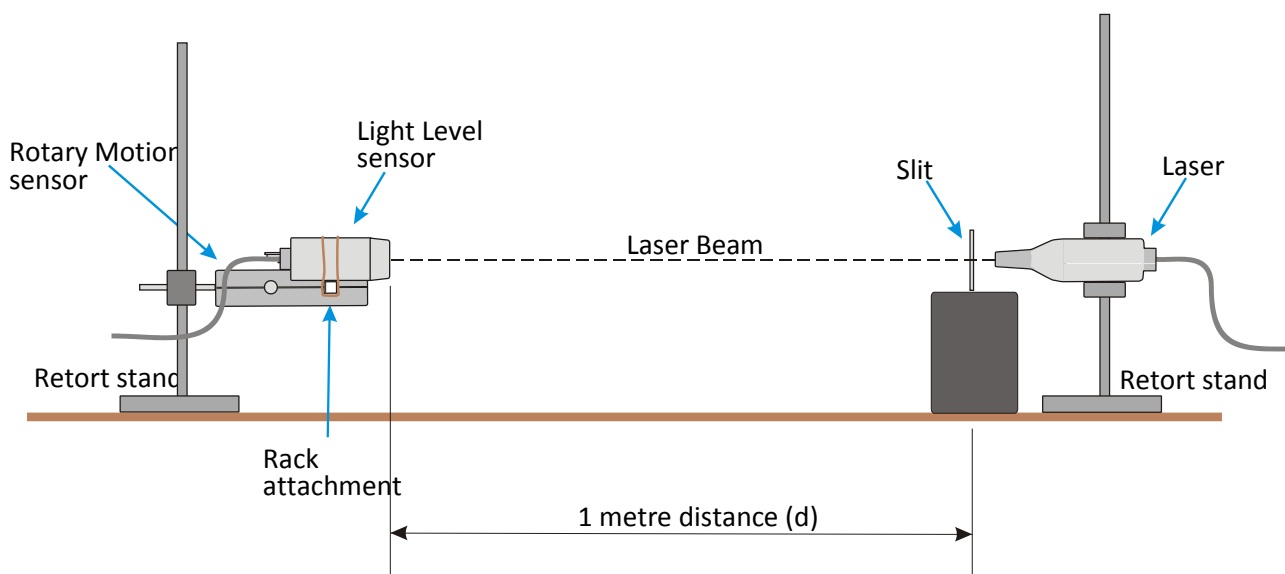
### Practical skills AT a, b, j, k, i

Thomas Young's experiment in 1801 provided experimental evidence for the wave nature of light. The corpuscular (particle) theory of light had held sway for about 150 years since Newton suggested it in the 17th century. Young demonstrated that when light from a single source was shone through two narrow slits close together, the light from the two slits interfered and produced a pattern of light and dark lines or fringes. This experiment can only be explained if light acts as a wave.

The bright fringes are caused by constructive interference between the light from the two slits, and the dark fringes are caused by destructive interference.

We now know that light exhibits both wave and particle properties. It consists of packets of energy i.e. particles called photons. In the twentieth century, a repetition of Young's experiment, using single photons showed that even individual photons have wave properties as well as particle properties.

In this experiment you are going to measure the distance between the fringes formed, when a laser beam of known wavelength, is shone through five sets of two slits. From that information you will investigate the relationship between the fringe width and the separation of the slits.



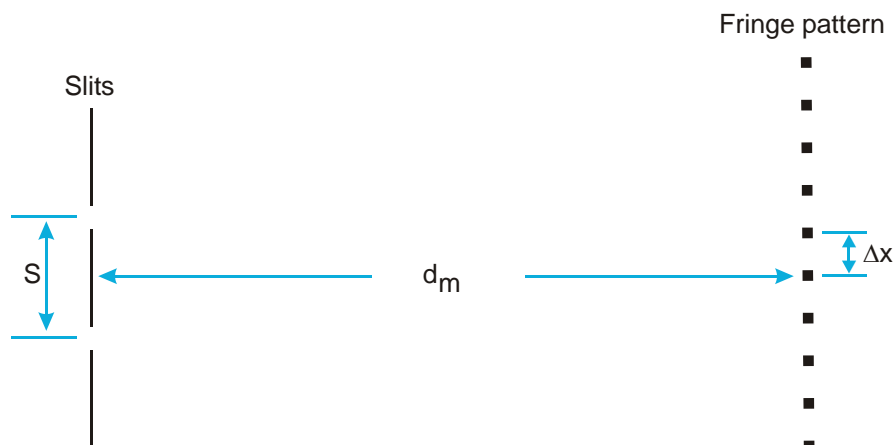
### Apparatus

1. A data logger capable of fast logging
2. Light Level sensor – 1,000 Lux fast range
3. Rotary Motion sensor set to linear distance range
4. Rotary Motion Linear Rack attachment
5. Laser – Class 2, 1 mW, wavelength 645 – 665 nm
6. Slits F to J on the optical slide
7. Metre rule or, preferably, 3 - 5m metal tape
8. Sticky tape
9. Blu-Tack or equivalent
10. 1 - 2 clamp stands with bosses and clamps

## Risk assessment

When using a laser safety precautions should be rigidly observed.

1. The laser beam should not be viewed by looking directly into the beam or a regularly reflected beam.
2. It must not be shone into the face of another person.
3. Ensure that you are aware of any local safety regulations with respect to the use of lasers.
4. The laser is a Class 2 laser, which means that if it is shone into the eye of someone, the blinking reflex will normally close the eye before permanent damage is done.



The dots represent bright fringes.

Key: -

$\Delta x$  = distance between successive fringes

$\lambda$  = wavelength of the light

$d$  = distance between the slits and the fringe pattern

$s$  = distance between the slits

## Method

1. Set up the apparatus as shown in the diagram above. Connect the Light level sensor, Rotary Motion sensor and Laser to the data logger.
2. The Rotary Motion sensor is arranged so that the rack is horizontal with the teeth facing sideways.
3. The Light level sensor is mounted on the rack of the Rotary Motion sensor with the clamp provided in the accessory pack. Mount it so that the longest length of the sensor element is vertical.
4. Mount the slits so they are vertical, on a suitable block. Blu-Tack or plasticine may be used for this purpose.
5. Place the Rotary Motion sensor so that the distance  $d$  is 1 metre.
6. Place the laser immediately behind slit J, and switch on the laser. Adjust the height of the laser so that fringes are at the same height as the end of the Light sensor. The fringe pattern should appear

as a horizontal line of dots. If the fringe pattern is not horizontal, move the slits in their mounting so that they are vertical. A white card placed next to the Light sensor will help.

7. If the logger is not used for a short time it may go to 'sleep mode' and the laser will switch off. Pressing one of the buttons on the logger will 'wake' up the logger and the laser can then be switched back on by pressing the button on the laser.
8. Check that you can move the light guide across the fringe pattern with a smooth movement, by moving the rack backwards and forwards.
9. There is some vertical movement on the rack. It is advisable to hold the rack close to the Light sensor, and pull it through the fringes making sure that the Light sensor passes through the middle of each bright fringe.
10. Measure the value **d**. It makes the calculations easier if you arrange **d** to be exactly 1 metre.
11. Set up the data recording:

Recording Method	Time	Intersample time
Graph	20 s	5 ms

12. Zero the Rotary Motion sensor, with the reset button, when the Light sensor is at the end of a set of fringes.
13. Click on Start and move and guide the Light sensor smoothly through the fringes. The recording time is 20 second, during this time you should move the sensor slowly through the fringe pattern.
14. Check the curves you have obtained and save the file if they are satisfactory.
15. Repeat the measurements for the other slits. Keep the same value for '**d**', the slit – sensor distance for each slit. Always start from the same end of the fringe pattern and zero the Rotary Motion Sensor before clicking Start.
16. Note down the slit letter and slit separation '**s**' each time.

You should have collected a set of results similar to the sample shown below; these results are for a single pair of slits. It may take several attempts to get the feel of moving the sensor and keeping it on the line of fringes.

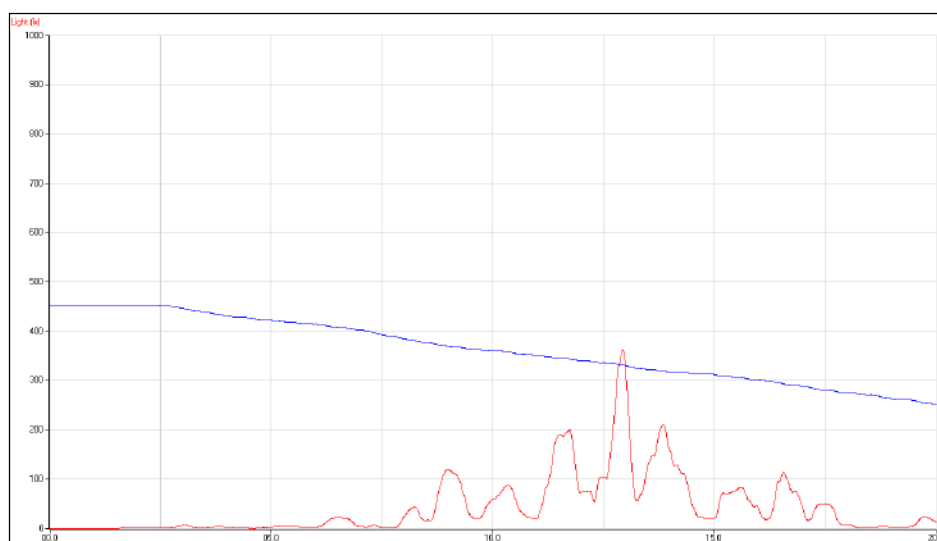


Fig 2.1 Example of how data collected will appear in the software.

## Results and analysis

Note down the following values: -

Wavelength of the laser light  $\lambda = \dots\dots\dots\text{m}$  use the mean value of the laser wavelength.

Distance from slits to Light Sensor  $d = \dots\dots\dots\text{m}$

You will have obtained graphs of Light level and Distance (Linear rack) against time. Use Sensor settings from the Display menu, to scale the graphs.

The analysis of the results will involve the following steps: -

### Generate Light level vs. Distance graphs as X – Y plots

1. Calculating  $\Delta x$  (the fringe spacing) from the Light level vs. Distance graph. This is achieved most effectively using a spreadsheet program such as Excel.
2. Plotting graphs of  $s$  vs.  $\Delta x$ , and  $1/s$  vs.  $\Delta x$ . Again use Excel to draw these graphs.

### Generate a Light level vs. Distance (Linear rack) graph, as an X – Y plot

1. In Options click on the X –Axis tab.
2. Select Channel. Click on Finish.
3. The graph will now display an X – Y plot. Click in the space between the axis and the edge of the graphing area to make the X axis Linear Rack and the Y axis Light.

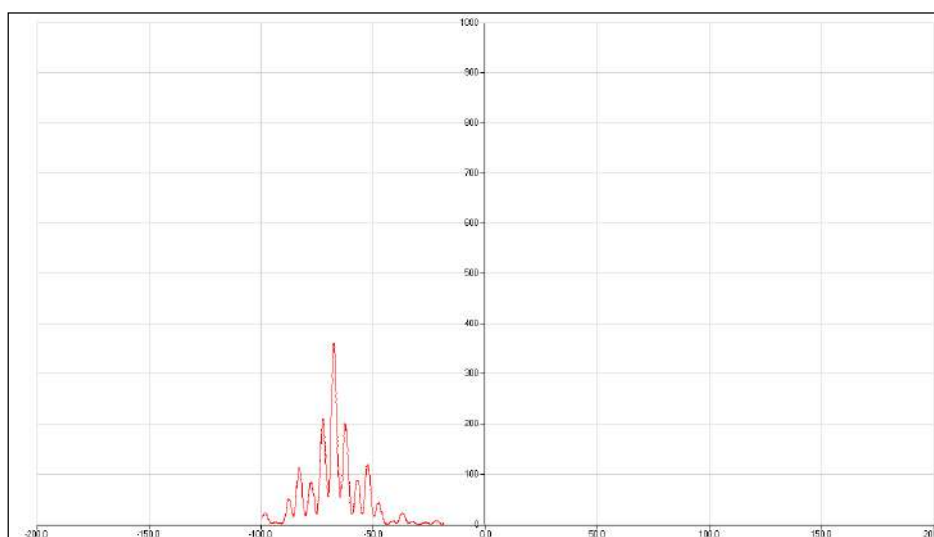


Fig 2.2 Example of plot of distance against light intensity

4. Use Zoom or Autoscale to scale the graph as needed.
5. Use Smoothing (Tools menu) to smooth the curve if necessary, you may have to smooth both Light and Linear distance.

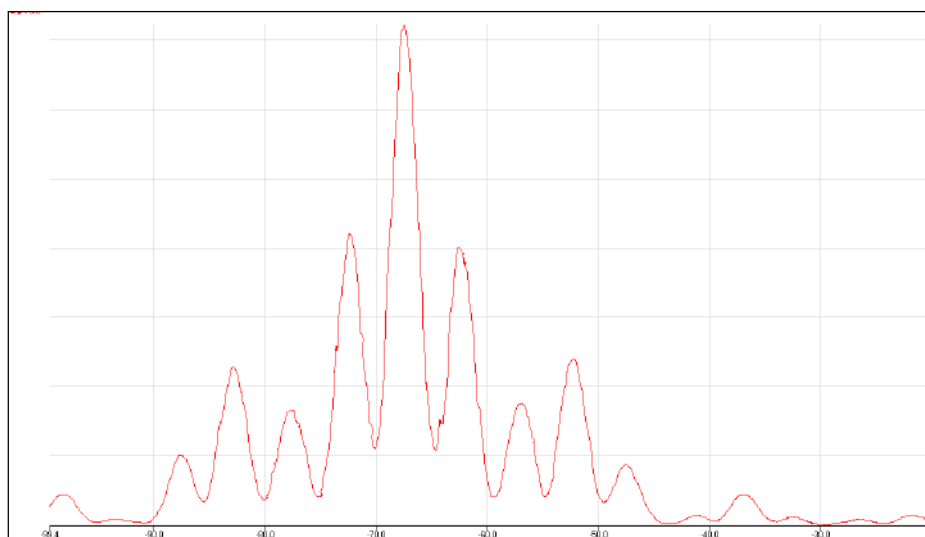


Fig 2.3 Example of how data will look after Autoscale applied

### Calculating $\Delta x$ from the Light level vs. Distance X – Y graph

1. Click on Values and place the cursor on the maximum of the first identifiable fringe. Read the distance reading  $L_1$ , and enter the value in the table below.
2. Move the cursor to the last identifiable maximum, and read the value of distance  $L_2$ . Enter the value into the table below.
3. Complete the interval column where Interval =  $L_2 - L_1$
4. Count the number of complete fringes between the first and last fringes you used.
5. Fringe width  $\Delta x = \text{Interval} \div \text{number of fringes}$ .

### Draw the graphs of $\Delta x$ vs. $s$ , and $\Delta x$ vs. $1/s$ using the spreadsheet program – or by hand

1. In the Chart Wizard in Excel choose XY Scatter.
2. Follow the instructions in the software.
3. Draw the trendline for the graph of  $\Delta x$  vs.  $1/s$ .

### Results table

This table is most conveniently completed in a spreadsheet such as Excel.

Slit letter	Slit separation $s$ m	$1/s$ m <sup>-1</sup>	Reading 1st fringe $L_1$ m	Reading last fringe $L_2$ m	Interval $L_2 - L_1$ m	No of fringes	$\Delta x$ m



## Questions

1. From the  $\Delta x$  vs.  $s$  graph what can you conclude about the relationship between  $\Delta x$  and  $s$ ?
2. The graph of  $\Delta x$  vs.  $1/s$  is a straight line. Explain clearly what this graph tells you about the relationship between  $\Delta x$  and  $s$ .
3. Use the equation in the Learning Summary to calculate the value of the wavelength from one of your results.
4. List the sources of error in the experiment, and estimate the total error in the value you have calculated for the wavelength of the laser. Compare your value with the stated value.

## Extension

1. Investigate the relationship between the slit to sensor distance 'd' and the fringe width  $\Delta x$ .
2. Use the slits to measure the wavelength of a light source.

## Learning summary

From the investigation you will have come to the following conclusions: -

1. The value of the fringe width  $\Delta x$ , decreases as the slit separation 's' gets larger.
2.  $\Delta x$  is inversely proportional to  $s$  i.e.

$$\Delta x \propto \frac{1}{s}$$

The complete relationship is:

$$\Delta x = \frac{d\lambda}{s}$$

$$\therefore \lambda = \frac{s \times \Delta x}{d}$$

**Note:** The value of  $\Delta x$  is also affected by the ratio  $\lambda/s$ . There is only significant interference if the slit separation is comparable in magnitude to the wavelength of light. If  $s \gg \lambda$  then the fringes will be too close together for the effective measurement of  $\Delta x$ .

Key:-

$\Delta x$  = distance between successive fringes.

$\lambda$  = wavelength of the light.

$d$  = distance between the slits and the fringe pattern.

$s$  = distance between the slits.

## Further questions

A laser beam is directed at a pair of double slits with a slit spacing of 0.4 mm. The bright fringes seen on a screen 1.0 m. away from the slits are 1.4 mm apart. Calculate the following:-

- a. The wavelength of the laser light.
- b. How far, and in which direction would the screen have to be moved to obtain a fringe spacing of 1.8 mm?
- c. If the laser is replaced with a violet laser of wavelength 405 nm, and the screen is moved to 750 mm from the slits, what is the new fringe spacing?

## Teachers' notes

### 3. Boyle's law ( $P + V$ )

#### Practical skills AT a, b, k

Boyle's law relates the volume and pressure of a fixed mass of air kept at constant temperature.

The law states "The volume of a fixed mass of gas is inversely proportional to the pressure, provided the temperature remains constant."

In this investigation SnapShot mode is used to collect the pressure information for a fixed mass of gas that is being compressed in volume. The function wizard is then used to produce the graph of  $P$  vs.  $1/V$ . If Boyle's law is correct the plot of  $P$  vs.  $1/V$  will be a straight line.

#### Apparatus

1. 0 - 700 kPa Gas Pressure sensor
2. 50 cm<sup>3</sup> plastic syringe
3. 3 mm inside diameter PVC tubing (1.5 cm long)
4. 3 way tap (not essential)

#### Set up

Recording method	Pre-log Function
SnapShot	General, Asks for Value

When the Start icon is clicked SnapShot waits for the user to tell it when to collect a sample. The user is required to click anywhere in the graph area to indicate that a sample is to be recorded. After the data has been recorded a dialogue box appears and asks for the value.

If the asks for volume function is not available, make sure each reading is taken at a standard volume e.g. every 10 cm<sup>3</sup> of the plunger movement.

Allow a short pause between readings to allow the heat of compression to be dissipated

#### Practical notes

##### Connecting the sensor to the syringe

A 50 cm<sup>3</sup> syringe is not essential, smaller syringes can be used. However, a larger syringe does allow the experimenter to have more control over the "push and hold".

For good results it is important that there is a good airtight seal between all the components. 3 mm inside diameter PVC tubing (as used for aquarium accessories) provides a good fit.

The three way tap allows the pressure to be equalized in the apparatus before the investigation starts, it is not essential.

3 mm outside diameter polyurethane / nylon pneumatics tubing makes very good link connectors that fit inside PVC tubing and three-way tap "sockets". Repeated connection of the three way tap direct to the

syringe or sensor can cause the plastics on the tap to craze and fracture, using the pneumatics tube gives a good seal and transfers the strain to a more easily replaceable item.

When the sensor is connected to the syringe there will be a pressure recorded, this is the atmospheric pressure reading. The atmospheric pressure reading should be recorded and then subtracted from the other results to give the net pressure in the apparatus.

The students should push the syringe by  $0.5 \text{ cm}^3$  as marked on the syringe, and hold the plunger in place. The reading should be taken as quickly as possible. The whole set of readings should be taken quite quickly; there is always a slight leak of pressure in the system and the effect of this needs to be minimised.

The heating of the gas in the syringe due to compression should be accounted for. In this demonstration this can be discussed when considering the errors in the experiment.

### **Alternative using 1/P**

Some confirmations of Boyle's law use  $1/P$  as the plot. The basic method is the same, as is the method of analysis.

Collect the results as described in the main student's document.

Apply the **a /x+b** function to the pressure readings ( $a = 1$ ,  $x$  = the pressure data,  $b = 0$ ).

Pressure readings must be correct to atmospheric or the application of the reciprocal will give an even greater curve to the Pressure vs. Volume plot.

If a differential Pressure sensor is used, the pressure in the room must be added to the pressure values, we do not, for example have zero pressure in the syringe before we start the experiment (if we did we would have zero volume!).

### **Risk assessment**

The students should be warned against holding the syringe against their skin and pressing the plunger, there is real danger of air being pushed into the body.

### **Sample data and analysis**

Data was collected using a 0 - 700 kPa Pressure sensor and a  $60 \text{ cm}^3$  disposable syringe. The data has been treated to produce a  $1/V$  plot and is presented as an  $x$  vs.  $y$  plot (channel vs. channel).

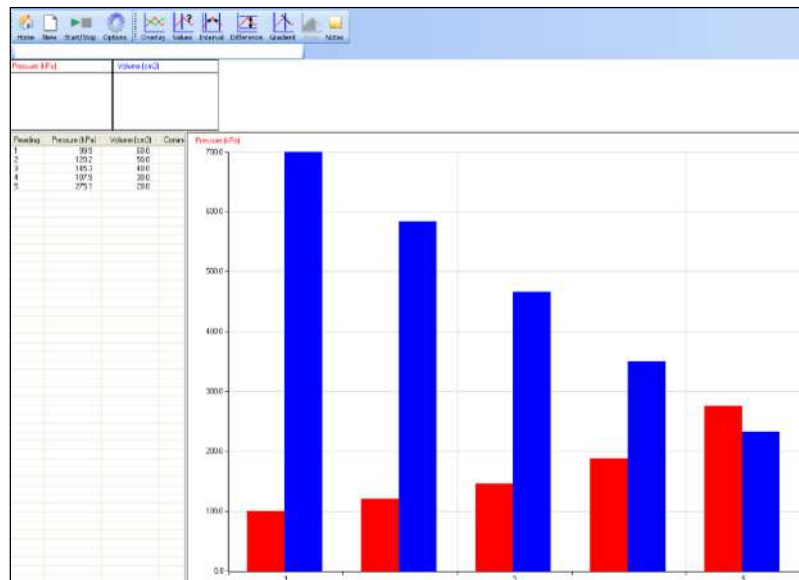


Fig 3.1 Data as collected

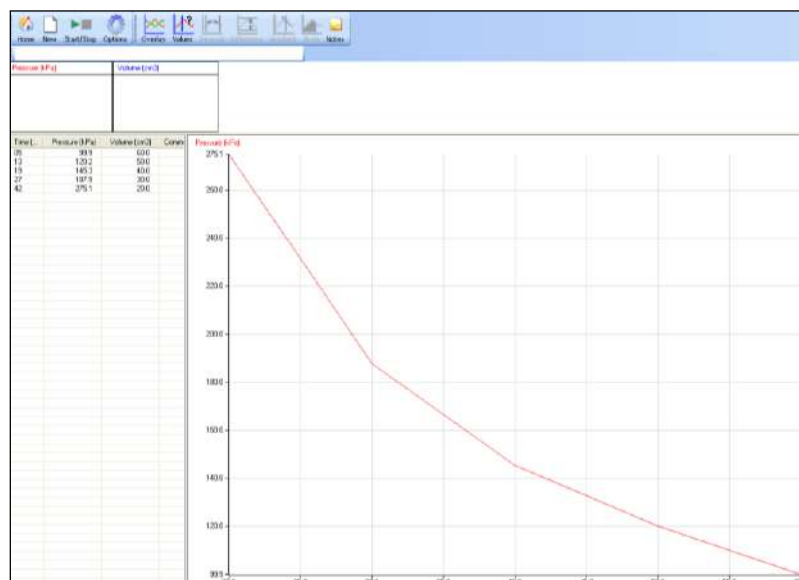


Fig 3.2 Data plotted a simple Pressure vs. Volume plot. Note the pronounced curve in the data. Plotting  $1/v$  will correct this to straight line and prove the inverse relationship.

### Plot of Pressure (y axis) vs. $1/\text{Volume}$ (x axis)

The data should be treated in three stages:

#### 1. Produce a $1/V$ data set from the pressure data

Use the function  $a/x+c$  to create the  $1/v$  data set. X is the volume data, other constants to be changed as required.

#### 2. Produce an $x/y$ plot of the data

Use Options to change the X axis to a data Channel and produce a graph of pressure against  $1/\text{Volume}$

Auto scale or manual rescaling of the axis will be required. As derived the data will, in all probability, produce what appears to be line running parallel to the pressure axis. After rescaling the graph will appear as shown below:

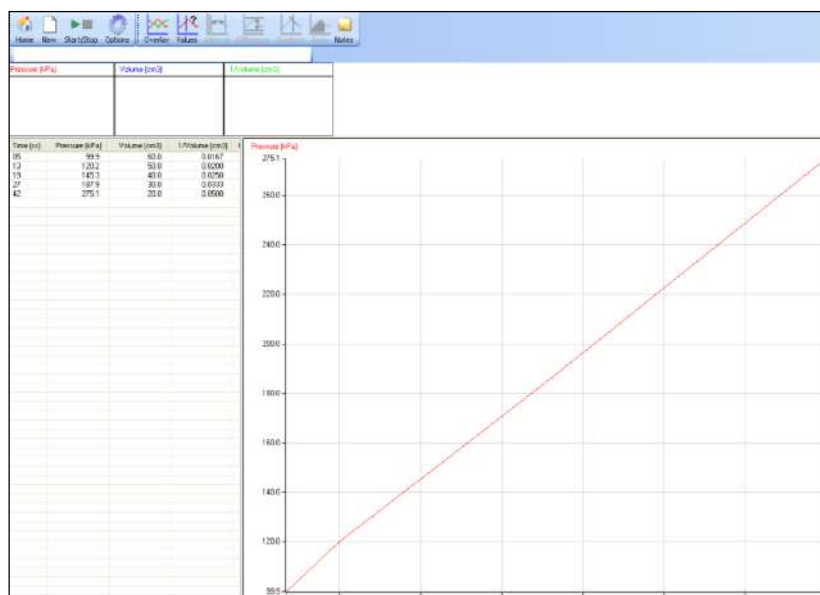


Fig 3.3 If Boyle's law is true the plot will show a straight line starting at the origin. If you have not used the absolute pressure then you will get a straight line but it will not intercept the origin.

### 3. Calculating k

The constant can be derived from  $P \times V$  and then averaged for the range of data collected.

- Use Tools, Post log Function, Channel, Channel multiplied by Channel.
- Channel 1 = Pressure
- Channel 2 = Volume
- Name of new channel is k (constant)
- Units  $P \times V$ .

If there has been no error in collecting the data the plot of  $P \times V$  vs. Volume will give a flat line, any slope in the line indicates errors in the experiment and will need accounting for. The most likely source of error is not letting the heat created in compressing the gas dissipate, this will give a high value for pressure.

### Gay Lussac's law (often used in association with Boyle's law)

Gay Lussac's law states that the pressure of a sample of gas at constant volume, is directly proportional to its temperature in Kelvin.

According to Gay-Lussac's law:

$$P_1 / T_1 = \text{constant}$$

After a change in pressure and temperature of a gas,

$$P_2 / T_2 = \text{constant}$$

Combine the two equations:

$$P_1 / T_1 = P_2 / T_2$$

### 3. Boyle's law ( $P + V$ )

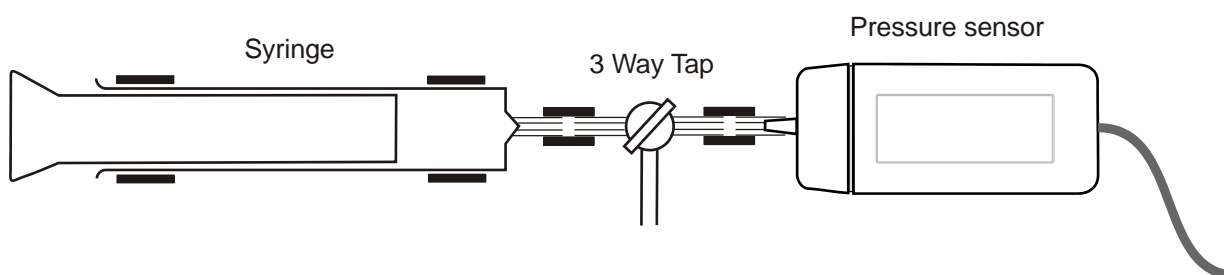
#### Practical skills AT a, b, k

The purpose of this laboratory activity is to experimentally determine the relationship between the pressure and volume of a sample of air at a constant temperature. Boyle's law states that for a given amount of a gas at a fixed temperature the pressure of the gas is inversely proportional to the volume.

In this experiment a Gas Pressure sensor will measure the change in pressure of a gas inside a cylinder as the volume of gas changes. The plot of pressure against  $1/\text{volume}$  will show the relationship between them.

#### Apparatus

1. 0 - 700 kPa differential Gas Pressure sensor
2. 50 cm<sup>3</sup> plastic syringe
3. 3 mm inside diameter PVC tubing (1.5 cm long)
4. 3 way tap (not essential)



#### Method

1. Connect the Gas pressure sensor to the data logger.
2. Connect the three way tap to the syringe; turn the tap valve to close off air movement into the syringe.
3. Connect the tap to the Pressure sensor; the sensor can be connected directly to the tap using the second "luer" connector or by a short piece of PVC tubing.
4. Turn the tap valve to isolate the sensor and allow air to be drawn into the syringe.
5. Fill the syringe to the maximum of the scale on the syringe. Make sure you understand the way the marks on the plunger are used to indicate the volume in the syringe.
6. Set up to record

Recording method	Tools, Pre-log Function
SnapShot	General, Asks for Value

7. Click on Start.
8. Turn the tap valve to allow air to move between the syringe and pressure sensor only.

9. Push the plunger to the first major graduation, hold the syringe in this position and click in the graph area to collect the data. You may need someone to help you with this task, especially as the volume decreases.
10. When the dialogue box opens, enter the volume value from the syringe.
11. Repeat step 9 until the plunger is fully depressed; you may find the tubing is pushed off at the last reading. As long as you have collected at least 4 readings this should not be a problem.
12. Click on Stop when you have collected all the pressure readings for the volumes.

## Results and analysis

SnapShot, by default, shows data as a bar chart. To help see the relationship between volume and pressure more easily the graph needs to be converted to a line graph. Click on Options and select the graph type as a Line graph.

The data should then be treated in 2 stages:

1. Produce a **1/Volume data** set from the Volume data.
2. Produce an **x/y plot** of the data.
3. Calculate the constant k

### 1. Producing the 1/Volume data set

Use the function **a/x+c** to create the 1/v data set. X is the volume data, other constants to be changed as required.

### 2. Produce an x/y plot of the data

Use Options to change the x axis to a data channel and produce a graph of pressure against 1/Volume

Auto scale or manual rescaling of the axis will be required. As derived the data will, in all probability, produce what appears to be line running parallel to the pressure axis. After rescaling the graph will appear as shown below,

If Boyle's law is true the plot will show a straight line starting at the origin. If you have not used absolute pressure then you will get a straight line but it will not intercept the origin.

### 3. Calculating k

The constant can be derived from  $P \times V$  and then averaged for the range of data collected.

- Use Tools, Post-log Function, Channel, Channel multiplied by Channel.
- Channel 1 = Pressure
- Channel 2 = Volume
- Name of new channel is k (constant)
- Units  $P \times V$ .

If there has been no error in collecting the data the plot of  $P \times V$  vs. Volume will give a flat line, any slope in the line indicates errors in the experiment and will need accounting for.

## Questions

1. From looking at your graphs, do the pressure and volume seem to be directly or inversely proportional? Does this agree with Boyle's Law?
2. Is there any relationship between the volume and pressure e.g. does pressure double if volume halves?
3. What are possible sources of error or limitations in this experiment? For each one, try to decide what effect it might have on the experimental results.
4. If we know there are no leaks in the system, can you explain why at the end of the experiment, the plunger does not return to its starting point?



## Teacher's notes

### 4. Temperature volume relationship in a gas (Charles' law, Gay-Lussac's law)

#### Practical skills AT a, b, k

The relationship between gas volume and temperature is studied in this investigation. The plot of the data as an x – y plot shows the linear nature of the relationship.

Historically, in 1802 Gay-Lussac was the first to show that the law applied to all gases, although he credits the discovery to unpublished work in the 1780s by Jacques Charles. The law was also discovered, independently, by John Dalton in 1801.

**Gay-Lussac's** statement of the law is:-

$$V_{100} - V_0 = kV_0$$

The value of k is the same for all gases

The plot of Volume vs. Temperature should have an intercept of zero volume = absolute zero. In the analyses described in the student's sheet the value of absolute zero is revealed in the answer to calculations, or by graphical methods.

The investigation should allow the students to,

1. Model the determination of absolute zero.
2. Showing the linear relationship between volume and temperature for a gas.

Understand the modern statement of **Charles'** law given below:

Charles' law states that the volume of a given amount of dry ideal gas is directly proportional to the Kelvin Temperature provided the amount of gas and the pressure remain fixed. When we plot the Volume of a gas against the Kelvin temperature it forms a straight line. The mathematical statement is that  $V / T = a$  constant.

$$V_1 / T_1 = V_2 / T_2$$

The graph data should provide evidence of this relationship.

#### Apparatus

1. Temperature sensor (unhoused if possible)
2. Rotary Motion sensor set to the linear distance range
3. A RMS Linear rack attachment
4. Large flask (250 cm<sup>3</sup> minimum)
5. Bung with two holes, one hole fitted with glass or plastic delivery tube
6. Gas syringe 100 cm<sup>3</sup> capacity
7. Water bath
8. Bunsen or other heater for water bath

## Set up

As the duration of the experiment is unknown it is best to use **EasyLog**.

## Practical notes

The investigation produces the best results if the heating of the apparatus is not too rapid. If the apparatus is left in the water bath and allowed to cool the cooling curve will often give better results, but it can take a long time to cool.

The gas syringe should be cleaned before use and checked to see the plunger moves easily along the barrel of the syringe. Wiping with a clean cloth dampened with acetone removes most oily materials from the plunger, but make sure the acetone has completely evaporated before refitting the plunger to the barrel.

A temperature of  $100^{\circ}\text{C}$  is not needed in the apparatus as the results can be extrapolated to find the  $100^{\circ}\text{C}$  value and the  $0^{\circ}\text{C}$  value, however taking the temperature to  $100^{\circ}\text{C}$  makes analysis easier.

## Errors

The gas used may contain water vapour, as this is not an ideal gas, the results will be strongly affected by its presence. To remove the water vapour silica gel can be placed into the apparatus and left for about an hour before use.

The gas cools as it enters the syringe and the volume decreases, careful observation in the course of the investigation will show the plunger advancing and then retreating slightly. The cooling curve is not affected by this as much as the gas is moving back into the flask. There is no easy method to eliminate this, you could try wrapping the barrel of the gas syringe with insulating material e.g. bubble wrap. At this level of work it may be better to use the experiment as a model and leave the errors present, discussion of the potential sources of error can be more valuable than the collection of an accurate result at this stage of learning.

## Sample data and analysis

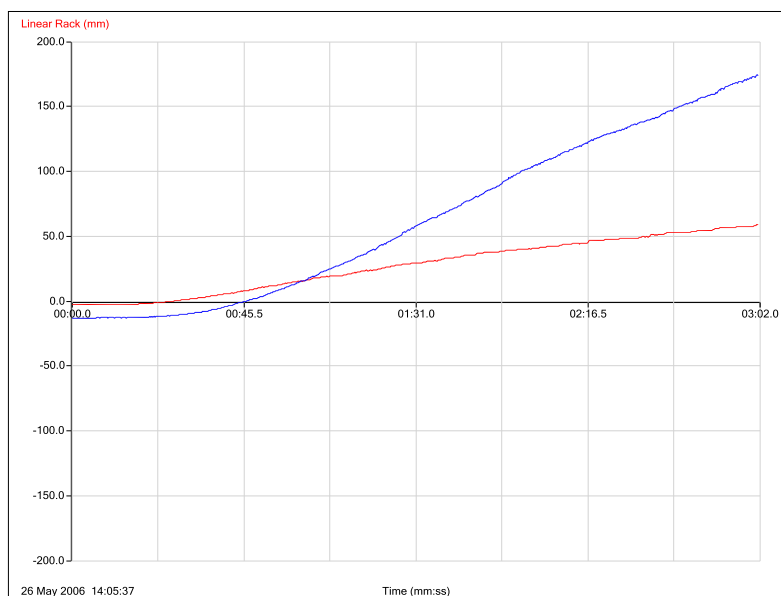


Fig 4.1 Data collected will be Linear distance and Temperature vs. Time

**Convert linear distance to volume**

- The Linear rack measurements need to be only positive. If necessary use the Post-log Function, General, Tare to achieve this. It is impossible to have negative values of Volume.
- Use Test Mode, Meters (in software) or Meters on the logger. Find the linear rack measurement when the syringe plunger is fully in (this represents 0 volume + Volume of apparatus) and when the plunger has moved out to the end of the gas syringe scale. Use this to calculate the correction (in  $\text{cm}^3/\text{mm}$ ) for linear rack to volume in syringe. You may be lucky and find they are both the same
- Apply the correction to the linear rack data by using Post-log Function, General, Multiply by a Constant. Give the new data the name Volume and units  $\text{cm}^3$ .

**Add the volume of the apparatus to the change in Volume data**

- Find the volume of the apparatus, by filling with water and either using increase in mass or recording volume. Use  $1 \text{ g} = 1 \text{ cm}^3$ . (for more precision check data tables for water density at the experimental temperature)
- Add this volume to the Volume data created by using Post-log Function, General, Add a Constant. Give the new data the name Total Volume.

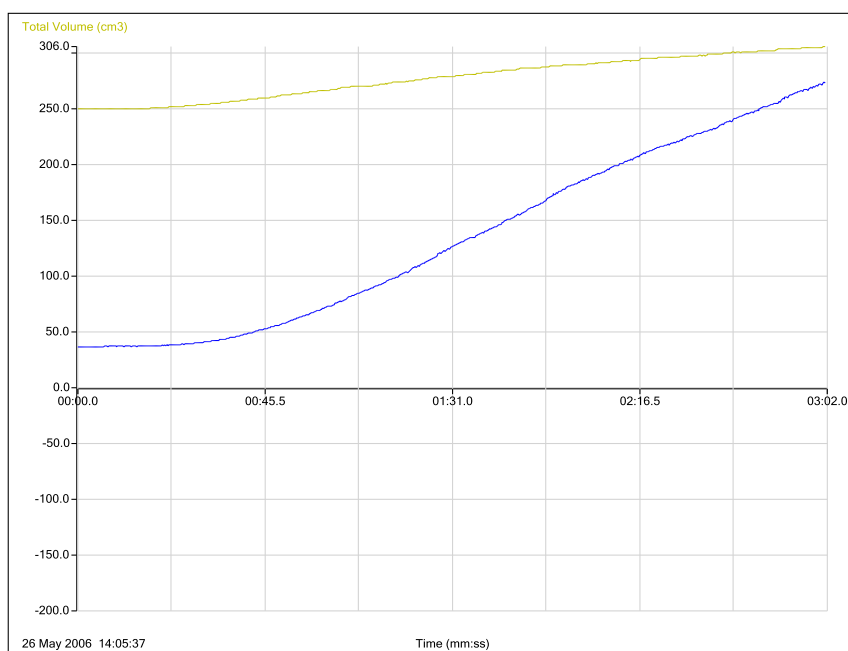


Fig 4.2 Total Volume and Temperature plotted against Time.

**Plotting the data**

- Select Options and click on the X-Axis tab. Select Channel as the x –axis, OK.
- Click in the space to the side / below the axis scale to change the axis to be Volume on the y axis and Temperature on the x – axis. Use Zoom to enlarge the graph.

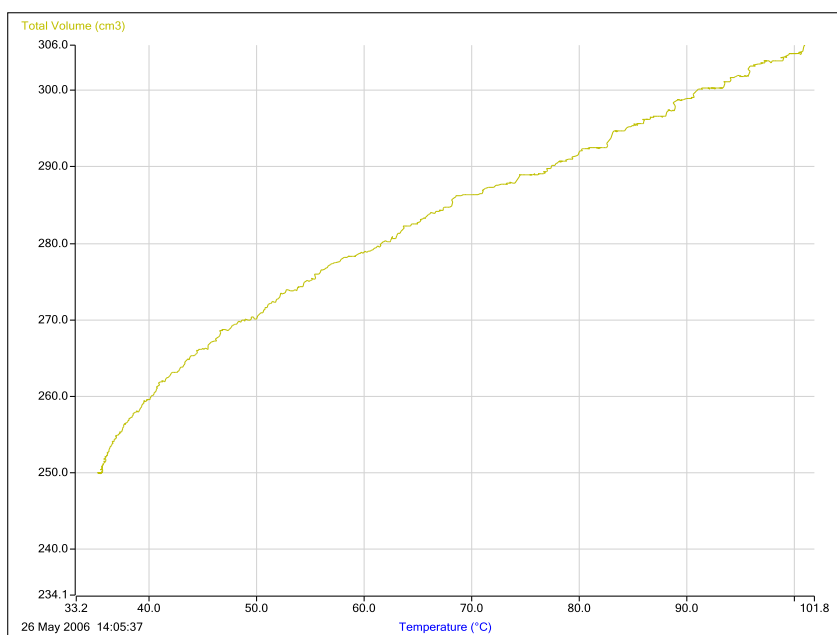


Fig 4.2 Plot of volume against temperature.

### Historical approach to calculating Absolute Zero

Historically the graph of the data was used to estimate the values of the Volume at  $0^{\circ}\text{C}$ , and  $100^{\circ}\text{C}$ . These values were then used to calculate the value of  $T$  the Absolute Zero.

The diagram below shows the data graph extrapolated to obtain an intercept on the Temp axis for when Volume = 0

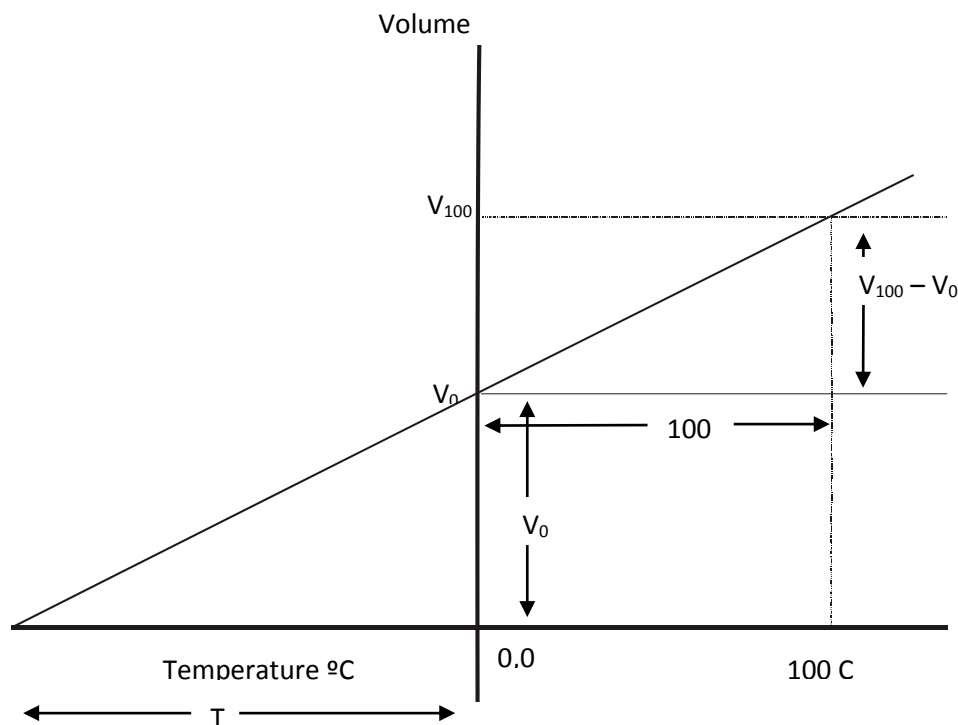


Fig 4.3 Finding the data for the calculation from a graph of volume against temperature

The gradient of the graph

$$\therefore T = \frac{100 \times V_0}{(V_{100} - V_0)}$$

Absolute Zero  $T = (\text{Volume at } 0^\circ\text{C} \times 100) \div (\text{Volume change } 0^\circ\text{C to } 100^\circ\text{C})$

**NOTE:** From Gay-Lussac's equation, we get:

$$k = (V_{100} - V_0) \div V_0$$

$$\therefore T = 100 \div k$$

If the temperature data has not reached  $100^\circ\text{C}$  or  $0^\circ\text{C}$  there are two ways to obtain these values.

1. Manually:

You will have to print out the graph and use a pencil and ruler to draw a best fit line extrapolated back to  $0^\circ\text{C}$  and to  $100^\circ\text{C}$ . You will need to find the temperature and volume at the two temperatures.

2. Use the equation of the graph

Draw a Best Fit line (Tools menu).

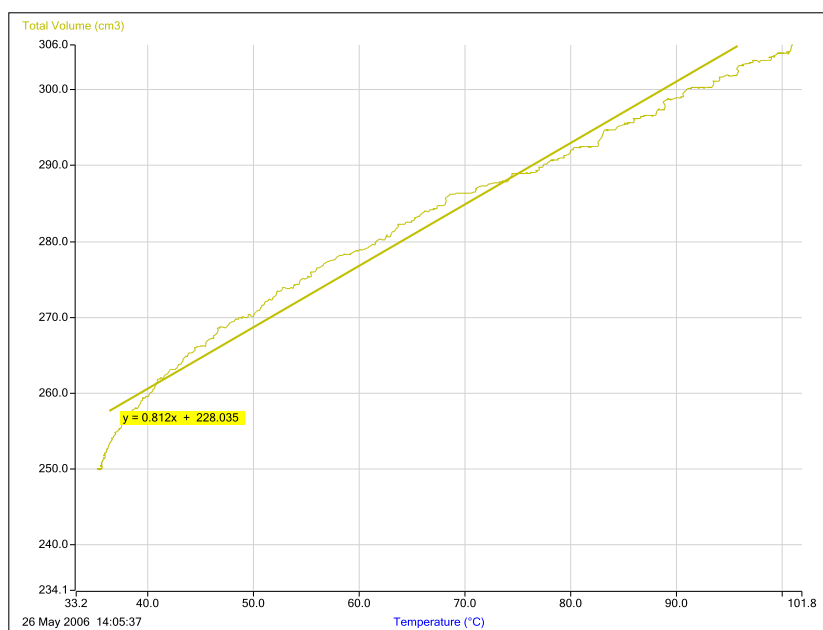


Fig 4.5 Addition of best fit line to calculate gradient.

The equation of the Best Fit line will be displayed. It will look like this  $y = 0.???x + ????$  (e.g.  $y = 0.0.812x + 228.035$ ) equivalent to  $y = mx + c$ .

**NOTE:**  $y$  is the Volume, and  $x$  is the temperature in  $^\circ\text{C}$

The last number (the  $c$  value) is intercept of the  $y$  axis when  $x = 0$ , and gives us the volume of the apparatus when the temperature is zero.

Calculate the value of  $y$  when  $x = 100$ . This will give the value of the volume at  $100^{\circ}\text{C}$ .

### Calculate absolute Zero by:

Absolute Zero  $T = (\text{Volume at } 0^{\circ}\text{C} \times 100) \div (\text{Volume change } 0^{\circ}\text{C to } 100^{\circ}\text{C})$

In the sample data experiment the Temperature of an apparatus containing  $250\text{ cm}^3$  of air was raised to  $103^{\circ}\text{C}$ .

The data was recorded as above, and treated in the same way as described.

- The best fit line gave a line whose equation was  $y = 0.812x + 228.035$ .
- The volume at  $0^{\circ}\text{C}$  was therefore  $228.0\text{ cm}^3$
- The volume at  $100^{\circ}\text{C}$  was  $305.8\text{ cm}^3$
- Volume change was  $305.8 - 228.0 = 82.3$

Solving,

$$\begin{aligned}\text{Absolute Zero } T &= (\text{Volume at } 0^{\circ}\text{C} \times 100) \div (\text{Volume change } 0^{\circ}\text{C to } 100^{\circ}\text{C}) \\ &= (228.0 \times 100) \div 81.2 \\ &= -281^{\circ}\text{C}\end{aligned}$$

Alternative approach using modern graphing

Using the equation of the Best Fit Line:

$$y = 0.812x + 228.0$$

Putting in the symbols for Volume ( $V$ ) and temperature ( $t$ ):

$$V = 0.812t + 228.0$$

If  $V = 0$  then:  $0.812t = -228.0$

Rearranging:  $t = -228 \div 0.812$

$$t = -281^{\circ}\text{C}$$

### Extrapolating manually

From the Display menu select Sensor settings.

Change Total Volume to 0 to just above the maximum value of the Total Volume. Change the temperature to  $-350^{\circ}\text{C}$  to  $100^{\circ}\text{C}$ . You will get a graph like the one below.

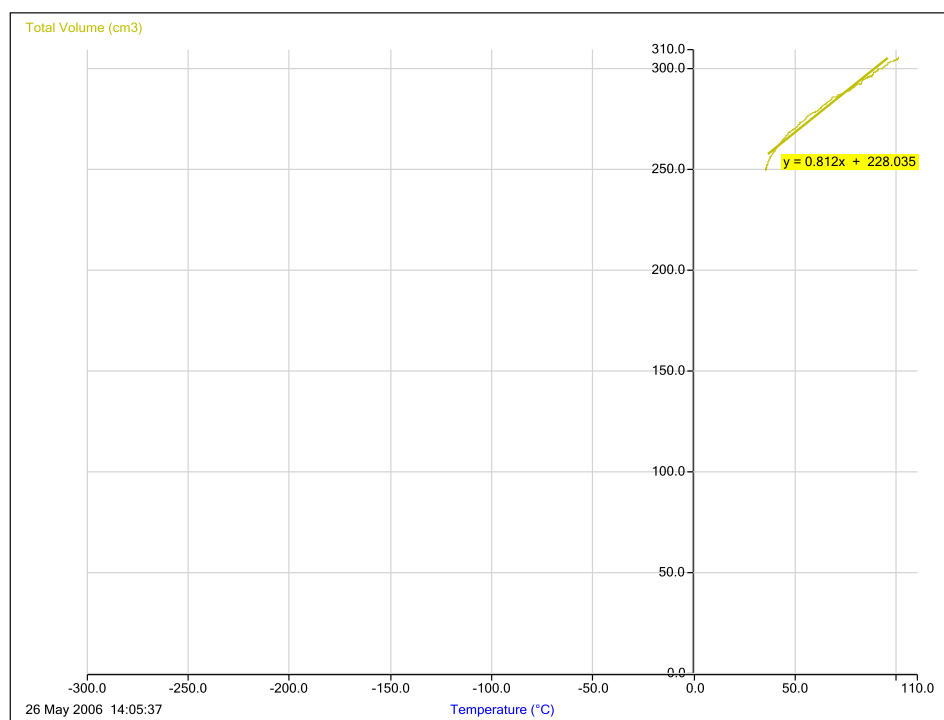


Fig 4.6 Rescaling the data and extrapolating back to zero volume to estimate absolute zero. Temperature is the x axis.

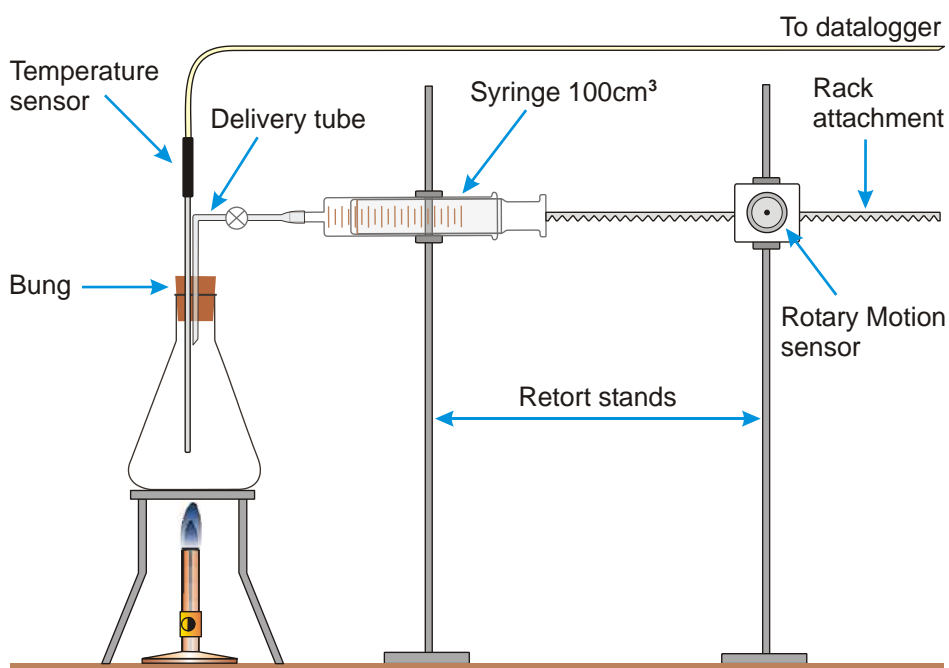
Extend the best fit line to the temperature axis or use a prediction line to draw back to the x axis intercept.

## 4. Temperature volume relationship in a gas (Charles' law, Gay-Lussac's law)

### Practical skills AT a, b, k

The French scientist Jacques Charles was an early balloonist, he wanted to understand why the gas in the balloon enabled him to fly. He studied the relationship between the volume of a gas and its temperature, as the balloons he had flown used hot air to fly.

In this investigation you will study the relationship between the temperature of air and its volume. The work of Charles was later refined and published by Gay-Lussac. You will also work out a value for the Absolute Zero of temperature. It is the lowest possible temperature. If a gas could exist at this temperature, its volume would be zero. In practice all gases liquefy above this temperature.



Note: For best results there should be a water bath surrounding the flask, this keeps the temperature increase in the flask more constant.

### Apparatus

1. Temperature sensor
2. Rotary Motion sensor set to the Linear distance range
3. RMS Linear rack attachment
4. Large flask (250 cm<sup>3</sup> minimum)
5. Bung with two holes, one hole fitted with glass or plastic delivery tube
6. Gas syringe 100 cm<sup>3</sup> capacity
7. Water bath
8. Bunsen or other heater for water bath



## Method

1. Connect the Temperature and Rotary Motion sensor to the data logger.
2. Assemble the apparatus as shown in the diagram. Make sure the track attachment touching the syringe is correctly aligned to give a free movement of the plunger and rod. The bung will need to be out of the apparatus to test this. Use a piece of Blu-Tack or something sticky to fix the rack attachment to the syringe plunger.
3. Set the plunger to the zero point on the syringe scale.
4. Select EasyLog as the recording method.
5. Select Test Mode (Tools menu), Press the zero button on the Rotary Motion sensor and make a note of the distance, you will need this to make a correction later.
6. Move the plunger out to the 100 cm<sup>3</sup> mark. Make a note of this distance, push the plunger back to zero.
7. Place the bung into the flask and note the temperature in the flask. Stop Test Mode.
8. Light the Bunsen and place under the apparatus, have the flame small. You want to heat the apparatus slowly to allow the heat to transfer from the flame to water in the bath to air in the flask.
9. Click on Start to begin recording.
10. Keep a watch on the apparatus to make sure the plunger does not come out of the syringe. If the plunger reaches the maximum of the syringe scale stop logging.
11. Remove the heat from the apparatus, and leave the apparatus alone
12. When the logging has stopped click on Options, and select Channel as the X axis. This will allow you to produce a graph of Temperature vs. Distance. The graph should be approximately a straight line. If it isn't you will need to repeat the experiment. The most likely reason for a curved line is heating the apparatus too quickly.
13. Save the data.
14. Select Overlay and click on Start to collect the data when the temperature is falling in the apparatus. Stop the recording when the syringe volume is back to zero.
15. When you have collected all the temperature pressure data. Fill the flask with water and use a measuring cylinder to find the volume of the flask.

## Results and analysis

You will need to:-

1. Calibrate the linear distance to read volume.
2. Calculate the Total Volume of gas
3. Plot the data as an x – y plot.

Then find the Absolute Zero by one of two methods:-

- Using an historical approach
- Using modern graphical analysis.

### 1. Calibrating the linear distance to read volume

The Linear rack measurements need to be only positive. If necessary use the Post-log Tare function to achieve this. It is impossible to have negative values of Volume.

Using your results, from steps 2 to 4 above, to find out how much distance is recorded when the syringe goes from 0 cm<sup>3</sup> to 100 cm<sup>3</sup>. This will give the mm of linear distance for 100 cm<sup>3</sup>.

Calibration factor  $n = 100 \div \text{Linear distance (for 0 cm}^3 \text{ to 100 cm}^3 \text{ graduations)}$

$n$  is in cm<sup>3</sup> / mm

Use this calibration constant to create a volume measurement from the linear measurement. Name this derived data Volume

### 2. Calculate the Total Volume of the Gas

You need to add the volume of the flask to the Volume data created above, to obtain the Total Volume of the gas in the apparatus.

### 3. Plot the data as an x – y plot

1. Click on Options, X Axis and select Channel as the x axis.
2. Click on the axis labels to select the horizontal axis as Temperature and the vertical axis as Total volume.

### The historical calculation

These calculations require us to have the volume at 100°C and 0°C. To find this information the graph line needs to be extrapolated.

1. Select Options, Sensor settings and adjust the volume scale to ensure the volume can be read off the axis when the line is extended to 100°C and 0°C.
2. Print the graph out.
3. Use a ruler to draw a best fit line to extend the line forwards to 100°C and backwards to 0°C.
4. Read off the volumes of the gas at 0°C and 100°C.
5. Add the volume of the apparatus to the 0°C and 100°C readings and find the volume increase from 0°C to 100°C.

### The calculation

Charles' law uses;

- The volume at 100°C.
- The volume at 0°C.
- The change in volume from 0°C to 100°C.
- The change in temperature.

For the calculation the temperature is assumed to have risen by 100°C.

The volume of the apparatus at 0°C and 100°C are derived from the printed and extrapolated graph.

Substitute the values and solve;

$$(\text{Volume at } 0^\circ\text{C} \times 100) \div (\text{Change in volume } 0^\circ\text{C to } 100^\circ\text{C}) = \text{Absolute Zero T}$$

You will have to place the negative in front of the number.

### Calculating Absolute Zero using the graph

Draw a best fit line on the graph of Total Volume vs. Temperature.

Right click on the screen and select Zoom In. Use Zoom so that the graph occupies most of the screen.

Use Tools, Best Fit, select Manual, select Y-Axis = Total Volume and X-Axis = Temperature, select OK. Click at one end of the straight section and drag the pointer to the other, and release the mouse button. The Best Fit line is displayed and the equation of the line is shown in the form:-

$$y = mx + c.$$

### Using the Best Fit line equation

The equation for the best fit line is of the form:-

$$y = mx + c$$

Substitute V and t for y and x. The equation becomes:

$$V = mt + c$$

You require the value of t for zero volume:

$$0 = mt + c$$

Solving for t:

$$t = -c \div m$$

Substitute in the values of c and m (the gradient) from the Best Fit line equation, and calculate t.

### Manually extrapolating the graph

Right click on the screen and click on Zoom Off.

Use Sensor settings (Options) to change the value of the Temperature sensor to minus 300.

Print the graph and, using a ruler, extrapolate the Best Fit to the Temperature axis. Record the estimate of absolute zero

### Charles' law

The accepted value for the Absolute Zero is  $-273^{\circ}\text{C}$ . On the Kelvin scale of temperature, absolute Zero = 0K.

Therefore  $0^{\circ}\text{C} = 273 \text{ K}$

Charles Law states: The Volume of a fixed mass of gas is directly proportional to the Temperature in Kelvin as long as the pressure remains constant.

$$V \propto T$$

$$\therefore \frac{V}{T} = k$$

The Law can be usefully expressed as follows:-

$$\frac{V_1}{V_2} = \frac{T_1}{T_2}$$

## Questions

Draw a sketch of a graph of Volume vs. Temp for a gas, if the temperature is in Kelvin.

There are 5 litres of air, at a temperature of 300 K, enclosed in a cylinder with a piston that is free to move. The temperature is raised to 400 K, while the pressure remains the same, and the piston moves out. What is the new volume of air?

1. What are the sources of error in this investigation?
2. How could you control the investigation to reduce the errors?

## Teacher's notes

### 5. SHM: Simple harmonic motion in a spring mass system (using a Motion sensor)

#### Practical skills AT a, b, c, k

This is a simple investigation that gets the student used to using the Motion sensor to measure oscillations.

In this investigation, the position of an oscillating mass on a spring is continually monitored using the sensor.

The students will be introduced to using the tools in the software to create velocity, acceleration curves, remove an offset in distance data collected from the Motion sensor and how to measure the interval between wave peaks.

Learning objectives:

The following relationships can be investigated:-

Phase relationships between  $x$ ,  $v$ , and  $a$

1.  $x$  vs.  $t$
2.  $v$  vs.  $t$
3.  $a$  vs.  $t$

The effects of damping, as an optional extension.

Key:

$x$  = displacement

$v$  = velocity

$a$  = acceleration

#### Apparatus

1. Motion sensor with the range set to distance (metres)
2. Steel spring, the spring - mass system needs to have a period of at least one second
3. Masses in the range of 0.5 kg to 1.2 kg (depending upon the spring used)
4. Large G - clamp
5. 2 retort stands with bosses and clamps

#### Set up

Recording method	Recording time	Intersample time	Trigger on level
Graph	10 seconds	20 ms	When the Force sensor rises above 0 N

## Practical notes

Assemble the apparatus as shown on the worksheet. Use substantial stands and clamps to reduce flexing as the weight oscillates. If possible have the side arm as low as possible to reduce leverage on the stand.

The mass should be 0.5 m from the sensor when stationary to allow for amplitude of up to 20 - 25 cm.

Set the mass oscillating and check that it will not get closer to the Motion sensor than 17 cm. The mass may well start swinging from side to side; a few practice runs are advisable to get the feel of the force needed to produce a clean oscillation.

The spring it may need conditioning to open the coil slightly, or use sufficient mass to open the spring.

## Results and analysis

The following graphs were generated from a sample experiment. The spring was made from a pair of elastic bands, not a steel spring as recommended. Oscillation data is good but there is a significant damping effect.

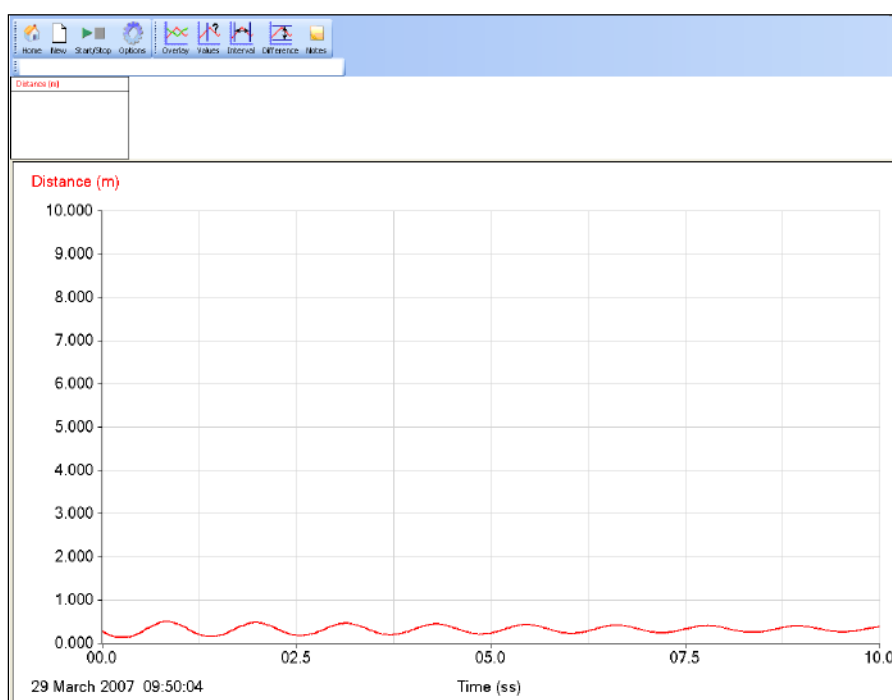


Fig 5.1 Shows the data as collected, no analysis

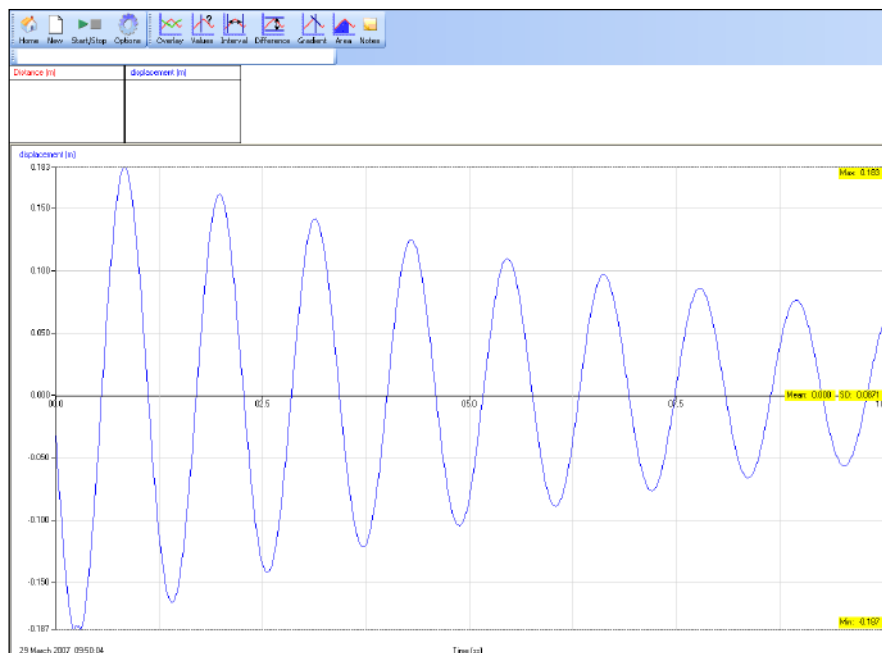


Fig 5.2 Distance from centre (displacement) axis limits changed to make the curve fit the whole graph area.

To create the displacement around the zero point of distance:

1. Select Analysis, Show Statistics to find the Max, Min and Mean. Make a note of the mean.
2. Click on Tools, Post-log Function. Select General and then Tare. Select the Distance as the data to be changed.
3. Rename the data set as Displacement.
4. Enter the mean as the tare value into the “Enter the Tare value” box. Click on Finish.

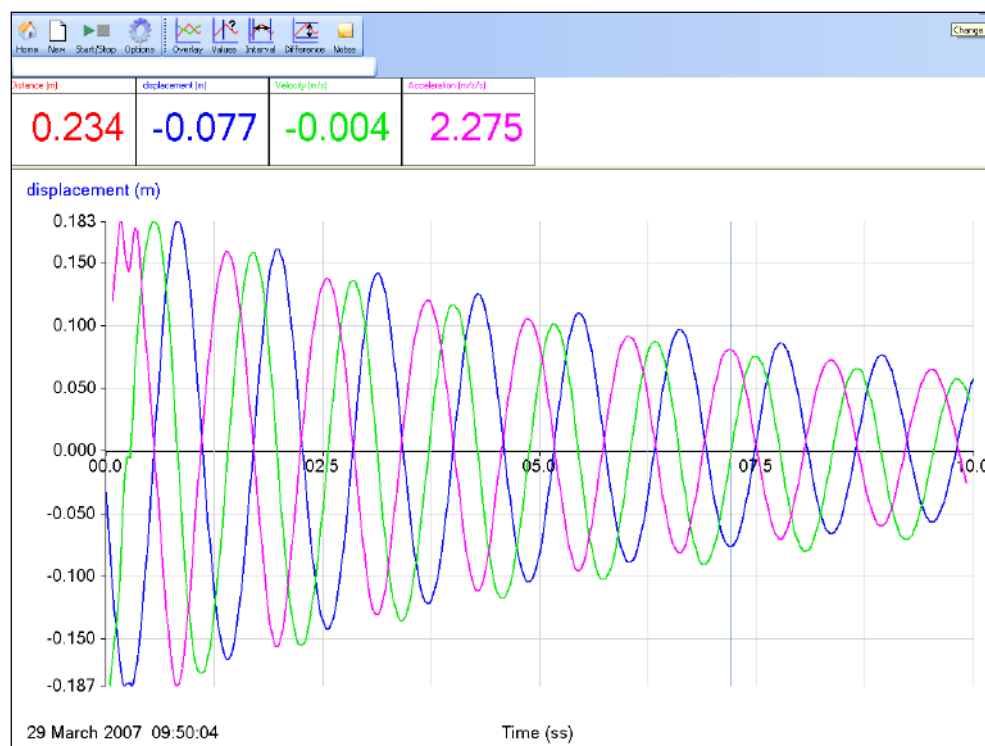


Fig 5.3 Displacement, velocity and acceleration data

**To create the Velocity curve:**

1. Click on Tools, Post-log Function.
2. Select Motion and then Velocity.
3. Select Displacement as the data to be used.
4. Name of the data set should be Velocity and check the units are correct for the displacement units used (this would normally be m; velocity would be m/s).
5. Click on Finish.

**To create the Acceleration curve:**

1. Click on Tools, Post-log Function.
2. Select Motion and then Acceleration calculated from position data or distance data (second derivative).
3. Select Displacement as the data to be used.
4. Name the data set should be Acceleration and check the units are correct for the displacement units used (this would normally be m; acceleration would be m/m/s).
5. Click on Finish.



## 5. SHM: Simple harmonic motion in a spring mass system (using a Motion sensor)

### Practical skills AT a, b, c, k

Vibrations play a very important part in our lives. The effects can be beneficial or destructive. Here are a few examples:-

- Vibration induced motion sickness
- Listening to music with a CD player or at a concert
- Earthquakes
- Clocks
- In car engines
- Spring-mass systems
- The Millennium bridge in London

Any motion that repeats itself is described as **harmonic motion**. We will be investigating a particular form of harmonic motion known as **simple harmonic motion (SHM)**.

In this investigation you are going to seek answers to the following questions:-

1. How does the distance (displacement) from the centre of oscillation change during each cycle?
2. What is the phase relationships between the:-
  - Displacement –  $x$
  - Velocity –  $v$
  - Acceleration –  $a$
3. How closely does the oscillation of a spring relate to SHM?

Key:

$T$  = period of the oscillation in seconds.

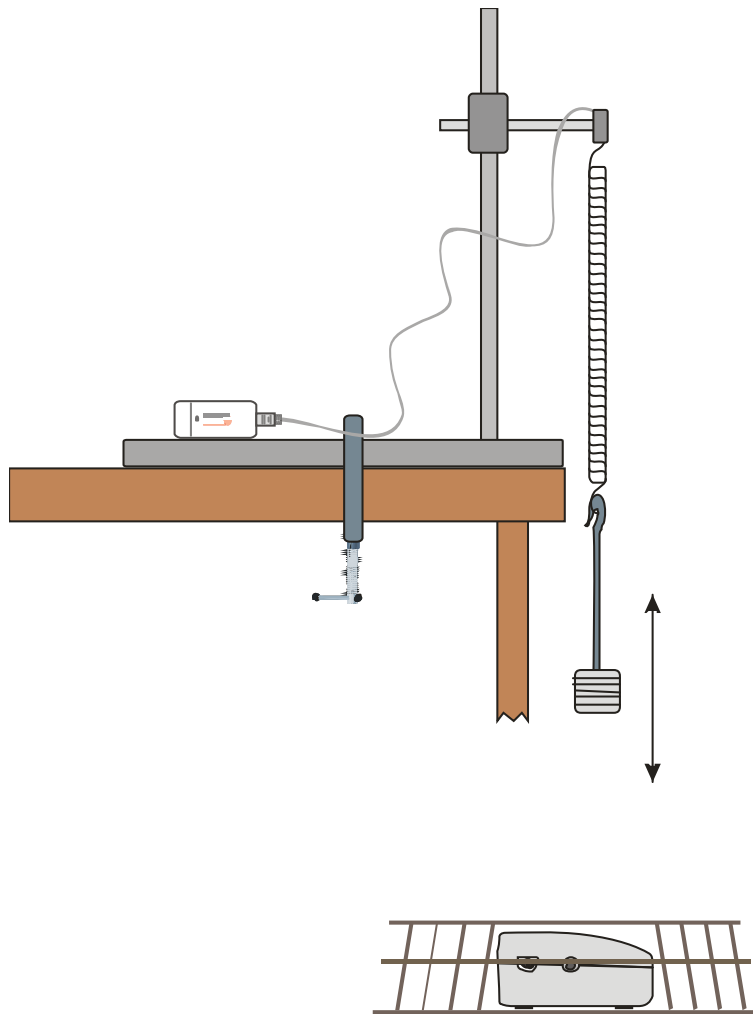
$\omega$  = angular velocity of the SHM in radians  $\text{sec}^{-1}$ .

### Preliminary Questions

1. Draw a sketch graph showing how you expect the displacement to change with time during two oscillations of the spring.
2. Make a copy of your sketch from question 1 and add to it curves showing how you expect the velocity and acceleration of the object will change during those two oscillations.

### Apparatus

1. Motion sensor with the range set to distance (metres).
2. Steel spring, the spring-mass system needs to have a period of at least one second.
3. Masses in the range of 0.5 kg to 1.2 kg (depending upon the spring used).
4. Large G - clamp.
5. 2 retort stands with bosses and clamps.



## Method

1. Weigh the spring and the suspended mass added together. They are the 'oscillating mass'.
2. Assemble the apparatus as shown above. Connect the Motion sensor to the data logger.
3. Make sure that the apparatus is as rigid as possible and when the mass is stationary it is about 50 cm from the Motion sensor.
4. Set up to record:

Recording method	Recording time	Intersample time	Trigger level
Graph	10 seconds	20 ms	When the Force sensor rises above 0N

5. Select Test Mode (Tools menu). Pull the spring downwards and set it oscillating to ensure that the Motion sensor will detect the mass throughout its travel. Stop the spring moving. Adjust as necessary.
6. Click on the Start icon to begin logging. The set up contains a trigger to start logging when the mass is at the top of an oscillation.

7. Pull the spring downwards and set it oscillating. Use an amplitude of between 15 to 25 cm; take care to not overstretch the spring.
8. Check that it is oscillating vertically.
9. Save the file if the curve is smooth, if not repeat. (Use Delete Data Sets from the Edit menu to remove any unwanted data sets).

## Results and analysis

Mass of spring and load = .....kg

### A) Displaying the results

The graph will show a Displacement vs. Time curve. Use Post-log Functions to:

1. Convert the Distance vs. Time curve to a displacement curve with a centre zero.
2. Obtain a Velocity vs. Time curve.
3. Obtain an Acceleration vs. Time curve.

### B) Analysing the results

#### 1. Phase Relationships

Compare the velocity and acceleration curves, with the displacement curve. Are they 'in phase' or out of phase with the displacement curve? If they are out of phase say by how much ( $\frac{1}{4}$  or  $\frac{1}{2}$  of an oscillation i.e.  $\pi/4$  or  $\pi/2$ )?

Curve	In phase OR phase difference?
Velocity	
Acceleration	

#### 2. Comparing the graphs

Using **Zoom**, display one whole cycle of the displacement graph. Fill in the following table. State the value of the displacement (choose from: maximum positive, maximum negative or zero) for the positions in the velocity and acceleration graphs, shown in the table.

Position in v, a graphs	Corresponding values in the displacement graph
Velocity zero	
Velocity maximum positive	
Acceleration maximum negative	
Acceleration maximum positive	

#### 3. Calculation of the Period and $\omega$ .

- a) Calculate the Period from the graph.
- b) Calculate the angular velocity  $\omega$  from the equation: -

$$T = \frac{2\pi}{\omega}$$

## Questions

1. If  $x = -A\sin(\omega t)$ , what is the value of  $\sin(\omega t)$  when the displacement is maximum?
2. If  $v = -A\omega\cos(\omega t)$ , what is the value of  $\cos(\omega t)$  when the value of the velocity is a maximum?
3. A small mass attached to a spring oscillates in simple harmonic motion with amplitude of 50 mm. It takes 30 seconds to complete 10 oscillations. Calculate its period, angular velocity, maximum speed and the maximum acceleration.

## Post-log Function help

To generate a displacement – time curve from a distance – time curve

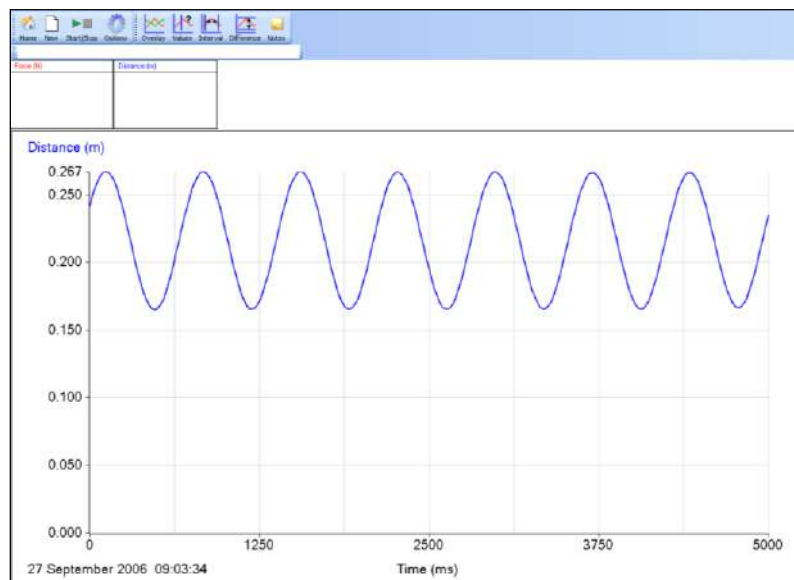


Fig 5.1 Data as collected, **Auto scale 0 to Max** used

- With only the Distance data shown, click on Analysis and Show Statistics.
- The distance data will be bracketed by the Max and Min values of the oscillation and the Mean will be shown. Make a note of the mean value.
- From the Tools menu select Post-log Function.
- Select Preset function: General, Tare then Next.
- Use the Distance data and click on Next.
- Name = Displacement
- Units = **m**
- Tare value = the mean value found above.
- Click on Finish.

Check the new curve is centred on zero.

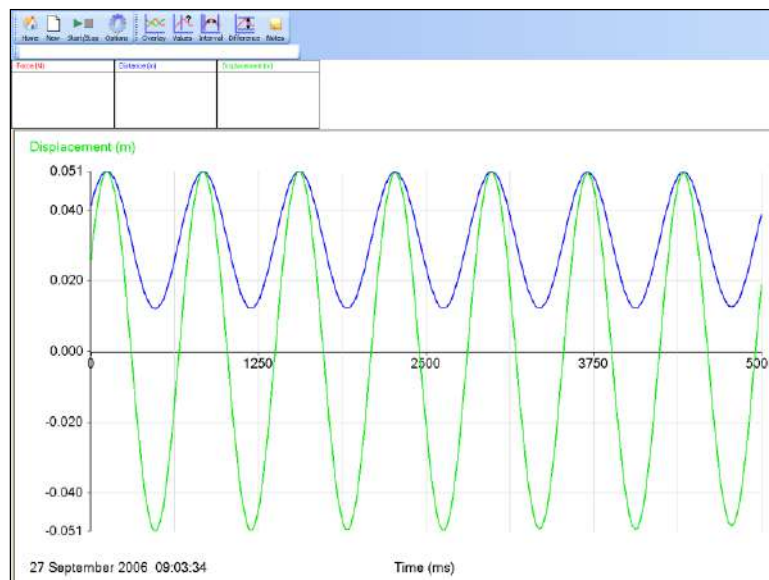


Fig 5.2 Data after Tare applied to produce displacement. Auto scale 0 to Max used.

**To generate the velocity – time curve from the displacement – time curve**

- From the Tools menu select Post-log Function
- Select Preset function: Motion, Velocity
- Data to be used = Displacement.
- Decimal places = 3
- Name = Velocity
- Units = m/s.
- Finish.

Use Smoothing (Tools menu) if necessary.

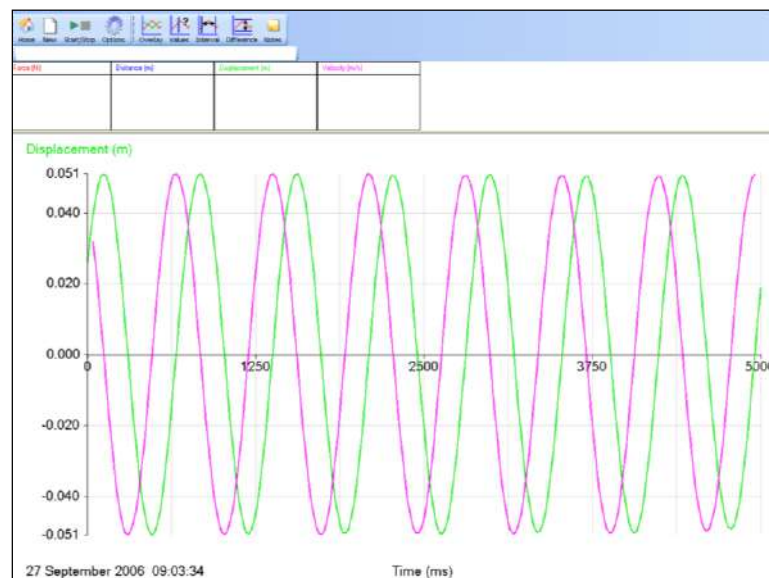


Fig 5.3 Velocity calculated from displacement. Original distance data hidden (right click on graph area, select Show or Hide channels, put a tick next to the data you want visible on the graph). Auto scale 0 to Max used.

**To generate the acceleration – time curve from the displacement – time curve**

- From the Tools menu select Post-log Function
- Select Preset function: Motion, Acceleration (second derivative of distance)
- Data to be used = Displacement.
- Name = Acceleration
- Decimal places = 3
- Units = m/s/s.
- Finish

Use Smoothing (Tools menu) if necessary.

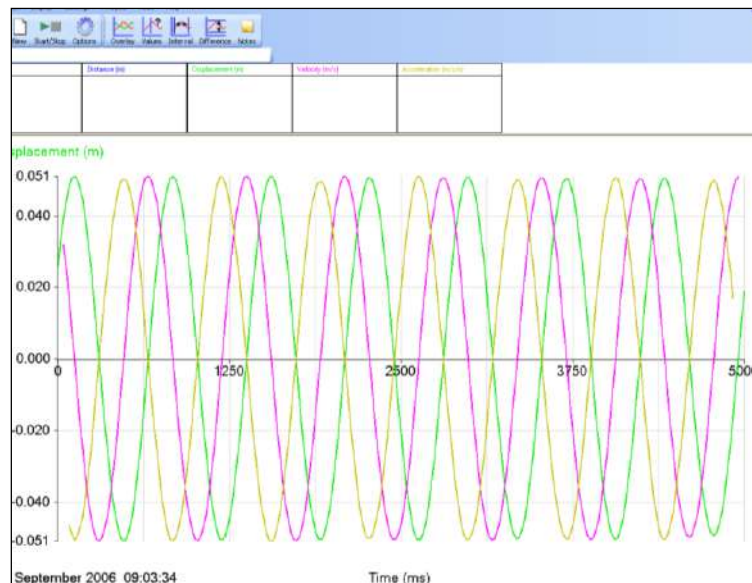


Fig 5.4 Acceleration calculated from displacement. Original distance data hidden. Auto scale 0 to Max used.

## Teacher's notes

### 6. SHM: Simple harmonic motion in a spring mass system (using Force and Motion sensors)

#### Practical skills AT a, b, c, k

In this investigation, the Force sensor is used to measure the force in the spring as it oscillates. At the same time the position of the mass is continually monitored using the Motion sensor.

Learning objectives:

The following relationships can be investigated:-

Phase relationships between  $F$ ,  $x$ ,  $v$ , and  $a$ .

1.  $F$  vs.  $t$
2.  $x$  vs.  $t$
3.  $v$  vs.  $t$
4.  $a$  vs.  $t$

Relate the above relationships to sine and cosine curves.

The effects of damping, as an optional extension.

Key:

$x$  = displacement

$v$  = velocity

$a$  = acceleration

$F$  = Force

#### Apparatus

1. Force sensor
2. Motion sensor with the range set to distance (metres)
3. Steel spring, the spring-mass system needs to have a period of at least one second
4. Masses in the range of 0.5 kg to 1.2 kg (depending upon the spring used)
5. Large G - clamp
6. Retort stand with boss and clamp

#### Set up

Recording method	Recording time	Intersample time	Trigger level
Graph	10 s	20 ms	When the Force sensor rises above 0 N

## Practical notes

Assemble the apparatus as shown in on the student worksheet. Use substantial stands and clamps to reduce flexing as the weight oscillates. If possible have the side arm as low as possible to reduce leverage on the stand

The adjuster on the Force sensor is used to set the force to zero with the masses hanging from it. The masses should be static when this adjustment is made. To get as close to zero as possible a small flat bladed screwdriver should be used.

The mass should be 0.5 m from the sensor when stationary to allow for amplitude of up to 20 to 25 cm. The trigger is set to operate at 0 N so that recording begins at the centre of the oscillation.

Set the mass oscillating and check that it will not get closer to the Motion sensor than 17 cm. The mass may well start swinging from side to side; a few practice runs are advisable to get the feel of the force needed to produce a clean oscillation.

The 'effective mass' of the spring in an oscillating spring mass system is taken as  $\frac{1}{3}$  its mass for an 'ideal spring'. However if the ratio of the load mass ( $M$ ) to the spring mass ( $m$ ) i.e.  $M/m$  is more than 7 the value of the 'effective mass' decreases and eventually becomes negative. In most cases the ratio  $M/m$  will be much greater than 7 (in the case of the sample data it was 48) so it is sensible to ignore the mass of the spring.

## Results and analysis

The following graphs were generated from a sample experiment, with the trigger set so that the logger started logging as the value on the Force sensor rose through 0 N. The displacement, from the centre of oscillation, was therefore negative during the first half cycle.

The curves obtained will therefore relate to the following equations:-

1.  $x = -A\sin(\omega t)$
2.  $v = -A\omega\cos(\omega t)$
3.  $a = A\omega^2\sin(\omega t) = -\omega^2x$

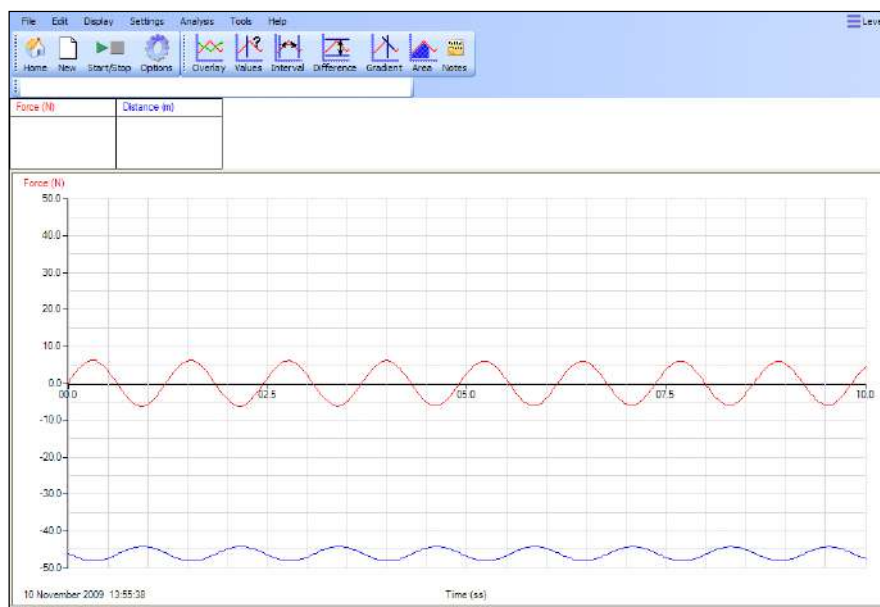


Fig 6.1 The data as collected by the students, no analysis.



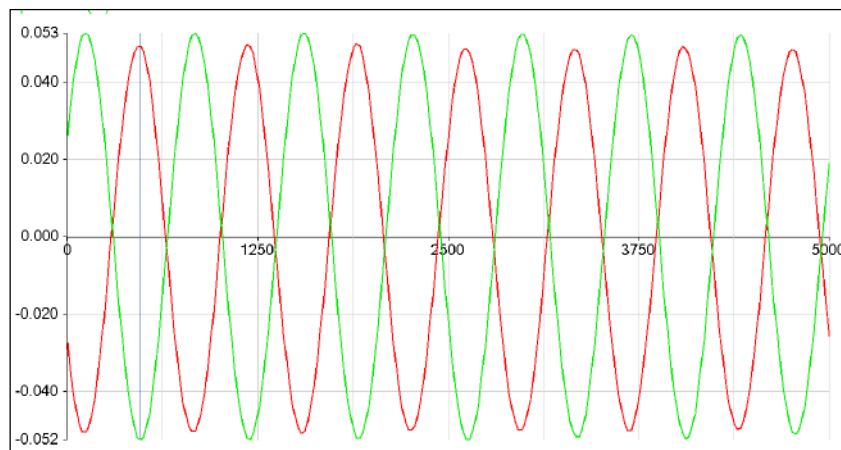


Fig 6.2 Distance from centre (displacement) axis limits changed to make the curves fit the whole graph area.

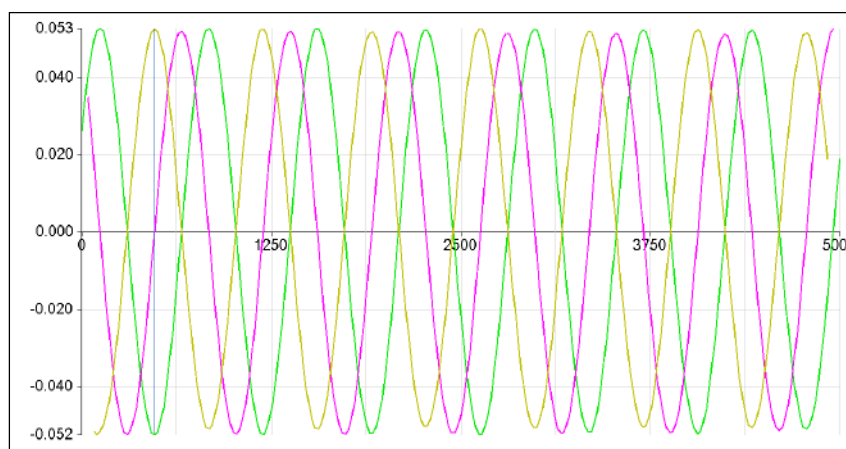


Fig 6.3 Displacement, velocity and acceleration data.

**To generate the velocity – time curve from the displacement – time curve**

1. Click on Tools, Post-log Function.
2. Select Motion and then Velocity.
3. Select Displacement as the data to be used.
4. Name of the data set should be Velocity and check the units are correct for the displacement units used (this would normally be m; velocity would be m/s).
5. Click on Finish.

**To generate the acceleration – time curve from the displacement – time curve**

1. Click on Tools, Post-log Function.
2. Select Motion and then Acceleration calculated from position data or distance data (second derivative).
3. Select Displacement as the data to be used.
4. Name the data set should be Acceleration and check the units are correct for the displacement units used (this would normally be m; acceleration would be m/m/s).
5. Click on Finish.

### Creating the Sine Curve

If we create a model of the ideal sine wave from the amplitude etc. data we can test the practical vs. the theory. This could be an interesting extension.

The equation for the Displacement 'x' will be of the form:-

$$x = -A\sin(\omega t) + c$$

You need to calculate  $\omega$  and A, the amplitude of the Oscillation. 'c' is a value that needs to be added if the displacement has not been measured from the centre of oscillation. In this case it will be 0.

### Calculation of $\omega$

1. Using **Interval** find the time for 5 cycles. Divide by 5 to calculate **T** the period.
2. Calculate  $\omega$  from the formula;

$$\omega = \frac{2\pi}{T}$$

### Measuring the amplitude A

Use Values to measure the value of A.

### Creating the theoretical curve

1. From the Tools select the Post-log Function
2. Select Formula then **a sin(bt) + c** from the drop down menu.
3. Name = Sine Curve
4. Units = Degrees
5. Scale factor = 1
6. Decimal places = 3
  - **a** = -A from value measured above.
  - **b** =  $\omega$  from calculated value above
  - **c** = 0
7. Select Expand to fit, and Finish.

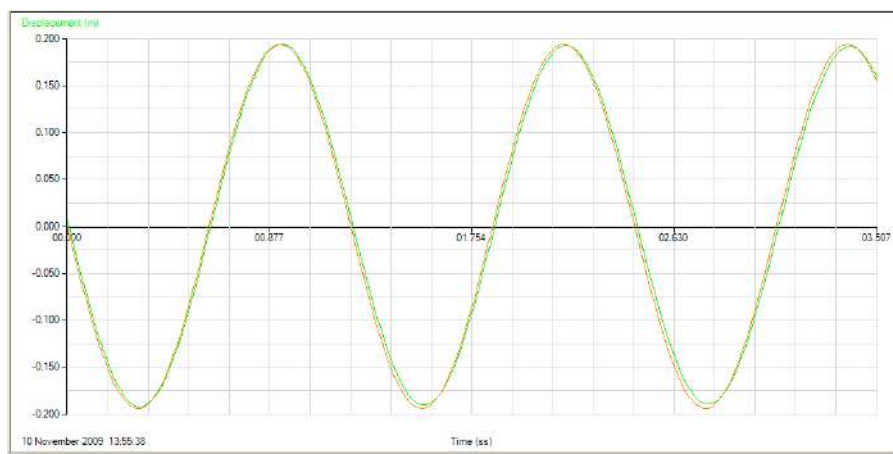


Fig 6.4 Generated theoretical Sine Curve compared with the practical derived Displacement. The two curves are effectively identical, demonstrating quite clearly that the SHM curves are sine or cosine curves.

The same process can be used to generate a cosine curve for the velocity, using the equation:-

$$v = -A\omega\cos(\omega t)$$

## 6. SHM: Simple harmonic motion in a spring mass system (using Force and Motion sensors)

### Practical skills AT a, b, c, k

Vibrations play a very important part in our lives. The effects can be beneficial or destructive. Here are a few examples:-

- Vibration induced motion sickness
- Listening to music with a CD player or at a concert
- Earthquakes
- Clocks
- In car engines
- Spring-mass systems
- The Millennium bridge in London

Any motion that repeats itself is described as harmonic motion. We will be investigating a particular form of harmonic motion known as simple harmonic motion (SHM).

The properties of SHM are:-

1. The period is independent of the amplitude of the motion.
2. The force is always pointed to the central point of the oscillation. This is often called the restoring force because it is always pointed at the central point.
3. The restoring force is directly proportional to the magnitude of the displacement, and opposite in sign to it.

$$F = -kx$$

**k** = the stiffness of the restoring system (spring constant).

In this investigation you are going to seek answers to the following questions:-

1. How does the distance (displacement) from the centre of oscillation change during each cycle?
2. What is the phase relationships between the;-
  - Restoring force, **F**
  - Displacement, **x**
  - Velocity, **v**
  - Acceleration, **a**
3. How closely does the oscillation of a spring relate to SHM?

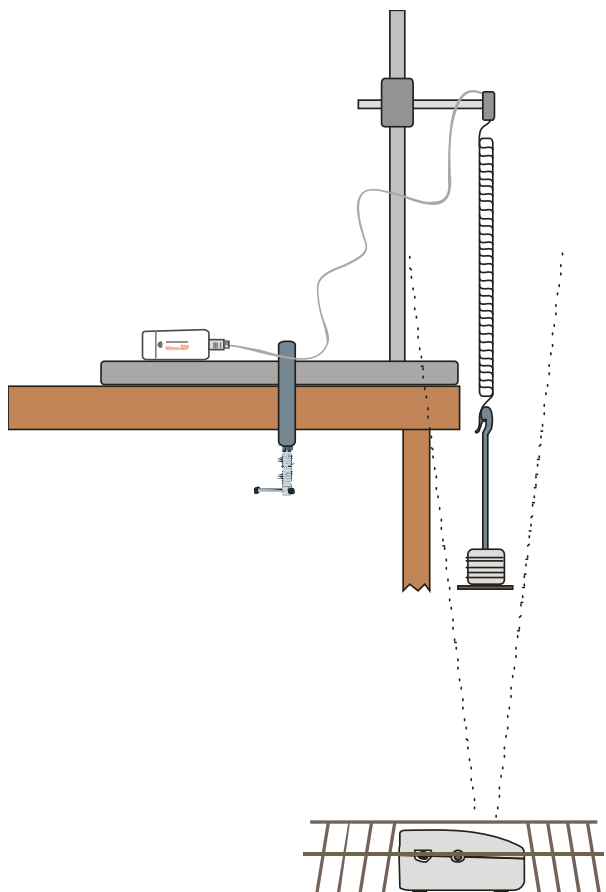
Key:

**T** = period of the oscillation in seconds.

**$\omega$**  = angular velocity of the SHM in radians sec<sup>-1</sup>.

### Preliminary Questions

1. Draw a sketch graph showing how you expect the displacement to change with time during two oscillations of the spring.
2. Make a copy of your sketch from question 1 and add to it curves showing how you expect the velocity and acceleration of the object will change during those two oscillations.



### Apparatus

1. Force sensor
2. Motion sensor with the range set to distance (metres)
3. Steel spring, the spring-mass system needs to have a period of at least one second
4. Masses in the range of 0.5 kg to 1.2 kg (depending upon the spring used)
5. Large G - clamp
6. Retort stand with boss and clamp

### Method

1. Weigh the spring and the suspended mass added together, write down the value in your results table. They are the 'oscillating mass'.
2. Assemble the apparatus as shown above. Connect the Force sensor to input 1 and the Motion sensor to input 2 of the logger.
3. Make sure that the apparatus is as rigid as possible and when the mass is stationary it is about 50 cm from the Motion sensor.

## 4. Set up to record:

Recording method	Recording time	Intersample time	Trigger level
Graph	10 s	20 ms	When Force sensor Rises above 0 N

- Select Test Mode (Tools menu). Pull the spring downwards and set it oscillating to ensure that the Motion sensor will detect the mass throughout its travel. Stop the spring moving.
- Zero** the Force sensor with the mass hanging stationary on the spring.
- Pull the spring downwards and set it oscillating. Use an amplitude of between 15 to 25 cm; take care to not overstretch the spring.
- Check that it is oscillating vertically.
- Click on the **Start** icon to begin logging. The set up contains a trigger to start logging when the mass goes downwards through the midpoint of an oscillation.
- Save the file if the curve is smooth, if not repeat. (Use Delete Data Sets from the Edit menu to remove unwanted data sets).

## Results and analysis

Mass of spring and load = ..... kg

### a) Displaying the results

There will be graphs of Force vs. Time, and Distance vs. Time displayed. For the analysis:-

- Use Sensor settings (or Auto scale) to make the curve cover the display area.
- Create a Velocity vs. Time curve, using the Post-log Functions.
- Create an Acceleration vs. Time curve, using the Post-log Functions.

### b) Analysing the results

How closely do the graphs you obtained match your predictions?

#### 1. Phase Relationships

Compare the velocity, acceleration and force curves with the displacement curve. Are they 'in phase' or out of phase with the displacement curve? If they are out of phase say by how much ( $\frac{1}{4}$  or  $\frac{1}{2}$  of an oscillation i.e.  $\pi/4$  or  $\pi/2$ )?

Curve	In phase OR phase difference?
Velocity	
Acceleration	
Force	

## 2. Comparing the graphs

Using **Zoom**, display one whole cycle of the displacement graph. Fill in the following table. State the value of the displacement (choose from: maximum positive, maximum negative or zero) for the positions in the velocity, acceleration and force graphs, shown in the table.

Position in v, a, or F graphs	Corresponding values in the displacement graph
Velocity zero	
Velocity maximum positive	
Acceleration maximum negative	
Acceleration maximum positive	
Acceleration zero	Force maximum positive
Force maximum positive	
Force Zero	

## 3. Calculation of the Period and $\omega$ .

- Calculate the Period, T from the graph.
- Calculate the angular velocity  $\omega$  using the equation: -

$$T = \frac{2\pi}{\omega}$$

## 4. Generating a sine curve

If the spring is oscillating in SHM, then the equation for the displacement 'x' will be of the form:-

$$x = -A\sin(\omega t)$$

You are to generate a sine curve and compare it with your displacement curve.

Find the value of A from your displacement graph.

Use the Post-log Function, Formula, **a sin(bt) + c** to generate the sine curve.

'c' is a value that needs to be added if the displacement has not been measured from the centre of oscillation. In this case it will be 0.

## Theory

The trigger is set so that the logger started logging as the value on the Force sensor rises above 0 N. The displacement, from the centre of oscillation, was therefore negative during the first half cycle.

The curves obtained will therefore relate to the following equations:-

- $x = -A\sin(\omega t)$
- $v = -A\omega\cos(\omega t)$
- $a = A\omega^2\sin(\omega t) = -\omega^2x$

The last equation shows that the acceleration, and hence the restoring force is always directed at the centre of oscillation.

## Questions

1. If  $x = -A\sin(\omega t)$  what is the value of  $\sin(\omega t)$  when the displacement is maximum?
2. If  $v = -A\omega\cos(\omega t)$  what is the value of  $\cos(\omega t)$  when the value of the velocity is a maximum?
3. From the acceleration graph read off the maximum value of acceleration. Read the corresponding value of the restoring force. Calculate the value of the mass. Does this agree with your measured value? Comment on sources of error.
4. A small mass attached to a spring oscillates in simple harmonic motion with an amplitude of 50 mm. It takes 30 seconds to complete 10 oscillations. Calculate its period, angular velocity, maximum speed and the maximum acceleration.

## Teacher's notes

### 7. SHM: Simple harmonic motion in a spring mass system (using Force and Rotary Motion sensors)

#### Practical skills AT a, b, c, k

In this investigation, the Force sensor is used to measure the force in the spring as it oscillates. At the same time the position of the mass is continually monitored using the Rotary Motion sensor.

Learning objectives:

The following relationships can be investigated:-

Phase relationships between  $F$ ,  $x$ ,  $v$ , and  $a$ .

1.  $F$  vs.  $t$
2.  $x$  vs.  $t$
3.  $v$  vs.  $t$
4.  $a$  vs.  $t$

Relate the above relationships to sine and cosine curves.

The effects of damping, as an optional extension.

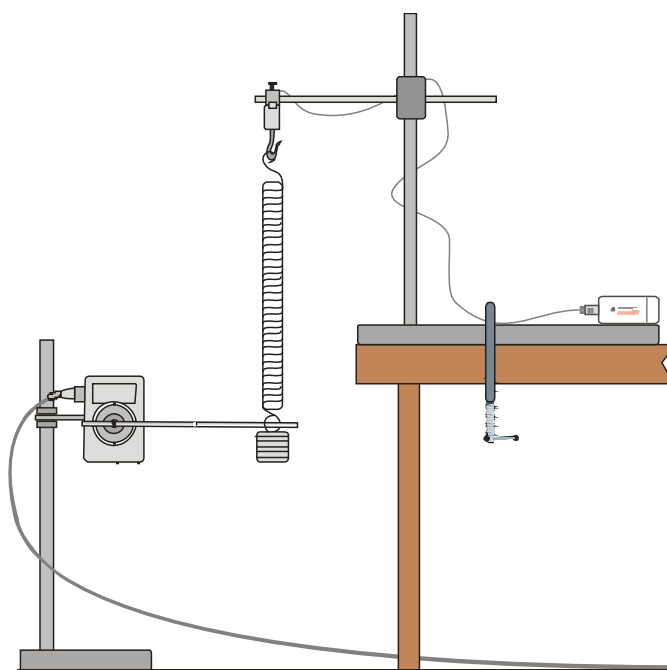
Key:

$x$  = displacement

$v$  = velocity

$a$  = acceleration

$F$  = Force





## Apparatus

1. Force sensor
2. Rotary Motion sensor with the range set to the pendulum range\*<sup>1</sup>
3. Pendulum rod or similar to connect RMS to oscillating mass
4. Steel spring, the spring - mass system needs to have a period of at least one second
5. Masses in the range of 0.5 kg to 1.2 kg (depending upon the spring used)
6. Large G - clamp
7. 2 retort stands with bosses and clamps

\*<sup>1</sup>There are 8 ranges on the RMS; Angular velocity could be selected to produce the velocity curve directly. If this range is selected then in the analysis Acceleration only needs to be derived. Use Acceleration (as first derivative of Angular velocity).

## Set up

Recording method	Recording time	Intersample time	Trigger level
Graph	5 seconds	20 ms	When the Force sensor rises above 0 N

## Practical notes

Assemble the apparatus as shown in the worksheet. Use substantial stands and clamps to reduce flexing as the weight oscillates. If possible have the side arm as low as possible to reduce leverage on the stand.

You will need a good mass to create enough force on the Force sensor to collect workable data. The range of the Force sensor is 50 N (~ 5kg). We would recommend something in the region of 20 N (~2 kg).

If you are using the spring for the Force sensor for the first time it will need conditioning / warming up to open up the coils.

When attaching the pendulum arm from the RMS to the oscillating mass you will need to use a flexible mount, a rubber band twisted around the pendulum arm and the mass carrier, works well. You may be lucky and find the pendulum arm fits through the hook of the mass carrier. When the pendulum rod has been attached make sure it is level when the mass is stationary, this will give a zero point for the pendulum.

Data Harvest sells an extension kit for the RMS which consists of a linear rack attachment, a pair of discs for angular momentum studies and a pendulum rod with adjustable masses. The pendulum rod from this kit has a central hole that can be used to tie the rod to the oscillating mass.

The adjuster on the Force sensor is used to set the force to zero with the masses hanging from it. The masses should be static when this adjustment is made. To get as close to zero as possible a small flat bladed screwdriver should be used.

The mass should be 0.5 m from the sensor when stationary to allow for amplitude of up to 25 cm. The trigger is set to operate at 0 N so that recording begins at the centre of the oscillation.

Set the mass oscillating and check that it will not get closer to the Motion sensor than 17 cm. The mass may well start swinging from side to side; a few practice runs are advisable to get the feel of the force needed to produce a clean oscillation.

Check that the mass and spring are matched; it is possible to get the spring fully closing on the 'up stroke' of the oscillation. This will be shown on the graph as a flat line at the top of the 'up' oscillation.

## Results and analysis

The following graphs were generated from a sample experiment, with the trigger set so that the logger started logging as the value on the Force sensor rose through 0 N. The displacement, from the centre of oscillation, was therefore negative during the first half cycle.

The curves obtained will therefore relate to the following equations:-

1.  $x = -A\sin(\omega t)$
2.  $v = -A\omega\cos(\omega t)$
3.  $a = A\omega^2\sin(\omega t) = -\omega^2x$

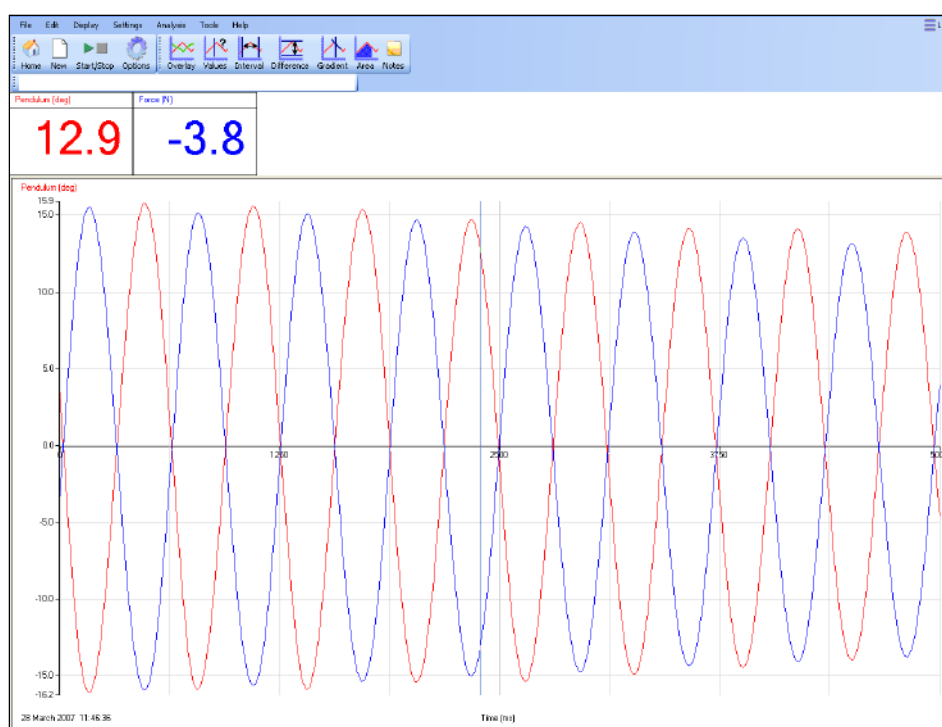


Fig 7.1 Data as collected by the students, auto scale applied, no analysis.

## Creating Velocity and Acceleration curves

### Velocity curve

1. Click on Tools, Post-log Function.
2. Select Preset function: Motion then Velocity.
3. Select 'Pendulum' as the source data.
4. Name = Velocity
5. Units = deg/s. (check the unit used for distance / displacement)
6. Scale factor = 1.
7. Click on Finish.

**Acceleration curve**

1. Click on Tools, Post-log Function.
2. Select Preset function: Motion then Acceleration (second derivative of position or distance).
3. Select 'Pendulum' as the source data.
4. Name = Acceleration
5. Units = deg/s/s. (check the unit used for distance / displacement)
6. Scale factor = 1.
7. Click on Finish

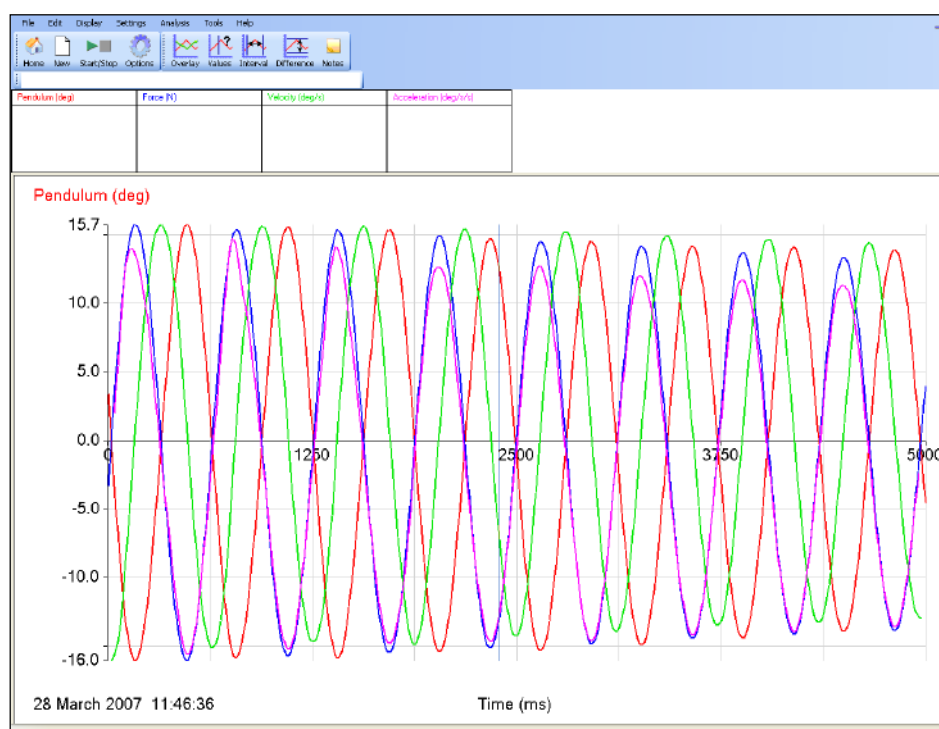


Fig 7.2 Pendulum, Velocity, Acceleration and Force data.

The equation for the Displacement 'x' will be of the form:-

$$x = -A \sin(\omega t) + c$$

You need to calculate  $\omega$  and A, the amplitude of the Oscillation. 'c' is a value that needs to be added if the displacement has not been measured from the centre of oscillation, in this case it will be 0.

**Calculation of  $\omega$** 

3. Use Interval to find the time for 5 cycles. Divide by 5 to calculate **T** the period.
4. Calculate  $\omega$  from the formula;

$$\omega = \frac{2\pi}{T}$$

**Measuring the Amplitude A**

Use Values to measure the value of A.

### Creating the curve

1. Click on Tools, Post-log Function.
2. Select Formula, **a sin(bt) + c**, Next.
3. Name = Sine Curve
4. Units = Degrees
5. Scale factor = 1
6. Decimal places = 3
7. a = -A from value measured above.
8. b =  $\omega$  from calculated value above
9. c = 0
10. Select Expand to fit, and Finish.

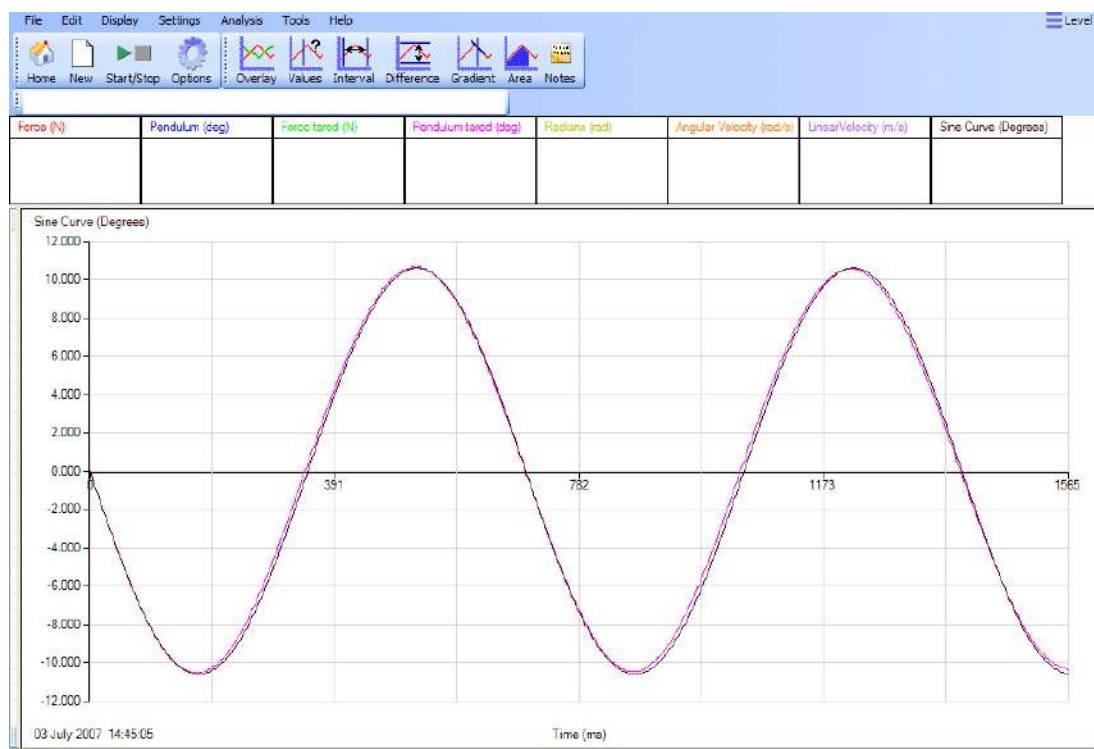


Fig 7.3 Generated, theoretical Sine Curve compared with the Pendulum (tared) practical based curve. Zoom and Auto scale has been used to select the first two cycles. The two curves are effectively identical, demonstrating quite clearly that the SHM curves are sine or cosine curves.

The same process can be used to generate a cosine curve for velocity, using the equation:  $v = -A\omega\cos(\omega t)$

## 7. SHM: Simple harmonic motion in a spring mass system (using Force and Rotary Motion sensors)

### Practical skills AT a, b, c, k

Vibrations play a very important part in our lives. The effects can be beneficial or destructive. Here are a few examples:-

- Vibration induced motion sickness.
- Listening to music with a CD player or at a concert.
- Earthquakes.
- Clocks.
- In car engines.
- Spring-mass systems.
- The Millennium bridge in London.

Any motion that repeats itself is described as harmonic motion. We will be investigating a particular form of harmonic motion known as simple harmonic motion (SHM).

The properties of SHM are:-

1. The period is independent of the amplitude of the motion.
2. The force is always pointed to the central point of the oscillation. This is often called the restoring force because it is always pointed at the central point.
3. The restoring force is directly proportional to the magnitude of the displacement, and opposite in sign to it.

$$F = -kx$$

**k** = the stiffness of the restoring system (spring constant).

In this investigation you are going to seek answers to the following questions:-

1. How does the distance (displacement) from the centre of oscillation change during each cycle?
2. What is the phase relationships between the:-
  - Restoring force, **F**
  - Displacement, **x**
  - Velocity, **v**
  - Acceleration, **a**
3. How closely does the oscillation of a spring relate to SHM?

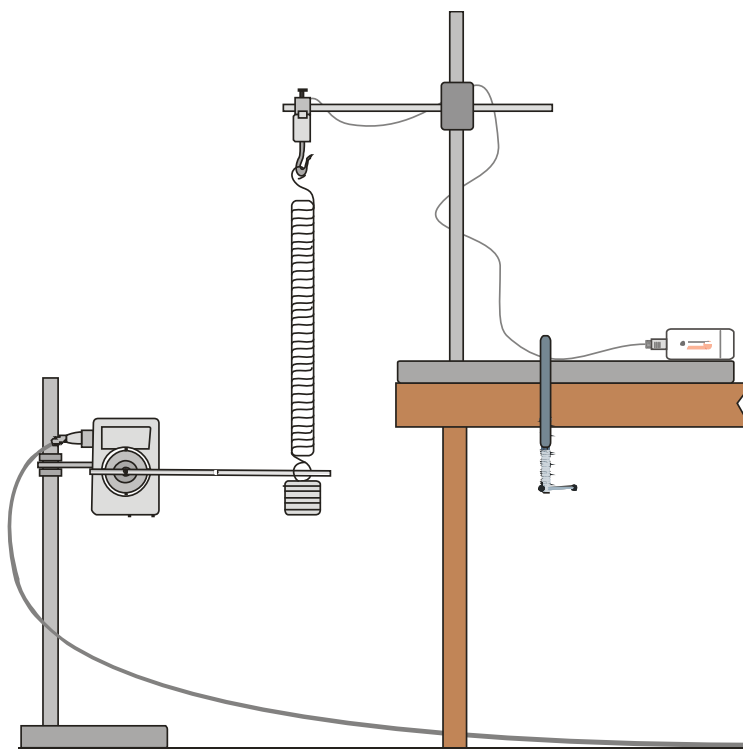
Key:

**T** = period of the oscillation in seconds.

**$\omega$**  = angular velocity of the SHM in radians sec<sup>-1</sup>.

### Preliminary Questions

1. Draw a sketch graph showing how you expect the displacement to change with time during two oscillations of the spring.
2. Make a copy of your sketch from question 1 and add to it curves showing how you expect the velocity and acceleration of the object will change during those two oscillations.



### Apparatus

1. Force sensor.
2. Rotary Motion sensor with the range set to pendulum.
3. Steel spring, the spring-mass system needs to have a period of at least one second.
4. Masses in the range of 0.5 kg to 1.2 kg (depending upon the spring used).
5. Large G - clamp.
6. 2 retort stands with bosses and clamps.

### Method

1. Weigh the spring and the suspended mass added together and write down the value in your results table. They are the 'oscillating mass'.
2. Assemble the apparatus as shown above. Connect the Force and Rotary Motion sensor to the data logger.
3. Make sure that the apparatus supporting the oscillating mass is as rigid as possible and when the mass is stationary it is about 50 cm from the floor.

## 4. Set up to record.

Recording method	Recording time	Intersample time	Trigger level
Graph	5 seconds	20 ms	When Force sensor rises above 0 N

5. Select Test Mode (Tools menu). Adjust the alignment of the Rotary Motion sensor arm to give a reading as close to 0 degrees as possible.
6. Zero the Force sensor with the mass hanging stationary on the spring.
7. Pull the spring downwards and set it oscillating. Use an amplitude of between 15 – 25 cm; take care to not overstretch the spring. Check that it is oscillating vertically.
8. Click on Start to begin logging. The set up contains a trigger to start logging when the mass is at the top of an oscillation.
9. Save the file if the curve is smooth, if not repeat. (Use Delete Data Sets from the Edit menu to remove any unwanted data sets).

## Results and analysis

Mass of spring and load = ..... kg

### a) Displaying the results

The graph will show a Force and Pendulum vs. Time. The analysis needs to:-

- Use Sensor settings (or Auto scale) to make the curve cover the display area.
- If necessary apply a tare to make the pendulum values oscillate around zero.
- Convert the Distance vs. Time curve to a displacement curve with a centre zero, using Post-log Functions.
- Obtain a Velocity vs. Time curve, using Post-log Functions.
- Obtain an Acceleration vs. Time curve, using Post-log Functions.

### b) Analysing the results

How closely do the graphs you obtained match your predictions?

#### 1. Phase Relationships

Compare the velocity, acceleration and force curves, with the displacement curve. Are they 'in phase' or out of phase with the displacement curve? If they are out of phase say by how much ( $\frac{1}{4}$  or  $\frac{1}{2}$  of an oscillation i.e.  $\pi/4$  or  $\pi/2$ )?

Curve	In phase OR phase difference?
Velocity	
Acceleration	
Force	

## 2. Comparing the graphs

Using Zoom, display one whole cycle of the displacement graph. Fill in the following table. State the value of the displacement (choose from: maximum positive, maximum negative or zero) for the positions in the velocity, acceleration and force graphs, shown in the table.

Position in v, a, or F graphs	Corresponding values in the displacement graph
Velocity zero	
Velocity maximum positive	
Acceleration maximum negative	
Acceleration maximum positive	
Acceleration zero	
Force maximum positive	
Force Zero	

## 3. Calculation of the Period and $\omega$

- Calculate the Period from the graph.
- Calculate the angular velocity  $\omega$  from the equation: -

$$T = \frac{2\pi}{\omega}$$

## 4. Generating a sine curve

If the spring is oscillating in SHM, then the equation for the displacement 'x' will be of the form:-

$$x = -A\sin(\omega t)$$

Generate a sine curve and compare it with your displacement curve. Use Values to measure the value of A from your displacement graph. It is the maximum value of the displacement.

Using Tools, Post-log Function, Formula, **a sin(bt) + c** to generate the sine curve.

## Theory

The trigger is set so that the logger started logging as the value on the Force sensor rose through 0 N. The displacement, from the centre of oscillation, was therefore negative during the first half cycle.

The curves obtained will therefore relate to the following equations:-

- $x = -A\sin(\omega t)$
- $v = -A\omega\cos(\omega t)$
- $a = A\omega^2\sin(\omega t) = -\omega^2x$

The last equation shows that the acceleration, and hence the restoring force is always directed at the centre of oscillation.



## Questions

1. If  $x = -A\sin(\omega t)$  what is the value of  $\sin(\omega t)$  when the displacement is maximum?
2. If  $v = -A\omega\cos\omega t$  what is the value of  $\cos(\omega t)$  when the value of the velocity is a maximum?
3. From the acceleration graph read off the maximum value of acceleration. Read the corresponding value of the restoring force. Calculate the value of the mass. Does this agree with your measured value? Comment on sources of error.
4. A small mass attached to a spring oscillates in simple harmonic motion with an amplitude of 50 mm. It takes 30 seconds to complete 10 oscillations. Calculate its period, angular velocity, maximum speed and the maximum acceleration.

## Function – help

### To generate the velocity – time curve from the pendulum displacement – time curve

1. From the Tools menu select the Post-log Function.
2. Select Preset function: Motion then Velocity
3. Data to be used = Pendulum (degrees).
4. Decimal places = 3
5. Name = Velocity
6. Units = deg/s.
7. Click on Finish
8. Use Smoothing (Tools menu) if necessary.

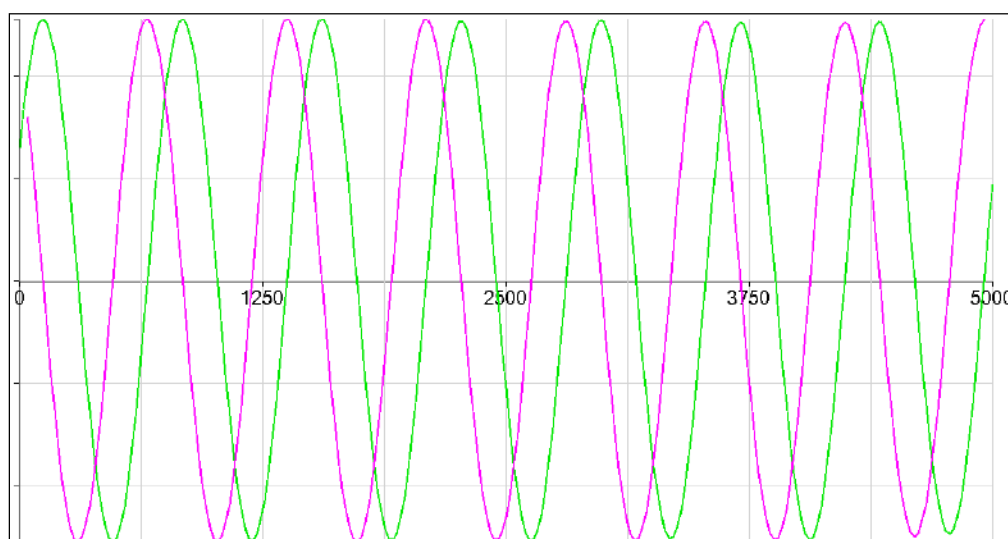


Fig 7.1 Velocity calculated from degrees. Force and original distance data hidden, Auto scale used (velocity and pendulum only shown)

### To generate the acceleration – time curve from the pendulum displacement – time curve

1. From the Tools menu select the Post-log Function.
2. Select Preset function: Motion then Acceleration as the second derivative of distance
3. Data to be used = Pendulum (degrees).
4. Decimal places = 3

5. Name = Acceleration
6. Units = deg/s/s
7. Click on Finish
8. Use Smoothing (Tools menu) if necessary.

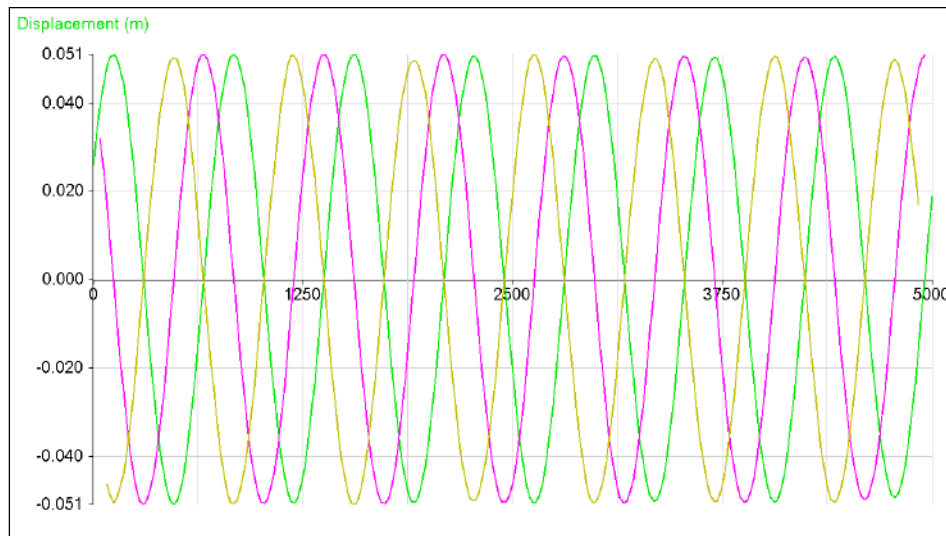


Fig 7.2 Acceleration calculated from displacement. Force and original pendulum data deselected, Auto scale used.

### Creating the theoretical Sine Curve

The equation for the Displacement 'x' will be of the form:-

$$x = -A\sin(\omega t) + c$$

You need to calculate the angular velocity,  $\omega$  and the amplitude, A of the Oscillation. 'c' is a value that needs to be added if the displacement has not been measured from the centre of oscillation. In this case it will be 0.

### Creating the curve

- From the Tools menu select Post-log Function.
- Select Formula, **a sin(bt) + c**.
- Name = Sine Curve
- Units = Degrees
- Scale factor =1
- Decimal places = 3
- a = -A from value measured above.
- b =  $\omega$  from calculated value above
- c = 0
- Select Expand to fit, and Finish

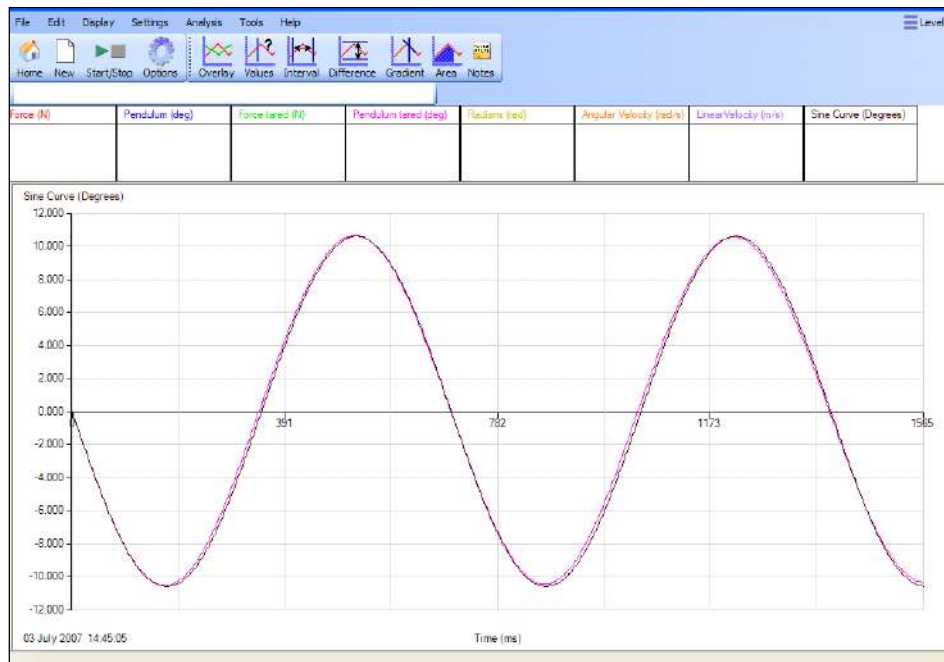


Fig 7.3 Generated theoretical Sine Curve compared with Pendulum (tared) from practical. Zoom and Auto scale has been used to select the first two cycles.

The same process can be used to generate a cosine curve for the velocity, using the equation:-

$$v = -A\omega\cos(\omega t)$$

## Teacher's notes

### 8. Period of an oscillating spring mass system

#### Practical skills AT a, b, c, k

Springs play an important part in the suspension systems of cars. The springs are used to make the ride smoother and help the car grip the road. The period of oscillation of the spring will affect the way the car bounces after it has hit a bump in the road. If the oscillation of the springs lets the car (or even single wheel of the car) lose contact with the road, then the forces holding the car on its line of travel become unbalanced and control is lost.

The period of oscillation of a spring is likely to depend on two factors:-

- The mass of the spring mass system
- The spring constant

The spring constant is a measure of how stiff the spring is. A spring that is very hard to stretch out has a large spring constant. A spring that is easy to stretch has a small spring constant. It is given the unit  $k$  and is measured in units of force and distance ( $\text{Nm}^{-1}$ ).

This investigation is to allow the students to,

1. Study the relationship between the time period ( $T$ ) and the oscillating mass ( $M$ ) of a spring – mass system.
2. Understand and use the equation  $T = 2\pi\sqrt{M/k}$ .
3. Measure (and calculate)  $k$ , the stiffness of a spring.

The investigation uses a mass suspended above a Motion sensor. The mass is set oscillating and the Motion sensor will monitor the movement and position of the mass.

#### Apparatus

1. Motion sensor set to a distance range
2. A spring of known  $k$  value, preferably in the region of  $8 - 10 \text{ Nm}^{-1}$
3. Masses and mass hanger e.g.  $6 \times 100 \text{ g}$
4. Balance
5. G clamp or similar to secure retort stand to bench.
6. Retort stand, boss and clamp.
7. Mesh guard to protect the Motion sensor.

#### Set up

Recording method	Recording time	Intersample time	Trigger level
Graph	20 s	20 ms	When Motion sensor rises above 0.3 m

## Practical notes

The suspended masses should have a large base area. 100 g masses with a diameter of 25 cm work well. If the masses you have are smaller than this they may work without modification. A thin card reflector can be mounted on the hanger base using light glue or double sided tape. Make sure the mass recorded after this addition.

Students may need reminding that mass and weight are interchangeable on Earth, for simplicity of English the recording of mass has been written as 'recording the weight' of the mass. This overcomes the construct of recording the mass of the mass!

Students may need a little practice in setting the mass oscillating, it is easy to get the mass jumping sideways after only a few oscillations, from experience this seems to be more of a problem if the spring is stiffer.

If you have difficulty with a spring elastic bands can be substituted, they do give a more rapid decay in amplitude but the period data is good.

## Results and analysis

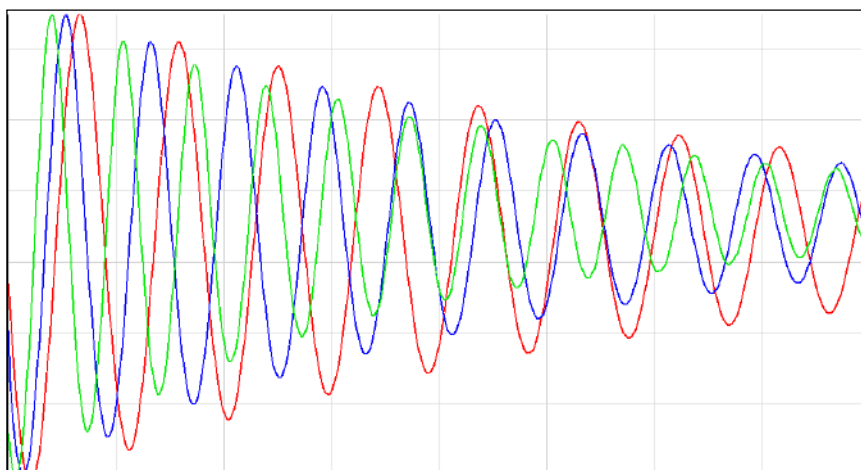


Fig 8.1 Sample data for 3 masses using elastic bands for the spring. The rapid decay of amplitude is clear.

### Calculating T for the graphs

1. Use Show or Hide channels to make the curve you want to study the only one visible.

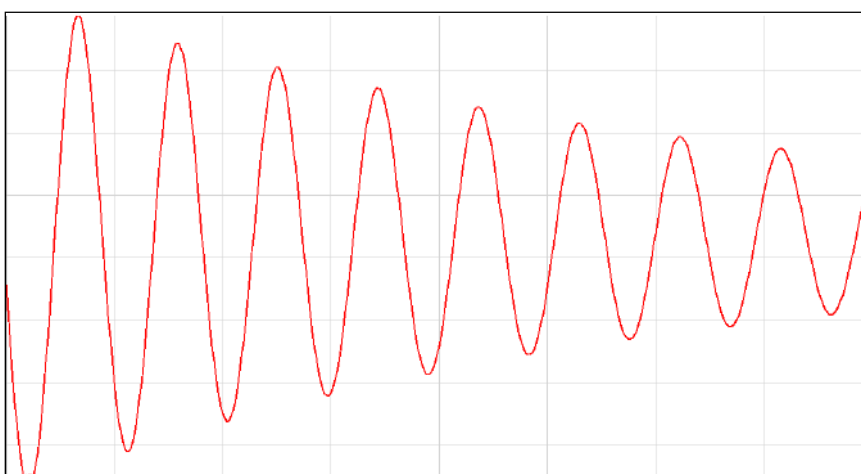


Fig 8.2 A single set of oscillations shown

2. Use Auto scale to maximise the graph.
3. Use Interval to find the time for a whole number of oscillations. Note how many oscillations you have used.

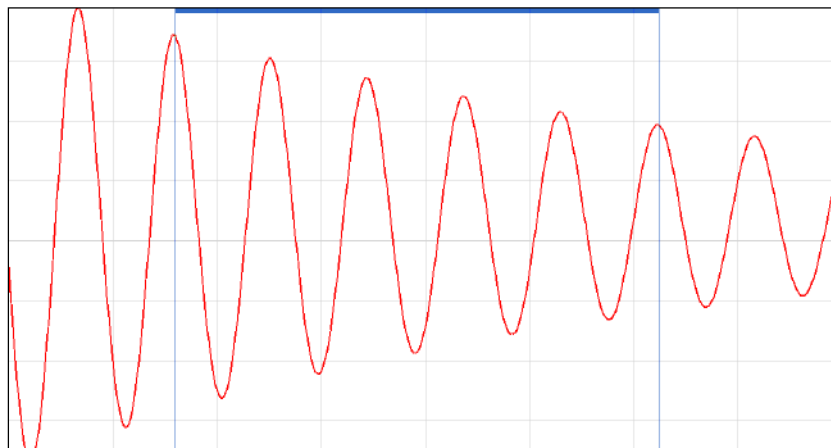


Fig 8.3 A sequence of 5 oscillations selected by the Interval tool.

4. Use a table like the one shown to record the mass  $M$ , interval, number of oscillations and the calculated values.

#### Sample data

Mass $M$ (kg)	Interval (s)	No of oscillations	Period $T$ (s)	$T^2$
0.21	9.82	10	0.982	0.964
0.31	11.88	10	1.188	1.411
0.41	13.62	10	1.362	1.855
0.51	15.2	10	1.520	2.310
0.61	16.62	10	1.662	2.762

#### Investigating $T$ vs. $M$ relationship

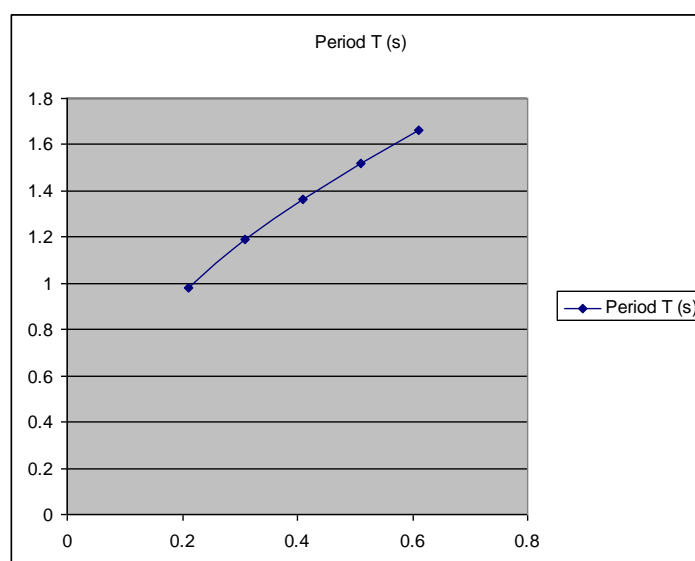


Fig 8.4 mass (x axis) against period (y axis)

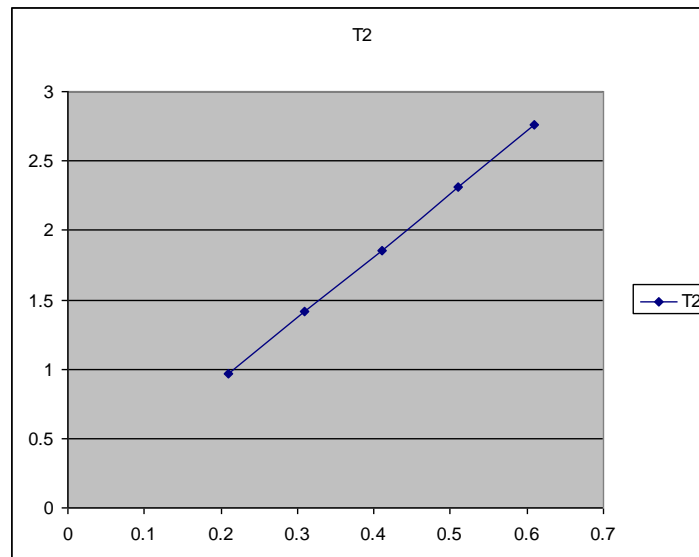


Fig 8.5 Use the data in the table to draw a graph of  $T^2$  vs.  $M$ .

### Further analysis

1. Calculate the gradient of the line of best fit of the  $T^2$  vs.  $M$  graph.
2. From the gradient calculate the value of  $k$ .
3. Plan an experiment to test the relationship between  $T$  and  $k$ . Explain in your answer how you would analyse the results.

### Oscillation of a spring – mass system theory

The equation for the period of an oscillation spring – mass system is

$$T = \frac{2\pi\sqrt{M}}{K}$$

Squaring the equation (to remove the 'square root') we get,

$$T^2 = \frac{4\pi^2 M}{K}$$

The graph of  $T^2$  against  $M$  will be a straight line through the origin.

The gradient of the line will be equal to,

$$\frac{4\pi^2}{K}$$

### Worked example of calculation of $K$ ,

Reading data off the plot of  $T^2$  vs.  $M$ .

	Mass	$T^2$
Highest co-ordinate	0.64	2.9
Lowest co-ordinate	0.06	0.30
Difference	0.58	2.6

Gradient of  $T^2$  vs.  $M = 2.6 \div 0.58 = 4.48$

$$\text{Gradient} = \frac{4\pi^2}{K}$$

$$K = k = \frac{4\pi^2}{\text{gradient}}$$

$$4\pi^2 = 39.478 \quad (4 \times \pi^2 \text{ or } 4 \times 9.8696)$$

$$K = 8.8 \text{ Nm}^{-1}$$



## 8. Period of an oscillating spring mass system

### Practical skills AT a, b, c, k

Springs play an important part in the suspension systems of cars. The springs are used to make the ride smoother and help the car grip the road. The period of oscillation of the spring will affect the way the car bounces after it has hit a bump in the road. If the oscillation of the springs lets the car (or even single wheel of the car) lose contact with the road, then the forces holding the car on its line of travel become unbalanced and control is lost.

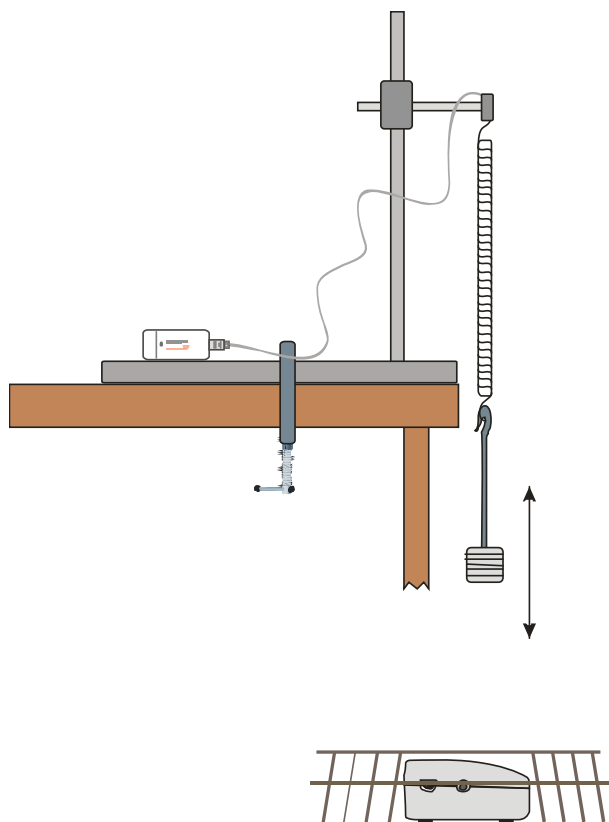
The period of oscillation of a spring is likely to depend on two factors:-

- The mass of the spring mass system
- The spring constant

The spring constant is a measure of how stiff the spring is. A spring that is very hard to stretch out has a large spring constant. A spring that is easy to stretch has a small spring constant. It is given the symbol  $k$  and is measured in units of force and distance ( $\text{Nm}^{-1}$ ).

### Pre-experiment questions

1. Write down a statement saying what you think the relationship is between the period of oscillation of a spring-mass system and the mass.
2. Draw a sketch graph showing what you would expect a  $T$  vs.  $M$  graph to look like.  $T$  = the time period of the oscillation,  $M$  = the oscillating mass.
3. State how you expect the spring constant ( $k$ ) to affect the period ( $T$ ).
4. Draw a sketch graph to show what you would expect a  $T$  vs.  $k$  graph to look like.



## Apparatus

1. A Motion sensor set to a distance range
2. A spring
3. Masses and mass hanger e.g. 6 x 100 g
4. Balance
5. G clamp or similar to secure retort stand to bench
6. Retort stand, boss and clamp
7. Mesh guard to protect the Motion sensor

## Method

1. Measure and record the weight of the mass and spring you are going to; use check with your teacher the appropriate values to use that will not damage the spring.
2. Set up the apparatus as shown in the diagram. Connect the Motion sensor to the data logger.
3. Make the apparatus as rigid as possible. All clamps must be tightened firmly.
4. Set up to record:

Recording method	Recording time	Intersample time	Trigger level
Graph	20 s	20 ms	When Motion sensor rises above 0.3 m

5. Pull the mass down and click on Start. Release the mass to set it oscillating.
6. Check on the curve shown by the graph; make sure there is an even waveform. If not, repeat the recording (remember to delete the data set that wasn't acceptable).
7. Save the data.
8. Check that Overlay is on and repeat with a different mass (add or remove a 100 g mass, remember to weigh the mass system).
9. Repeat so that you have recordings for at least 4 mass sets.

Note: It may be worth making a mark to indicate the 17 cm above the Motion sensor.

## Results and analysis

Mass of spring =        kg

### Calculating T for the graphs

1. Use Show or Hide channels to make the curve you want to study the only one visible.
2. Use Auto scale to maximise the graph.
3. Use Interval to find the time for a whole number of oscillations. Note how many oscillations you have used.
4. Use a table like the one shown to record the Mass M, interval, number of oscillations and the calculated values.

Mass M (kg)	Interval (s)	No of oscillations	Period T (s)	T <sup>2</sup> (s <sup>2</sup> )

### Investigating T vs. M relationship

1. Use the data in the table to draw a graph of T vs. M
2. Use the data in the table to draw a graph of T<sup>2</sup> vs. M

### Questions

1. What do the graphs of T vs. M and T<sup>2</sup> vs. M tell you about the relationship between T and M?
2. How does your answer to Q1 compare with the predictions you made in the pre-experiment questions?

### Further analysis

1. Calculate the gradient of the line of best fit of the T<sup>2</sup> vs. M graph.
2. From the gradient calculate the value of k.
3. Plan an experiment to test the relationship between T and k. Explain in your answer how you would analyse the results.

### Oscillation of a spring – mass system theory

The equation for the period of an oscillation spring–mass system is

$$T = \frac{2\pi\sqrt{M}}{K}$$

Squaring the equation (to remove the 'square root') we get,

$$T^2 = \frac{4\pi^2 M}{K}$$

The graph of T<sup>2</sup> against M will be a straight line through the origin.

The gradient of the line will be equal to,

$$\frac{4\pi^2}{K}$$

Worked example of calculation of K,  
Reading data off the plot of  $T^2$  vs. M.

	Mass	$T^2$
Highest co-ordinate	0.64	2.9
Lowest co-ordinate	0.06	0.30
Difference	0.58	2.6

Gradient of  $T^2$  vs. M =  $2.6 / 0.58 = 4.48$

$$\text{Gradient} = \frac{4\pi^2}{K}$$

$$\text{Therefore } k = \frac{4\pi^2}{\text{gradient}}$$

$$= \frac{4\pi^2}{4.48} \quad 4\pi^2 = 39.478 \text{ (4 x } \pi^2 \text{ or 4 x 9.8696)}$$

$$= 8.8 \text{ Nm}^{-1}$$

## Teacher's notes

### 9. Relationship between period and the length of the pendulum (using a Motion sensor)

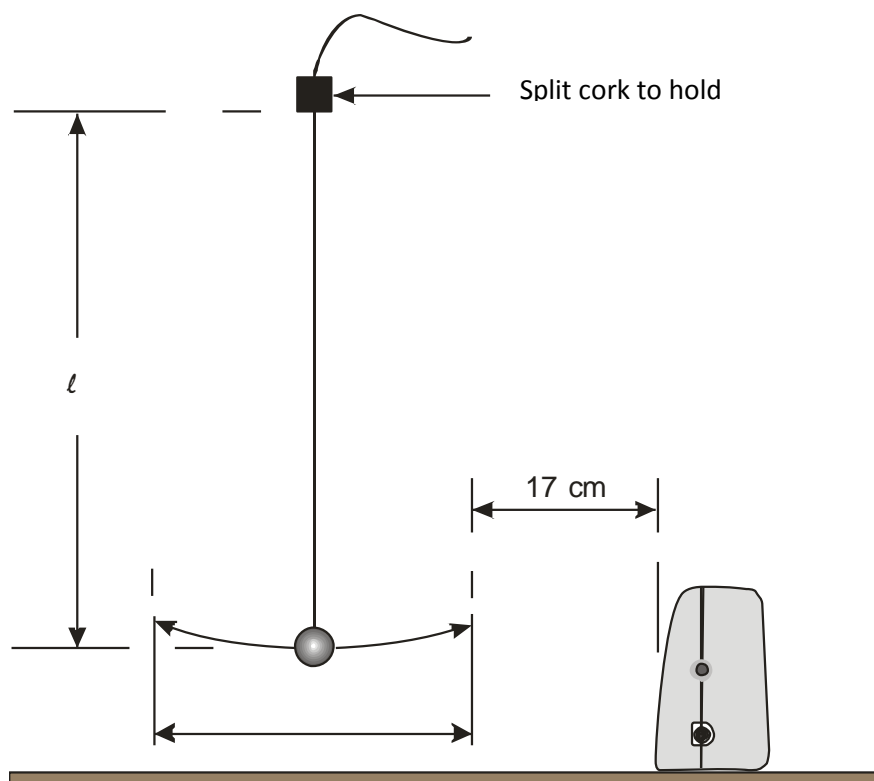
#### Practical skills AT a, b, c, k

The relationship between pendulum period and the length of the pendulum is for many counter intuitive. With a pendulum most people see the bob swinging more quickly as the period increases and therefore assume the time for the swing is getting faster.

The time taken for a number of swings can be measured and the time for a single swing calculated. Problems arise with the accuracy of the timer (both man and machine) and these become more exaggerated as the length of the pendulum becomes shorter. The errors can be enough to hide the relationship between period and length.

Using a Motion sensor provides a more complete picture of the pendulum swing. The data shows the change in distance against time. The time of the swing can be easily found using the interval tool; the student will need to think about which interval to measure. The graph formed shows a sine wave, the creation of a smooth wave shape from a back and forward motion can be a valuable teaching step. The visual conversion of a change of distance into an "up and down" sine graph makes the use of the Motion sensor worthwhile.

If it can be arranged a demonstration of a really big pendulum is useful in setting the scene, a large ball suspended from string (rope) connected to the ceiling or in a stairwell makes a dramatic starting point.



## Apparatus

1. Motion sensor set to a distance range
2. Pendulum mass
3. Thin string or wire for pendulum
4. Split cork ( or two pieces of wood)
5. Retort stand and clamps

## Set up

Recording method	Recording time	Intersample time	Trigger level
Graph	20 s	20 ms	Motion sensor rises above 0.4 m

## Practical notes

Assemble the apparatus as shown. Make sure that the pendulum can swing freely and that there isn't anything in the way that the Motion sensor can detect apart from the pendulum bob.

Position the Motion sensor 0.4 m from the string when the bob is hanging at rest. The software setup will set the logger to trigger when the distance value rises above 0.4 m.

The 'pendulum bob' should be level with the lower edge of the sensor transducer when it is stationary.

The bob of the pendulum should not go above the top of the sensor element at the highest point of the swing.

Use a starting value for 'L' (the length of the pendulum) of about 0.9 m

The "string" connecting the pendulum bob to the clamp should be as fine as possible and with a degree of stiffness; fine fuse wire makes an ideal "string". At this level fine cotton will be adequate however.

Use amplitude of < 100

A golf ball taped to the end of the pendulum string makes a good 'bob'. Using tape on the golf ball covers the dimples which can disperse the ultrasound.

**Hardware limitations:** The fastest speed the sensor can be used to collect data is fixed by the frequency at which the unit transmits its ultrasound pulses, 50 Hz (20 ms intersample time). Trying to collect data at a faster frequency than this will result in the ultrasound unit not firing.

**IMPORTANT:** Be aware of the size of the ultrasound cone, at one metre from the Motion sensor the cone will have a diameter of 0.2 m, at 2 metres it will be 0.4 m.

## Results and analysis

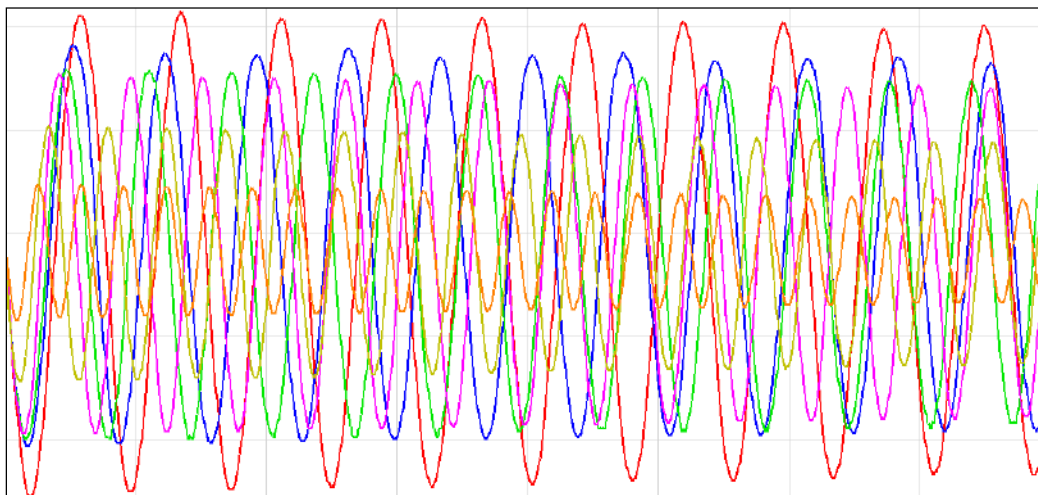


Fig 9.1 Data as collected, 6 different pendulum lengths

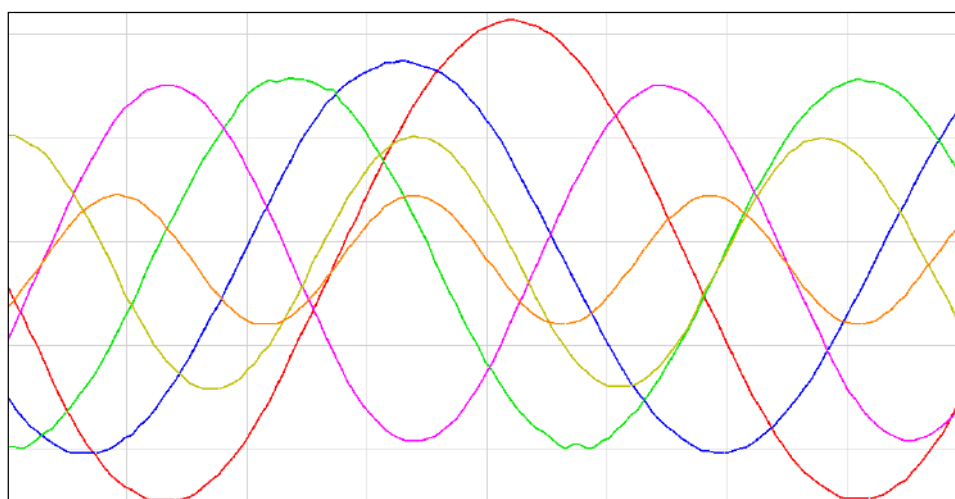


Fig 9.2 An area of the graph Zoomed in, the difference in periods is clearly shown.

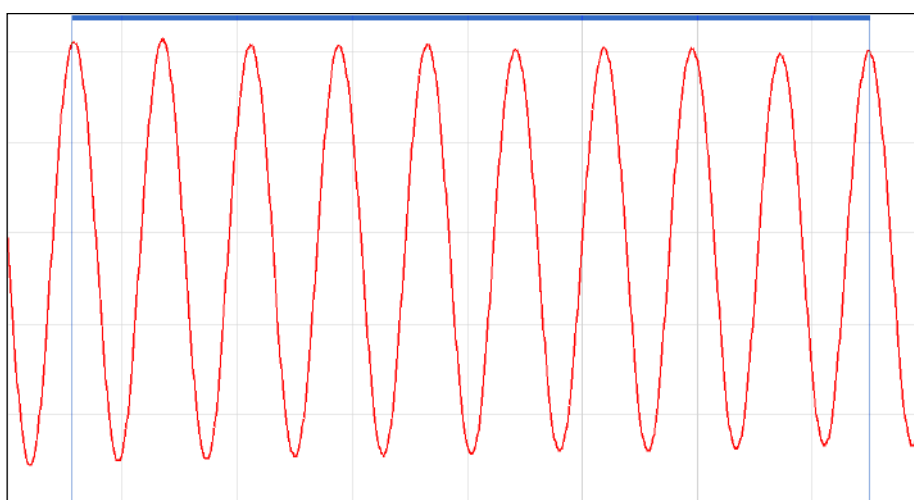


Fig 9.3 Show or Hide channels used to show only one set of oscillations. Interval being used to measure the time for 10 oscillations. 10 is used for convenience, data may mean other numbers have to be used.

Results T vs. L				
Length L (m)	Time for 10 oscillations (s)	T (s)	Log L	Log T
0.918	19.20	1.920	-0.037	0.283
0.764	17.52	1.752	-0.117	0.244
0.617	15.70	1.570	-0.210	0.196
0.465	13.68	1.368	-0.333	0.136
0.317	11.13	1.130	-0.499	0.053
0.167	8.18	0.818	-0.777	-0.087

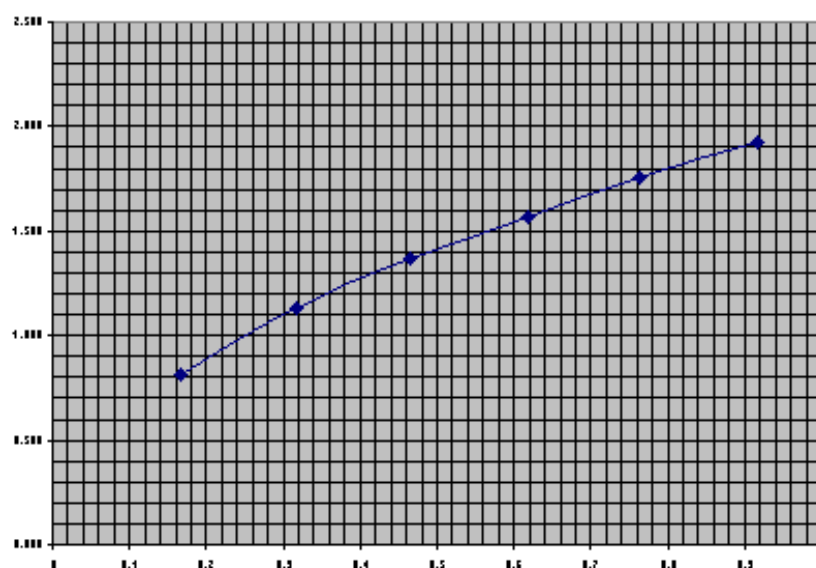


Fig 9.4 Spreadsheet plot of Period (T) vs. Length (L) of pendulum

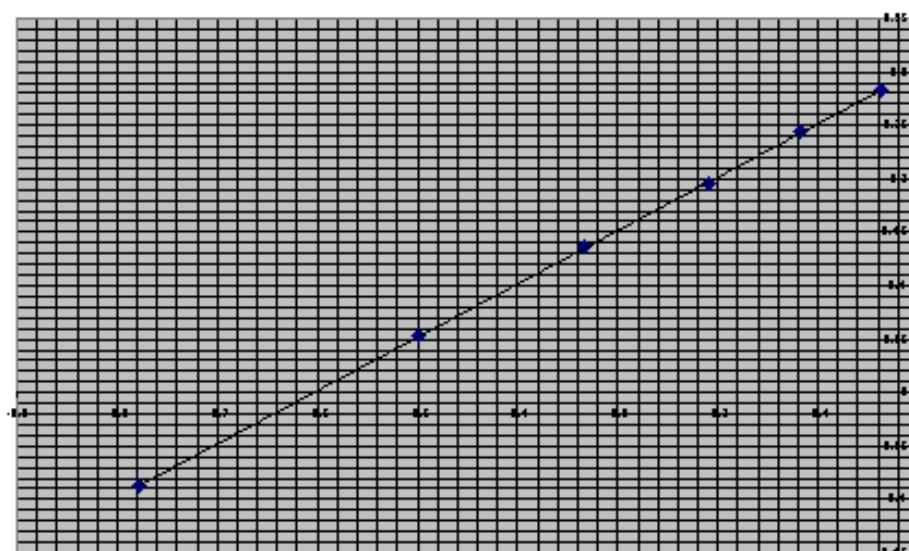


Fig 9.5 Spreadsheet plot of log period (logT) vs. log length (log L).

The linear relationship is clearly seen.



Gradient = 0.497 within 0.6% of 0.5.

Intercept = 0.302 giving a value of  $g = 9.83$

Checking the validity of the results

$$T = 2\pi\sqrt{\frac{l}{g}}$$

$$T = kl^n$$

$$k = \frac{2\pi}{\sqrt{g}}$$

Putting the values for  $\pi$  and  $g$  into the equation,

$$k = \frac{2\pi}{\sqrt{9.81}}$$

$$= 2.006$$

The intercept of the graph = 0.302 =  $\log k$

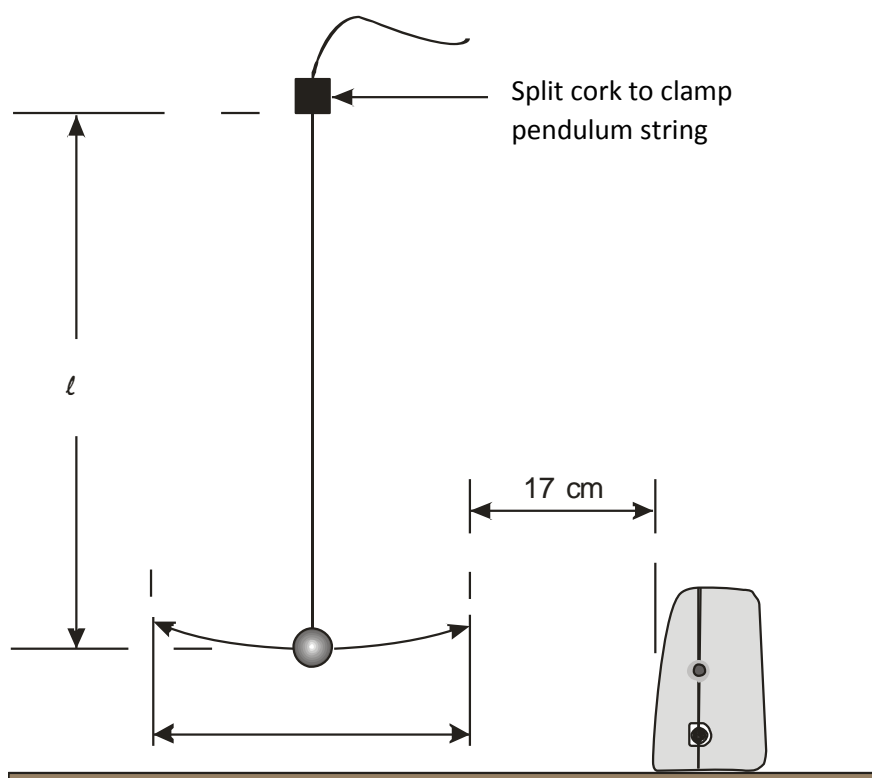
The antilog of 0.302 ( $k$ ) = **2.004**, which compares favourably with the mathematically derived value of **2.006**

## 9. Relationship between period and the length of the pendulum (using a Motion sensor)

### Practical skills AT a, b, c, k

The pendulum was the controlling mechanism for the first accurate clocks. Until the pendulum properties were discovered we did not have clocks that could measure time with any precision. The pendulum period (time taken to move through one “swing”) is independent of its swing amplitude (the distance of the swing). How does its period vary as you change the length of the pendulum?

The **period** of a pendulum is the time it takes for it to complete one complete swing backwards and forwards.



### Apparatus

1. Motion sensor set to a distance range
2. Pendulum mass
3. Thin string or wire for pendulum
4. Split cork (or two pieces of wood)
5. Retort stands and clamps

### Method

1. Assemble the apparatus as shown. Make sure that the pendulum can swing freely and that there is nothing in the way that the Motion sensor could detect apart from the pendulum bob.

2. Use a starting value for ' $l$ ' (the length of the pendulum) of about 0.9m
3. Measure the length of the pendulum ' $l$ ' and write the value down in a results table.
4. Connect the Motion sensor to the data logger and position the sensor 0.4m from the string when the bob is hanging at rest. The software setup will set the logger to trigger when the distance value rises above 0.4 m.
5. The 'pendulum bob' should be level with the lower edge of the sensor transducer when it is stationary.
6. Set up to record:

Recording method	Recording time	Intersample time	Trigger level
Graph	20 s	20 ms	When Motion sensor rises above 0.4 m

7. Set the pendulum swinging and check that it is swinging in a line. Use an amplitude of  $< 100$
8. Click on Start when the pendulum is at its closest to the sensor.
9. You should get a smooth graph. If not, reposition the pendulum and try again. You can erase unwanted results by using Delete Data Sets (Edit menu).
10. Check Overlay is selected and repeat the experiment 5 more times varying the length of the pendulum (down to a minimum of 0.15 m). The trigger will ensure the graphs are synchronised (click on Start to collect the data for each length on the same graph).
11. Save your file. It is good practice to save the results after each successful run.

## Results and analysis

- The six sets of results will be displayed on the same graph. You can display the graphs singly or together using Show or Hide channels (right click in the graph area).
- Use Auto scale to obtain good sized graphs.
- Use Show or Hide channels to select one of the curves. Use Interval to measure the time for 10 complete oscillations. Write down the result in a table (like the one below) in your report, or in Excel.
- Repeat for the other curves.
- Plot a graph of  $T$  versus  $l$ . This is easily done in a spreadsheet such as Excel; using a xy (scatter) chart. It will be a curve.

Length $l$ (m)	Time for 10 oscillations (s)	Time for one oscillation $T$ (s)

## Questions

What is the relationship shown by the graph? Write down your answer as fully as possible.

## Advanced Theory

The relationship will be of the form:  $T = kl^n$

$k = \text{constant}$

We can find 'n' (an unknown exponent) by using Log graphs.

Taking logs:

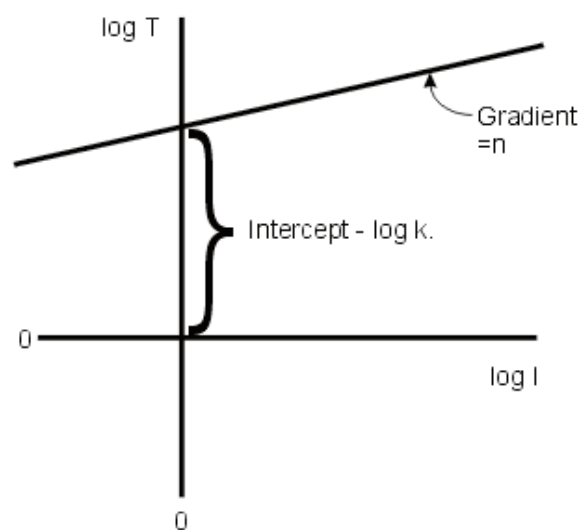
$$\begin{aligned}\log T &= \log(k L^n) \\ &= \log k + \log(L^n) \\ &= \log k + n \log L\end{aligned}$$

rearranging:

$$\log T = n \log L + \log k$$

$$(y = mx + c)$$

Therefore a graph of  $\log T$  versus  $\log L$  will give a straight line. The gradient will be 'n'. The intercept on the  $\log T$  axis is  $\log k$



## Further analysis

- Write down the logs to base 10 of  $T$  and  $L$  in a table like the one below.

Length $l$ (m)	Time for one oscillation $T$ (s)	$\log_{10} T$	$\log_{10} l$

2. Plot a graph of  $\log T$  versus  $\log l$ .
3. Draw the line of best fit and calculate its gradient. This is the value of 'n'.
4. Measure the intercept on the  $\log T$  axis; this is the value of  $\log k$ .
5. Write out the equation for the relationship putting in the values for 'n' and 'k' that you have determined.

## Teacher's notes

### 9a. Relationship between period and the length of the pendulum (using a Rotary Motion sensor)

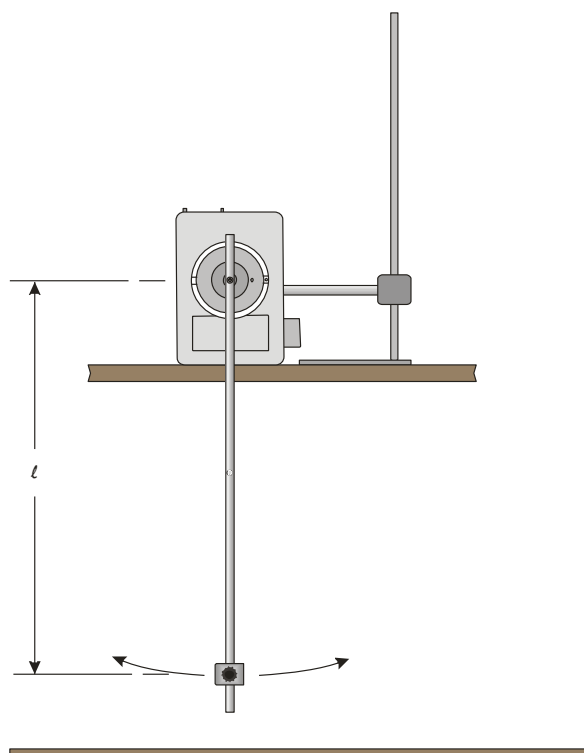
#### Practical skills AT a, b, c, k

The relationship between pendulum period and the length of the pendulum is for many counter intuitive. With a pendulum most people see the bob swinging more quickly as the period increases and therefore assume the time for the swing is getting faster.

The time taken for a number of swings can be measured, and the time for a single swing calculated. Problems arise with of the accuracy of the timer (both man and machine) and these become more exaggerated as the length of the pendulum becomes shorter. The errors can be enough to hide the relationship between period and length.

Using a Rotary Motion sensor provides a more complete picture of the pendulum swing. The data shows the change in angle against time. The time of the swing can be easily found using the Interval tool. The student will need to think about which interval to measure. The graph formed shows a sine wave, the creation of a smooth wave shape from a back and forward motion can be a valuable teaching step. The visual conversion of a change of distance into an “up and down” sine graph makes the use of the Rotary Motion sensor worthwhile.

If it can be arranged, a demonstration of a really big pendulum is useful in setting the scene; a large ball suspended from string (rope) connected to the ceiling or in a stairwell makes a dramatic starting point.



This apparatus shows the use of the pendulum accessory for the Rotary Motion sensor. For many experiments this will be all that is required. If a longer pendulum is required, use a string of thin wire attached to the centre spindle of the Rotary Motion sensor.

## Apparatus

1. Rotary Motion sensor set to the pendulum range.
2. Pendulum mass
3. Thin string or wire for pendulum or pendulum rod for the RMS.
4. Mass for pendulum bob.
5. Retort stand and clamps

## Set up

Recording method	Recording time	Intersample time	Trigger level
Graph	20 s	20 ms	Pendulum falls below 5 degrees

## Practical notes

Make sure that the pendulum can swing freely.

Make marks on the pendulum rod at 1 cm intervals to help with positioning of the masses. Students should measure length of pendulum from centre of fixing screw on the RMS to the centre of the pendulum mass. If you want the most accurate result then the balance point of the pendulum needs to be found and the distance from the attachment point to the balance point measured. The balance point will normally be in front of the mass.

It is best to create a marker to indicate the start point. The pendulum range reads  $\pm 20$  degrees, pendulum theories work best for angles of less than 10 degrees. If you move the pendulum more than 20 degrees the sensor will record 20 until the angle falls below 20. This will present itself on the curve as a flat top to the sine wave.

Use amplitude of  $< 10^\circ$ .

You may wish to apply a small amount of a light lubricant to the bearings before starting to prevent decay of the sine wave amplitude. The amplitude is not important in this exercise, but it can be confusing for the students if they see a large decay in the waveform. White spirit can be a good lubricant, it breaks down any oily lacquers that may have developed in storage and has enough oiliness to act as a lubricant.

### Using the RMS without the Pendulum accessory rod

If you do not have the accessory rod, a string can be attached to the RMS. See the diagrams below for details.

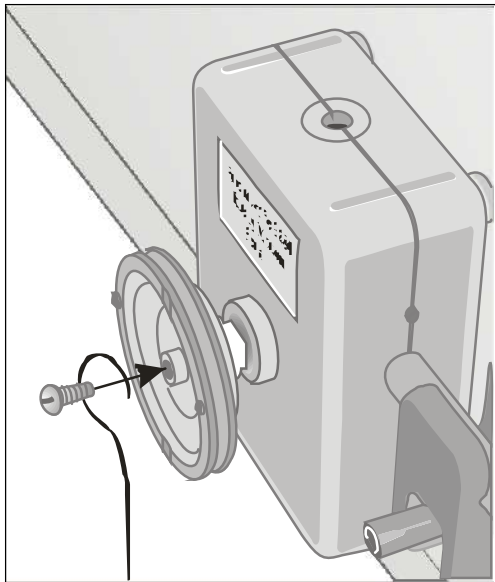


Fig 9.1 Attaching a wire pendulum to the Rotary Motion sensor.

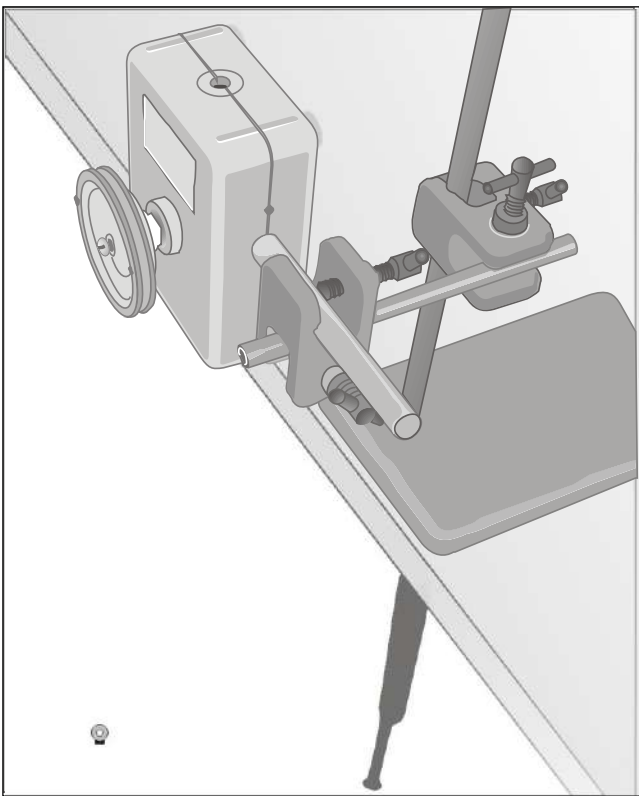


Fig 9.2 Assembled apparatus. Showing position of the sensor and support clamps

Results and analysis

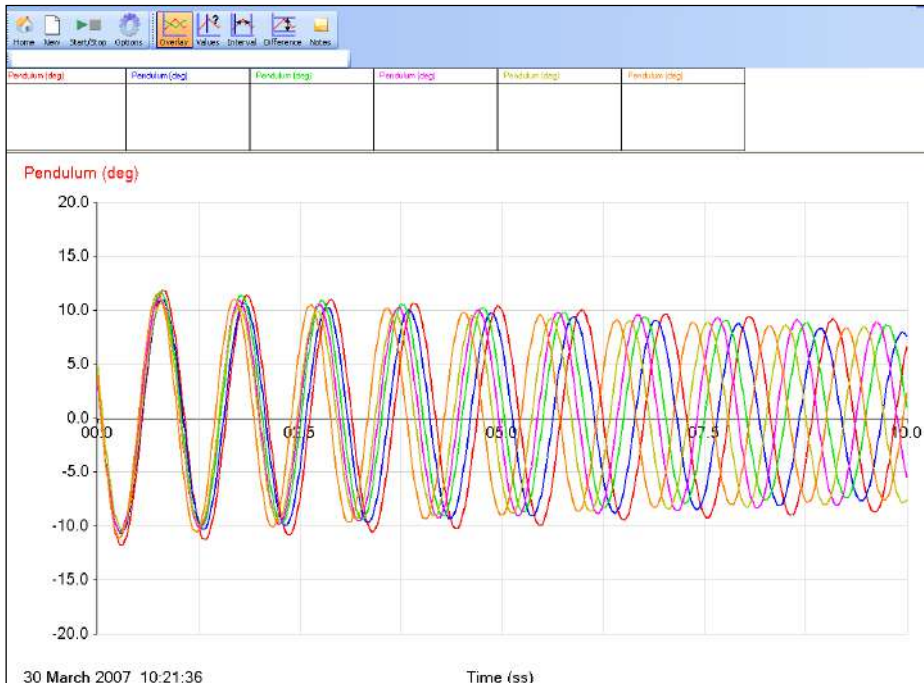


Fig 9.3 Data as collected, 6 different pendulum lengths



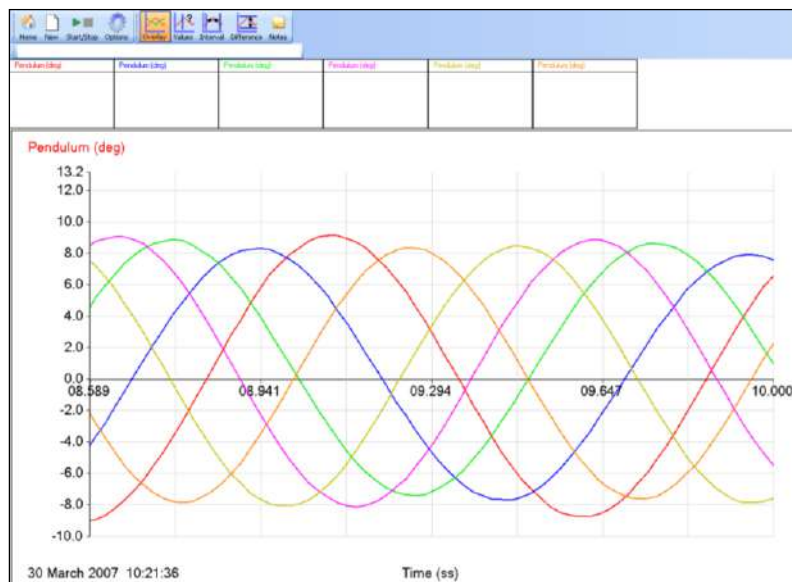


Fig 9.4 Area of the graph Zoomed in, the difference in periods is clearly shown

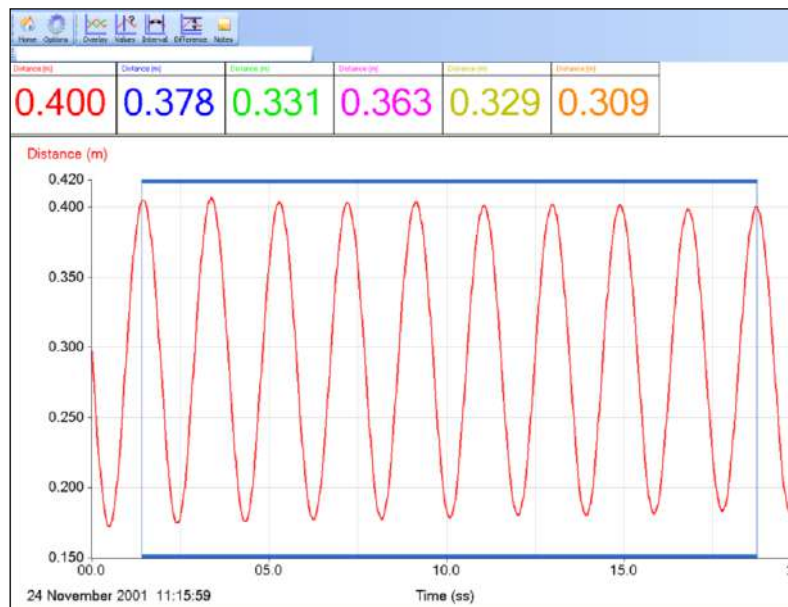


Fig 9.5 Show or Hide channels used to show only one set of oscillations. Interval being used to measure the time for 10 oscillations. 10 is used for convenience, data may mean other numbers have to be used.

Results T vs. L				
Length $l$ (m)	Time for 10 oscillations s	T s	Log $l$	Log T
0.918	19.20	1.920	-0.037	0.283
0.764	17.52	1.752	-0.117	0.244
0.617	15.70	1.570	-0.210	0.196
0.465	13.68	1.368	-0.333	0.136
0.317	11.13	1.130	-0.499	0.053
0.167	8.18	0.818	-0.777	-0.087

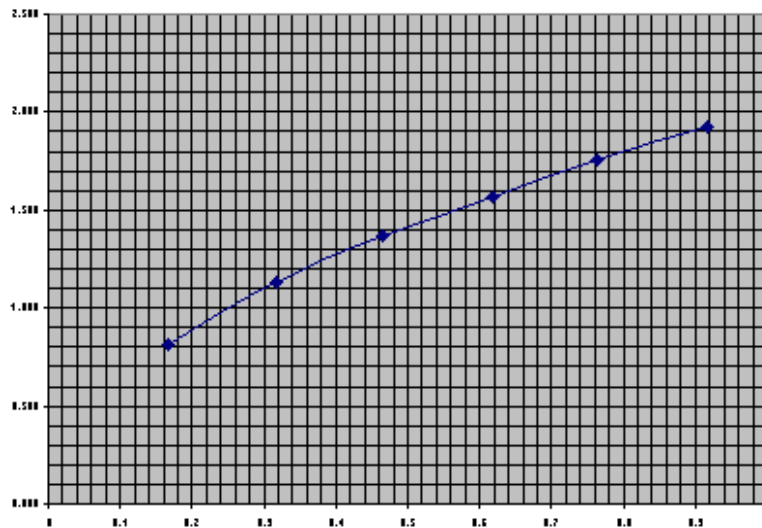


Fig 9.6 Spreadsheet plot of Period (T) vs. Length (L) of pendulum

Log T vs Log L

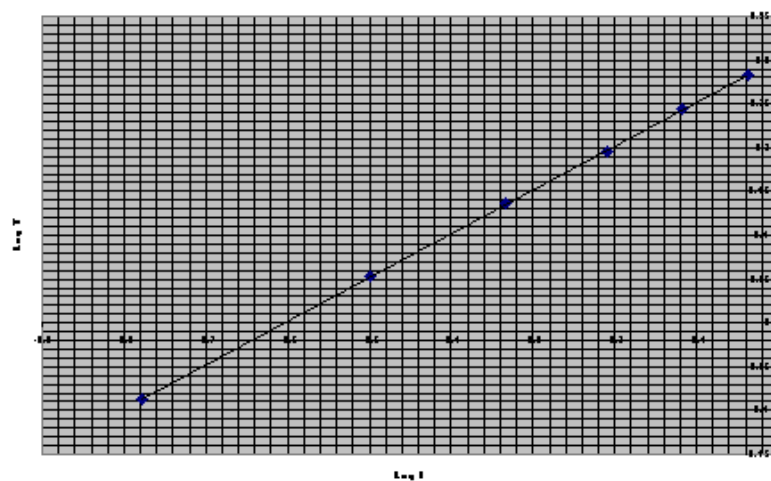


Fig 9.7 Spreadsheet plot of log period (logT) vs. log length (logL). The linear relationship is clearly seen.

Gradient = 0.497 within 0.6% of 0.5.

Intercept = 0.302 giving a value of  $g = 9.83$ **Checking the validity of the results**

Now,

$$k = \frac{2\pi}{\sqrt{g}}$$

Putting the values for pi and g into the equation,

$$k = \frac{6.3832}{\sqrt{9.81}}$$

= 2.006

The intercept of the graph = 0.302 = log k

The antilog of 0.302 (k) = **2.004**, which compares favourably with the mathematically derived value of **2.008**

## 9a. Relationship between period and length of the pendulum (using a Rotary Motion sensor)

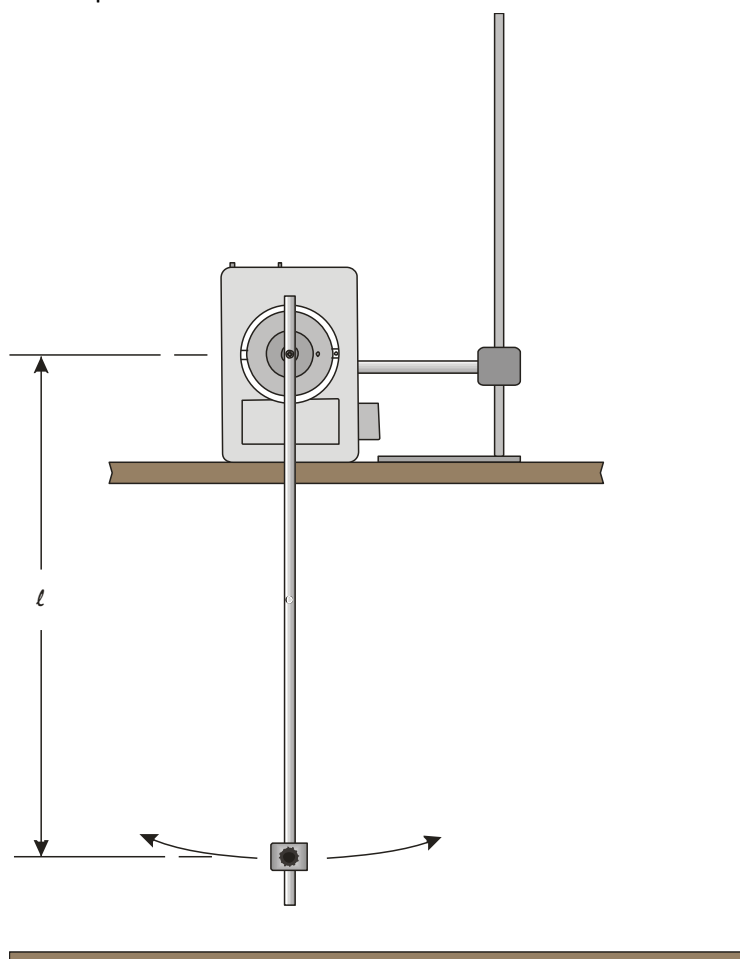
### Practical skills AT a, b, c, k

The pendulum was the controlling mechanism for the first accurate clocks. Until the pendulum properties were discovered we did not have clocks that could measure time with any precision. The pendulum period (time taken to move through one “swing”) is independent of its swing amplitude (the distance of the swing). How does its period vary as you change the length of the pendulum?

The **period** of a pendulum is the time it takes for it to complete one whole swing backwards and forwards.

### Apparatus

1. Rotary Motion sensor set to the pendulum range
2. Pendulum mass
3. Thin string or wire for pendulum or pendulum rod for the RMS
4. Retort stand and clamps



### Method

1. Assemble the apparatus as shown. Make sure that the pendulum can swing freely. You may wish to place a second stand next to the apparatus to make a marker for how far to bring the pendulum back before release.

2. Use a starting value for ' $l$ ' (the length of the pendulum) with the bob at the bottom of the pendulum rod. Measure  $l$  as the distance from the centre of the fixing screw on the Rotary Motion pulley to the centre of the bob mass. Write the value down in a results table.
3. Connect the Rotary Motion sensor to the data logger.
4. Set up to record:

Recording method	Recording time	Intersample time	Trigger level
Graph	20 seconds	20 ms	Pendulum falls below 5 degrees

5. With the pendulum at rest and hanging vertically, press the reset zero button on the RMS. Bring the pendulum arm back to give an amplitude\* of  $< 10^\circ$  for the pendulum swing.
6. Click on Start and release the pendulum.
7. You should get a smooth graph. If not, reposition the pendulum and try again. You can erase unwanted results by using Erase Data Sets (Edit menu).
8. Bring the pendulum back to its rest position and press the reset zero on the RMS.
9. Check Overlay is selected and repeat the experiment 5 more times varying the position of the pendulum bob on the pendulum arm by 1 cm each run. The trigger will ensure the graphs are synchronised (click on Start to collect the data for each length on the same graph).
10. Save your file. It is good practice to save the results after each successful run.

\*Amplitude is the height of the waveform from its lowest to its highest point. In this experiment it represents the furthest distance the bob has moved from the 'rest' position.

## Results and analysis

- The six sets of results will be displayed on the same graph. You can display the graphs singly or together by right clicking in the graph area and using Show or Hide Channels to select the data presented.
- Use Auto scale to obtain good sized graphs.
- Use Show or Hide Channels to select one of the curves. Use Interval to measure the time for 10 complete oscillations. Write down the result in a table (like the one below) in your report, or in Excel.
- Repeat for the other curves.
- Plot a graph of  $T$  versus  $l$ . This is easily done in a spreadsheet such as Excel, using a xy (scatter) chart. It will be a curve.

Length $l$ (m)	Time for 10 oscillations (s)	Time for one oscillation $T$ (s)

## Questions

What is the relationship shown, between period and length of pendulum, by the graph? Write down your answer as fully as possible.

## Advanced Theory

The relationship will be of the form:

$$T = k l^n$$

$k$  = constant

We can find 'n' (an unknown exponent) by using Log graphs.

Taking logs:

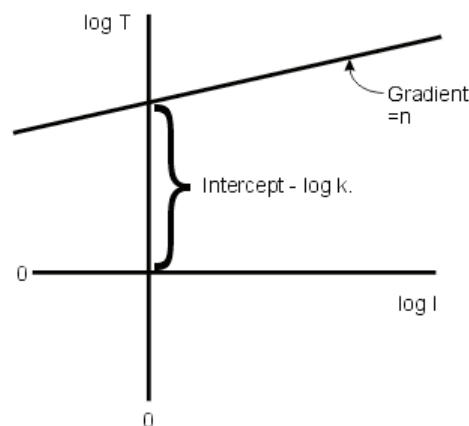
$$\begin{aligned}\log T &= \log(k l^n) \\ &= \log k + \log(l^n) \\ &= \log k + n \log l\end{aligned}$$

rearranging:

$$\log T = n \log l + \log k$$

$$(y = mx + c)$$

Therefore a graph of  $\log T$  versus  $\log l$  will give a straight line. The gradient will be 'n'. The intercept on the  $\log T$  axis is  $\log k$



## Further analysis

- Write down the logs to base 10 of  $T$  and  $l$  in a table like the one below.

Length $l$ (m)	Time for one oscillation $T$ (s)	$\log_{10} T$	$\log_{10} l$

2. Plot a graph of  $\log T$  versus  $\log l$
3. Draw the line of best fit and calculate its gradient. This is the value of 'n'.
4. Measure the intercept on the  $\log T$  axis; this is the value of  $\log k$ .
5. Write out the equation for the relationship putting in the values for 'n' and 'k' that you have determined.

## Teacher's notes

### 9b. Relationship between period and length of the pendulum (using a Light gate)

#### Practical skills AT a, b, c, d, k

The relationship between pendulum period and the length of the pendulum is for many counter intuitive. With a pendulum most people see the bob swinging more quickly as the period increases and therefore assume the time for the swing is getting faster.

The time taken for a number of swings can be measured, and the time for a single swing calculated. Problems arise with of the accuracy of the timer (both man and machine) and these become more exaggerated as the length of the pendulum becomes shorter. The errors can be enough to hide the relationship between period and length.

Using a Light gate with the EasySense software allows the student to show the period of the pendulum swing directly. There is no need for the student to record start and finish times. The accuracy of the results means that the relationship between period and length of pendulum can easily and quickly be investigated.

If it can be arranged, a demonstration of a really big pendulum is useful in setting the scene; a large ball suspended from string (rope) connected to the ceiling or in a stairwell makes a dramatic starting point.

#### Apparatus

1. Light gate
2. Pendulum mass
3. Thin string or wire for pendulum
4. Mass for pendulum bob
5. Split cork (or two pieces of wood)
6. Retort stand and clamps

#### Set up

Recording method	Recording	Recording what	Decimal places
Timing	Time	Period at A	2

#### Practical notes

Assemble the apparatus as shown. Make sure that the pendulum can swing freely.

You may find it easier to suspend the pendulum from a more traditional split cork clamped into a finger clamp. If you are using a Data Harvest Dynamics system the small bracket may have a small hole to attach a pendulum. If the hole is missing use a 2 mm drill to make a hole in the centre of the long arm of the bracket (i.e. 50 mm from the end). This will allow the pendulum to hang in the centre of the light gate.

Use a crocodile clip or similar to hold the pendulum string in position, adjust the length of the pendulum by shortening the string and using the clip to hold the string in place. Either lower the pendulum to swing

through the Light gate or raise the Light gate to the pendulum bob. The apparatus used will determine which method is most appropriate.

Use amplitude of  $< 10^\circ$ .

## Results and analysis

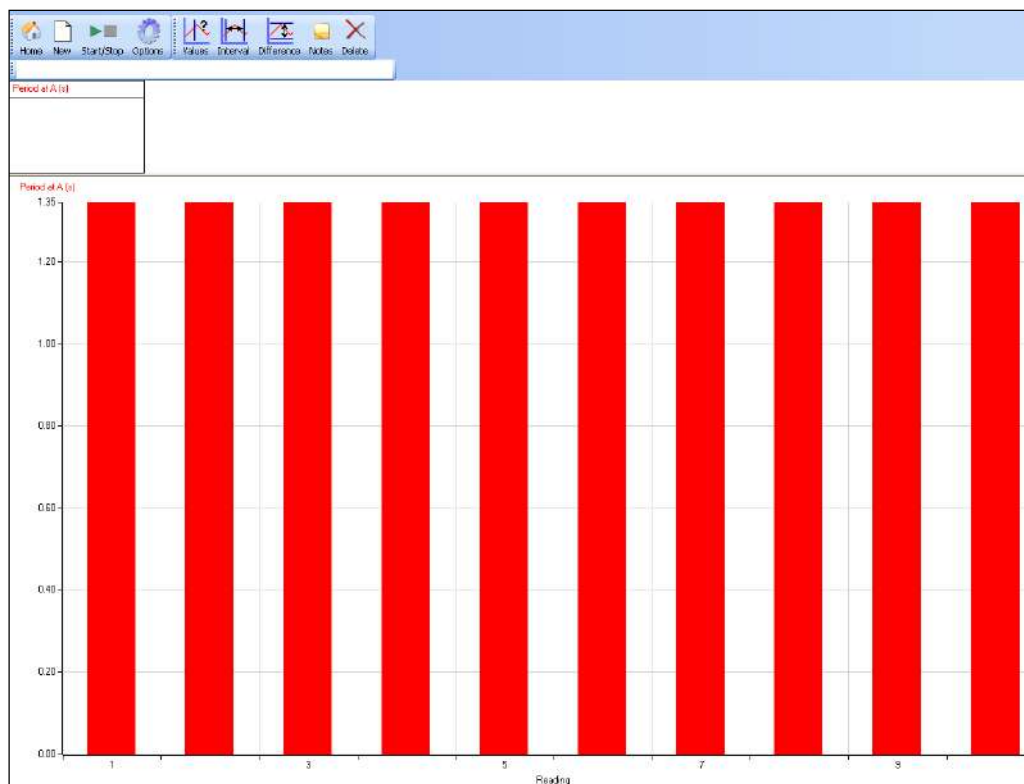


Fig 9.1 Data as collected, periodic time for 1 pendulum length, 10 repeats.

Results T vs. L			
Length L (m)	Average period T (s)	Log L	Log T
0.918	1.920	-0.037	0.283
0.764	1.752	-0.117	0.244
0.617	1.570	-0.210	0.196
0.465	1.368	-0.333	0.136
0.317	1.130	-0.499	0.053
0.167	0.818	-0.777	-0.087



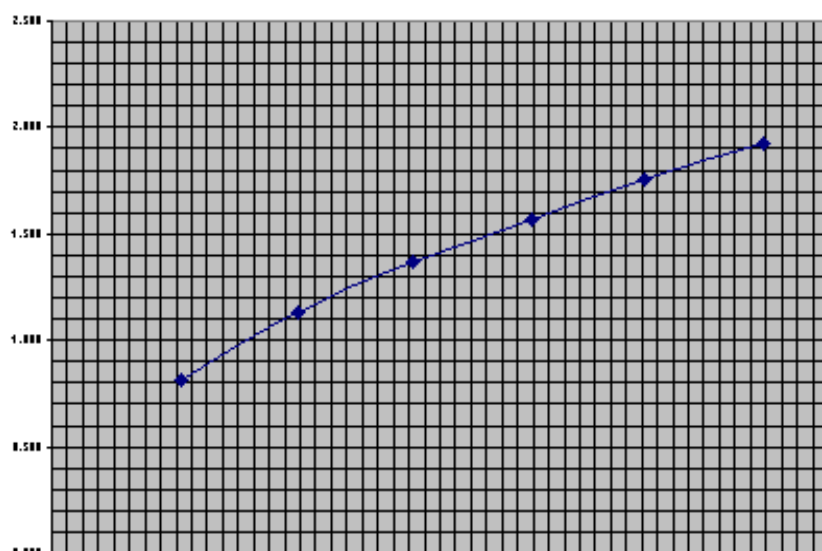


Fig 9.2 Spreadsheet plot of Period (T) vs. Length (L) of pendulum

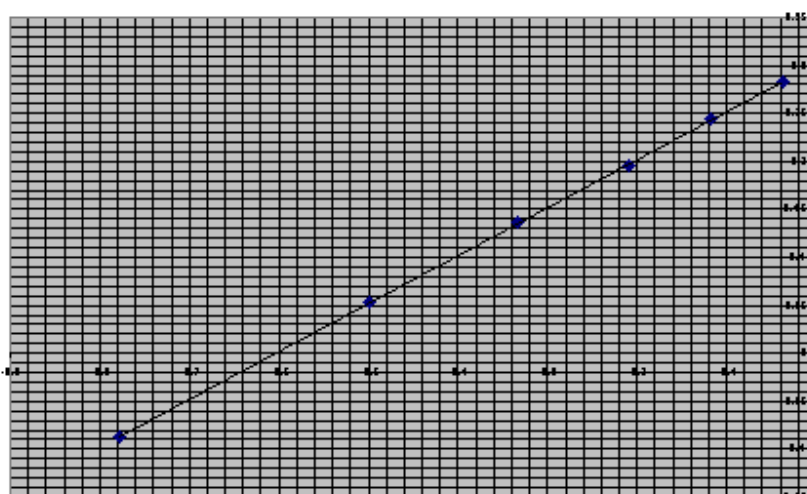


Fig 9.3 Spreadsheet plot of log period (logT) vs. log length (logL). The linear relationship is clearly seen.

**Gradient** = 0.497 within 0.6% of 0.5.

**Intercept** = 0.302 giving a value of  $g = 9.83$

**Checking the validity of the results**

$$k = \frac{2\pi}{\sqrt{g}}$$

Putting the values for  $\pi$  and  $g$  into the equation,

$$\begin{aligned} k &= \frac{2\pi}{\sqrt{9.81}} \\ &= 2.006 \end{aligned}$$

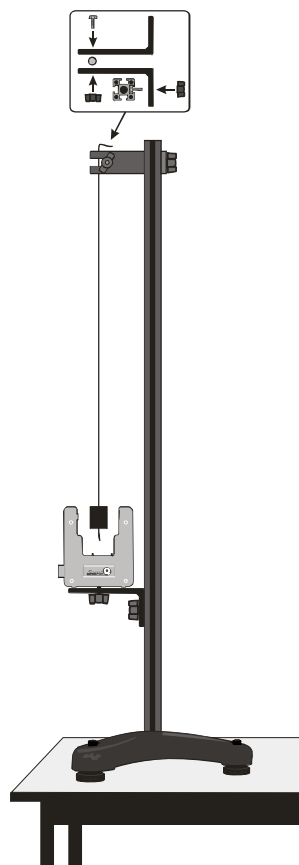
The intercept of the graph = 0.302 =  $\log k$

The antilog of 0.302 ( $k$ ) = **2.004**, which compares favourably with the mathematically derived value of **2.006**.

## 9b. Relationship between period and length of the pendulum (using a Light gate)

### Practical skills AT a, b, c, d, k

The pendulum was the controlling mechanism for the first accurate clocks. Until the pendulum properties were discovered we did not have clocks that could measure time with any precision. How is the pendulum period (time taken to move through one “swing”) dependent on amplitude (the distance of the swing). How does its period vary as you change the length of the pendulum?



### Apparatus

1. Light gate
2. Pendulum mass
3. Thin string or wire for pendulum
4. Split cork (or two pieces of wood)
5. Retort stand and clamps

### Method

1. Assemble the apparatus as shown. Connect the Light gate to the input labelled **A** on the data logger.
2. When the pendulum is at rest, the top of the bob should be level with the top of the Light gate arms. The bob should be in the centre (side to side) of the arms of the Light gate. You can use the moulding marks on the Light gate to help you align the bob.

3. Make sure that the pendulum can swing freely and moves between the arms of the Light gate.
4. Use a starting value for 'L' (the length of the pendulum) of about 0.9 m. Measure the length from where the string leaves the top clamp to the centre of the pendulum bob. Write the value down in a results table.
5. Set up to record

Recording method	Recording	Recording what	Decimal places
Timing	Time	Period at A	2

6. Move the pendulum back and release it, you should have swing (amplitude\*) of about 10 degrees or less.
7. After a few swings, click on Start.
8. Collect 10 period measurements and click on Stop.
9. Select Show Statistics (Analysis menu) and find the average period time for the 10 measurements
10. Repeat the experiment 5 more times varying the length of the pendulum by 2 cm each run.

\*Amplitude is the height of the waveform from its lowest to its highest point. In this experiment, it represents the furthest distance the bob has moved from the 'rest' position.

## Results and analysis

Plot a graph of **T** versus **L**. This is easily done in a spreadsheet such as Excel, using a xy (scatter) chart. It will be a curve.

Length L (m)	Average period Time T (s)

## Questions

1. What is the relationship shown, between period and length of pendulum, by the graph? Write down your answer as fully as possible.
2. How much did the period vary for a set length of pendulum? Try collecting the data for a long time, how much does it vary then?
3. What happens to the pendulum over time?
4. When you see a clock using a pendulum what is the clock work doing? What makes a pendulum clock accurate?

## Advanced Theory

The relationship will be of the form:

$$T = kL^n$$

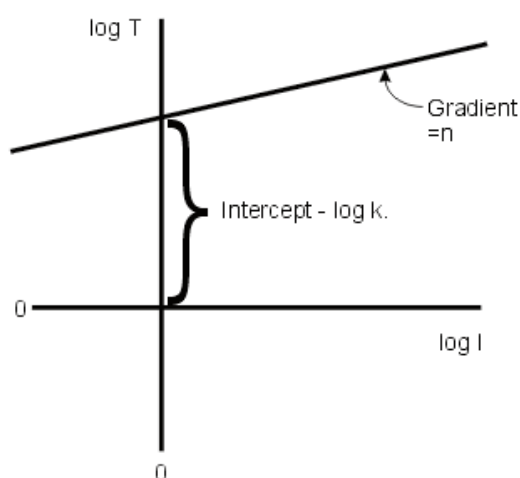
$k = \text{constant}$

We can find 'n' by using Log graphs.

Taking logs:

$$\log T = \log k + n \log L$$

Therefore a graph of  $\log T$  versus  $\log L$  will give a straight line. The gradient will be 'n'. The intercept on the  $\log T$  axis is  $\log k$ .



## Further analysis

1. Write down the logs to base 10 of T and L, in a table like the one below.

Length L (m)	Time for one oscillation T (s)	$\log_{10} T$	$\log_{10} L$

2. Plot a graph of  $\log T$  versus  $\log L$ .
3. Draw the line of best fit and calculate its gradient. This is the value of 'n'.
4. Measure the intercept on the  $\log T$  axis, this is the value of  $\log k$ .
5. Write out the equation for the relationship putting in the values for 'n' and 'k' that you have determined.

## Teacher's notes

### 10. Determination of 'g' via a plot of $2h/t$ vs. $t$ (using two Light gates)

#### Practical skill AT a, b, c, d, k

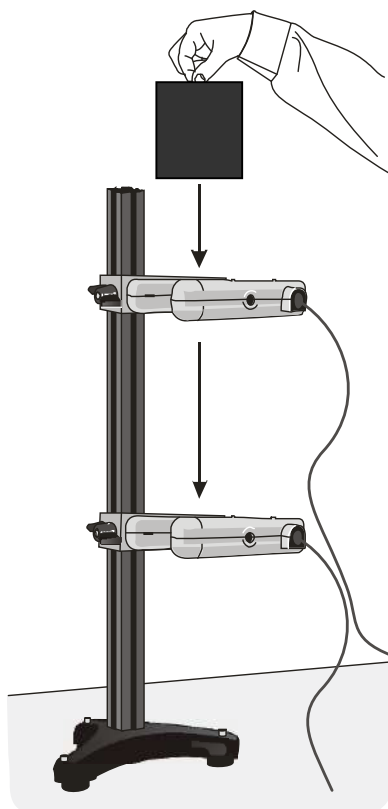
Nuffield sciences introduced the dropping a ball bearing to determine  $g$  to a wider audience. It is a testament to its design that the same basic practical keeps re-appearing. This variation of the practical uses two Light gates and a hand released object, removing the need for electromagnets and power supplies.

The assembly of the basic apparatus can be used for interrupt cards, picket fences, ball bearings or exercise books. The most important part of the apparatus is to get everything in line both vertically and horizontally.

The extension to this practical includes advice on how to modify the apparatus to work with the 2015 specification guidance on practical skills practical determination of " $g$ " by a free fall" (using ball bearings).

#### Apparatus

1. 2 Light gates
2. A single interrupt card or small ball (e.g. golf ball)
3. Ruler (with mm divisions)
4. Retort stand (marked with equal divisions) and clamps
5. 2 axis spirit level (option)
6. Large steel ball bearing, suggest 20 mm
7. Plumb line
8. Catch box filled with something to slow catch the falling ball e.g. soft dry sand, crumple cloth, etc.



## Set up

Use the following information in Timing to set up the logger to record the data as time from A to B (used for determination via a plot of  $2h/t$  vs.  $t$ ).

Recording method	Measure time	Apparatus	Decimals	Units
Timing	Time from A to B	Single interrupt card	0.0000*	s

Note: The number of decimals is set by default to 3. The number of decimals shown for each section can be set independently. After collecting results, click on Settings, Change Units and select the section you wish to alter. The number of decimals is indicated by zeroes.

The single interrupt card is the option for any object passing through the Light gates that only has two edges e.g. a card, exercise book, ball, etc.

## Practical notes

Assemble the apparatus as shown in the diagram. Position the Light gate connected to input A as the higher of the two Light gates, and the Light gate connected to input B at the lower of the two Light gates. Start with the Light gates separated by 10 cm, experience will show if this needs to be modified to match the apparatus you have available.

The key to collecting successful data is in getting the apparatus “vertical”. Use as 2 axis spirit level or better a plumb bob to align the apparatus. Alignment of the apparatus is critical, in the spirit of the key skills, this is a very exacting test of understanding of the relationship between the apparatus, results and final understanding. Minutes spent here will give significantly superior results.

The measured acceleration from A to B will be displayed on the screen (it should be approximately  $10 \text{ ms}^{-2}$ ). Repeat the experiment a few more times. Encourage the students to note and delete any obviously obscure readings and calculate the average measurement, check that they understand the reason for deletion.

A large ball bearing (20mm diameter) works well, a golf ball will also work well if the apparatus is correctly aligned.

You may need to spend a little time explaining how we determine if any difference is significant. The experiment suggests 5 drops; this should provide an upper and a lower limit for errors. The magic 3 repeats may not be valid here – 3 is often chosen as it is the smallest number of samples to get a decent average, it is not always the best number of repeats. If the apparatus has a “natural” or systematic error within it, you should do more repeats to reduce this error to a low value. 3 repeats assume a certainty in collecting the data that may not be present. It is also a good idea to determine the number of repeats before the investigation starts and to make sure they are done and you don’t simply stop when you get the “correct” answer!

The repeatability of the drop reveals the systematic error from the imprecise position of the edge cutting the light beam and setting the timer going.

When using Light gates all timing is accomplished by the cutting of the light path within the Light gates. The top gate starts timing, the lower gate stops timing. There is no latency in the activation of the timing function, the Data Harvest Light gates have a 4  $\mu\text{s}$  delay from the edge cutting the beam and timing starting / finishing.

The choice of which apparatus and method to use will hinge on the full expectations of the practical, is it:

1. To show how  $g$  can be determined.
2. To create confidence in equipment by familiarity of use.
3. To create the back ground for an investigation of errors
4. To show how elements of formulae in use can be moved around and substituted to provide the answer.

The ball bearing practical, as sponsored by Nuffield has an equal bias to the calculations and the understanding of errors and limitations of the practical.

### Sample data

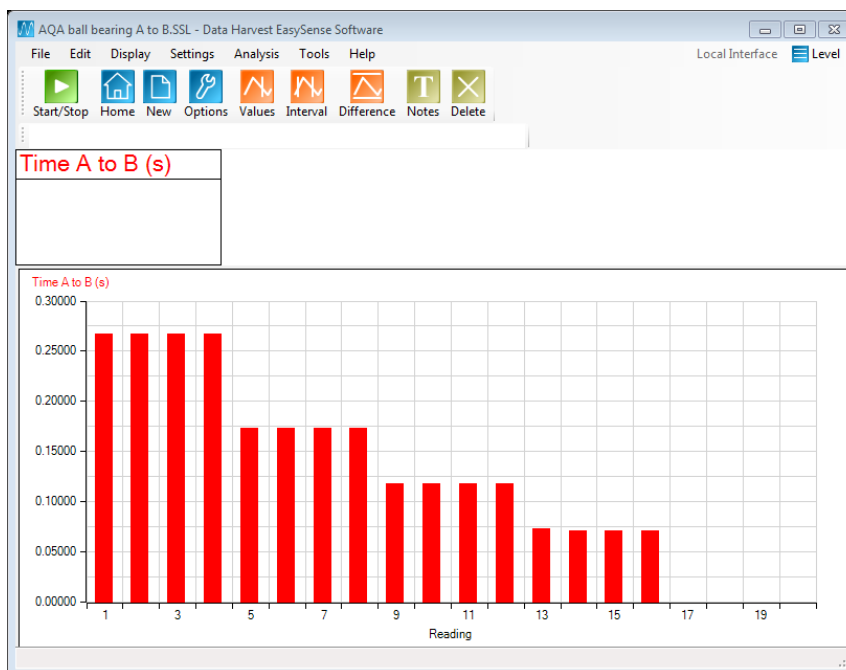


Fig 10.1 Data collected from drop of 20 mm steel ball

### Calculation of $g$ by free fall:

The value for  $g$  is calculated from

$$s = \frac{1}{2}at^2$$

By a simple substitution of  $g$  for  $a$  and  $s$  for  $h$  we arrive at

$$h = \frac{1}{2}gt^2$$

By rearranging

- $h = ut + \frac{1}{2}gt^2$
- $2h \div t = gt + 2u$  (this is in the form of  $y = mx+c$ )

The gradient of the slope ( $m$ ) is gravity

The  $y$  intercept is  $2u$ .

**Additional note:**

Dependent on the apparatus used the graph line may not pass through the origin. This implies that there is a time of fall even when the ball falls no distance. This is obviously not true and must therefore represent a systematic error.

The gradient gives a good estimation of  $g$ , so we are looking at an “offset” in the data. Students should be challenged as to why this error appears. The most plausible explanation is that (in the traditional method) the timing is started by the loss of power to the electromagnet, there is a time for loss of magnetism and before the ball falls, not surprisingly this is a constant and shifts the data.

With timing cards and Light gates to trigger timing events this error will diminish. An alternative apparatus would quickly show this. It also explains why a minimum distance between Light gates is recommended in the current exam board sponsored practical. If timing is measured by Light gates and free fall is achieved almost immediately then the need for a minimum separation is questionable – room for another investigation?

**Understanding and analysis of the results**

The data should give a determination very close to the accepted value. There will be some skill in the best fit, but be aware of the individual who fits the line to the right answer! It could be worth testing how well the human eye determines the best fit compared to a best fit in excel, which would you consider correct? Or trust!

This experiment provides an opportunity to discuss experimental design and how it can be used to reduce or eliminate errors. The experiment contains systematic errors:

1. The path of the ball through the light beam.
2. The latency in the cutting of the light beam

The time latency should be negligible, the response of the Light gate is in the order of 4  $\mu$ s. The flight path of the ball in free fall can result in the “cutting edge” of the ball in the light being advanced or retarded. The reduction of these errors is an important aspect of this practical and a comparison of this method of measuring  $g$  to direct measurement of  $g$  by velocities at A and B and alternative methods should be considered.

1. Can the systematic error be quantified?
2. If so can the error be reduced in significance by, for example, increasing the fall time?
3. Consider the point when  $h$  is infinite, or at least very large. The value of  $t$  will also become very large, so the error in it will be small or negligible.

Consequently large values of  $h$  will give more accurate values of  $g$ . In the results table, add a column for  $2h/t^2$ ; the values should approach an accurate value for  $g$ . Plot a graph of  $2h$  against  $t^2$  as before.

1. Does this plot give a curve or a straight line?
2. If it is curve does this determine where the value of  $g$  is calculated?



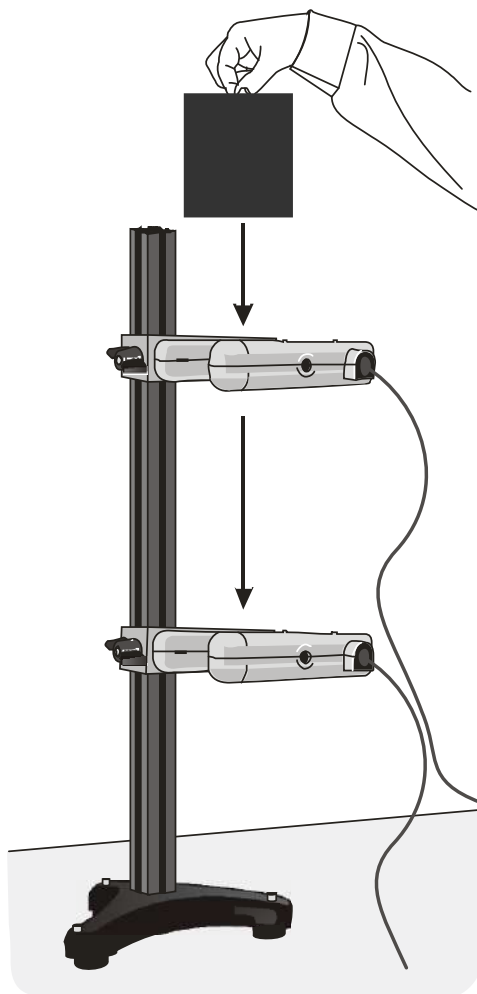
## 10. Determination of 'g' via a plot of $2h/t$ vs. $t$ (using two Light gates)

### Practical skill AT a, b, c, d, k

This practical is about determining the value of  $g$  by free fall. Free fall is motion of a body where weight is the only force acting upon it.

The practical as illustrated uses a timing card and two Light gates.

The light path is narrow and the ball must pass through both Light gates evenly, use of plumb lines and spirit levels to get an accurate drop will be required.



### Apparatus

1. 2 Light gates
2. A single interrupt card or small ball (e.g. golf ball)
3. Ruler (with mm divisions)
4. Retort stand (marked with equal divisions) and clamps
5. 2 axis spirit level (option)
6. Large steel ball bearing, suggest 20 mm
7. Plumb line
8. Catch box filled with something to slow catch the falling ball e.g. soft dry sand, crumpled cloth, etc.

## Method

1. Set up the apparatus to have the Light gates one above the other. Use a plumb line to get them vertically and horizontally in line.
2. Have the Light gates vertically 50 cm apart from each other. This will be the first position.
3. Position the catching box to stop the card/ball from hitting the bench and rolling away.
4. Connect the Light gates to the data logger, checking the leads go into the correct ports for a) timing, b) order of start stop.
5. The ball will drop through the centre of the light beam of the Light gates when released.
6. Set up to record time A to B, refer to set up table below.

Recording method	Measure	Apparatus	Decimals	Units
Timing	Time from A to B	Single interrupt card	0.0000	s

7. Start data collection.
8. Hold the card/ball above the top Light gate then release.
9. Repeat, check for consistency, modify apparatus layout if necessary.
10. Restart the logger / software and discard any data.
11. Collect data for 50, 40, 30, 20, 10 cm of Light gate separation. Record / save results after each run or set of runs.
12. Transfer the data to a table (or excel) and calculate data  $2h/t$ .
13. Plot graph of  $2h/t$  against  $t$ .
14. Draw the best fit line through points and find the gradient ( the graph should be a straight line with the intercept on the y axis of  $2u$ )

### Calculation of g by free fall:

The value for g is calculated from

$$s = 1 \div 2at^2$$

By a simple substitution of g for a and s for h we arrive at

$$h = 1 \div 2 gt^2$$

By rearranging

- $h = ut = gt^2 \div 2$
- $2h \div t = gt + 2u$  (this is in the form of  $y = mx+c$ )

The gradient of the slope (m) is g in  $\text{ms}^{-2}$

The y intercept is  $2u$ .

## Teacher's notes

### 11. Acceleration due to gravity – by free fall (using a falling ball)

#### With analysis of energy changes and conservation of energy (extension)

#### Practical skills AT a, b, k

Movement takes place when forces are unbalanced. In this investigation a ball is dropped and the motion of its descent and first bounce are studied. If a heavy ball is used then in effect the only force acting upon it is gravity. There will be some marginal effect due to air resistance. The speed it falls should show uniform increase as the force pulling it down to the ground is gravity, which is constant.

A bounce of the ball is used for analysis as it includes a clearly defined up and down portion of the balls movement.

At the end of the exercise students will have,

1. Measured the velocity of a falling object
2. Measured  $g$
3. Found that acceleration on a bouncing ball is the same when the ball is going up and down
4. Extend analysis of data to visualise energy changes

#### Apparatus

1. Motion sensor with the range set to distance (metres).
2. A large, bouncy ball. A basketball was used for the sample data.
3. A retort stand, boss and clamp.
4. A G clamp or counterweight for the stand.

#### Set up

Recording method	Recording time	Intersample time	Trigger level
Graph	10 seconds	20 ms	Distance sensor rises above 0.5 m

#### Practical notes

The ball needs to have a reasonable weight to it and a good “bounce”. A beach ball will not be suitable.

The ball needs to fall vertically beneath the Motion sensor to collect the best results for analysis. A small period of practice is needed before collecting the “final” data.

The Motion sensor has an upper limit to the sample frequency, if the sensor is not heard to emit a series of clicks check the intersample time is not set at less than 20 ms.

A hard surface for the ball to bounce on is required. You may need to provide a piece of wood (or similar) for the ball to bounce.

It may take a couple of attempts to get a good set of data. Common errors are not moving hands away, moving hands through the Motion sensors beam when it is recording and the ball hitting a 'bump' as it bounces and moving off in a different direction.

## Results and analysis

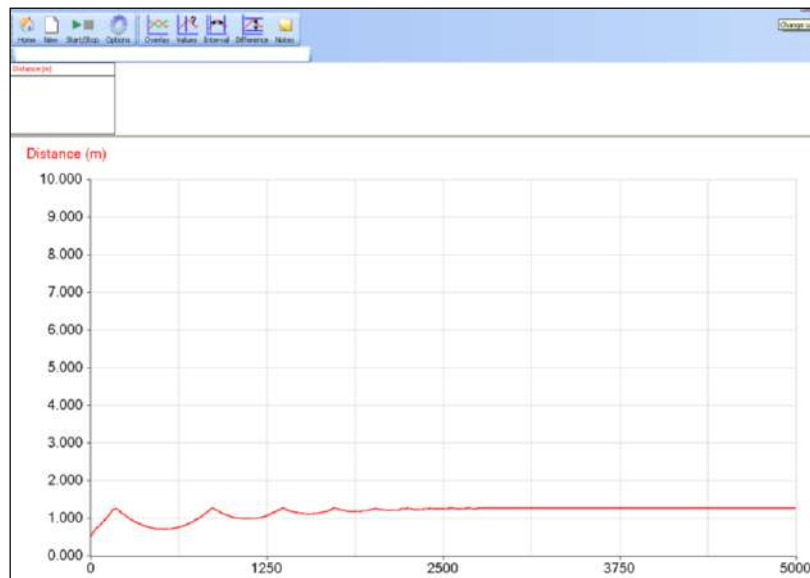


Fig 11.1 Raw data from the experiment. Showing several bounces

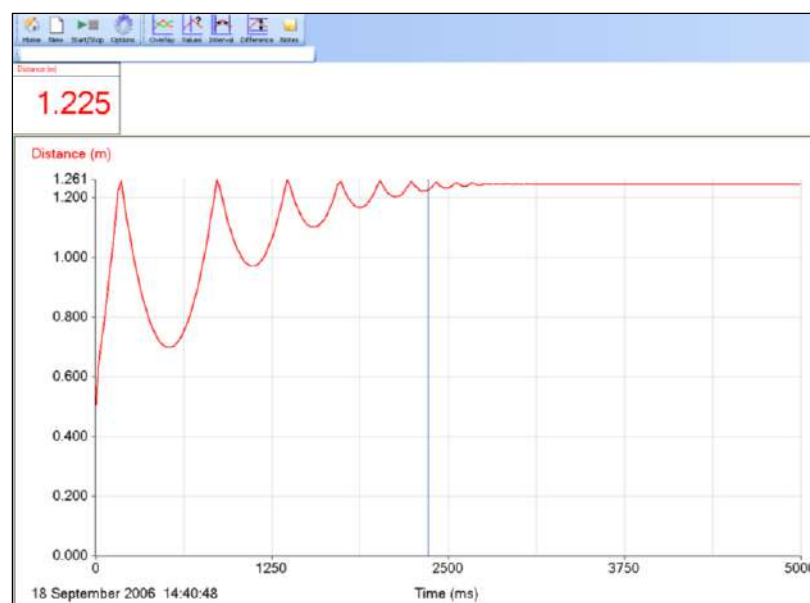


Fig 11.2 Auto scale used to make the bounces clearer

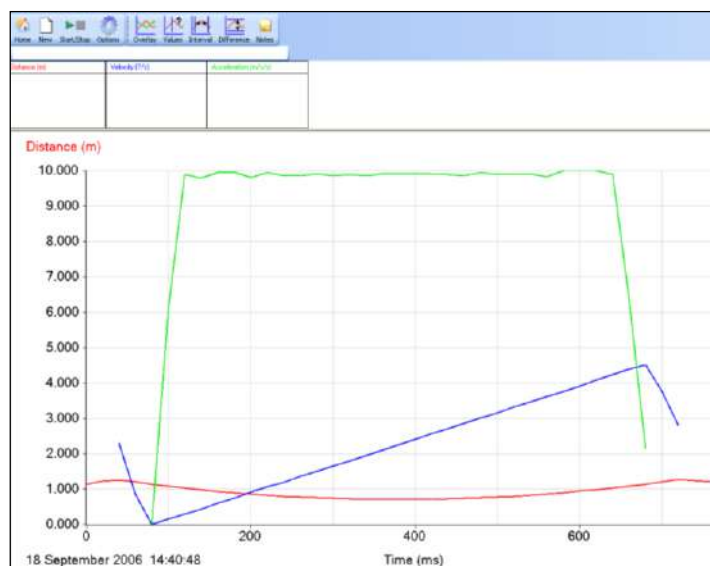


Fig 11.3 Velocity and acceleration derived from the raw data. Use Selection (Edit menu) has been used to isolate a small area of data for analysis.

**Note:** The software calculates the gradient of a graph by taking a chord across 5 data points on the curve. This causes a 'turning point' to be displaced 0.06 s either side of the original turning point. Thus the acceleration graph has 0.12 s displacement at each end of the uniform section, shortening it by 0.12 s.

### Measurement of $g$

Range of values is from  $g = 10.03$  to  $9.53$ , a reasonable estimate of the mean would therefore be  $g = 9.8 \pm 0.3$

An error of 3% is certainly an acceptable error in this experiment.

### Extension. Analysis of the data to show energy changes

The following graphs were obtained using a PVC football with a mass 0.696 kg. For the analysis a single bounce from the original data needs to be selected.

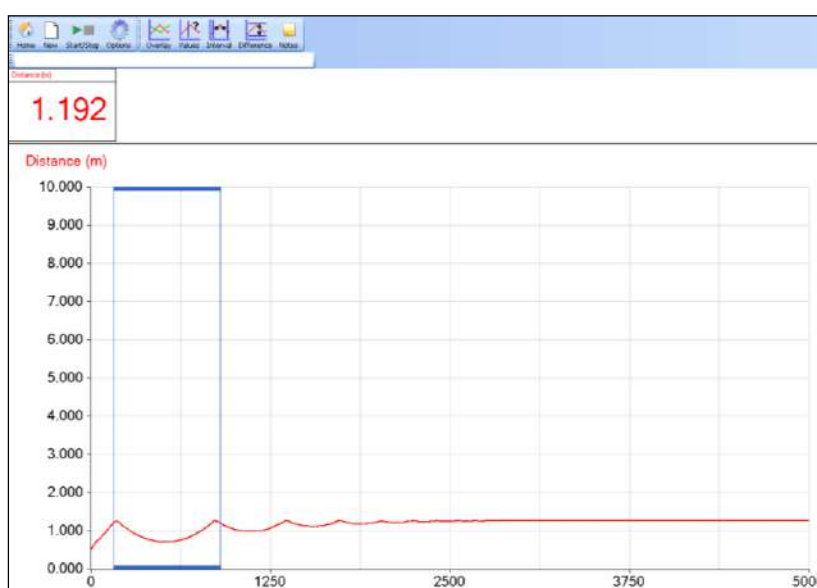


Fig 11.4 A single bounce being selected

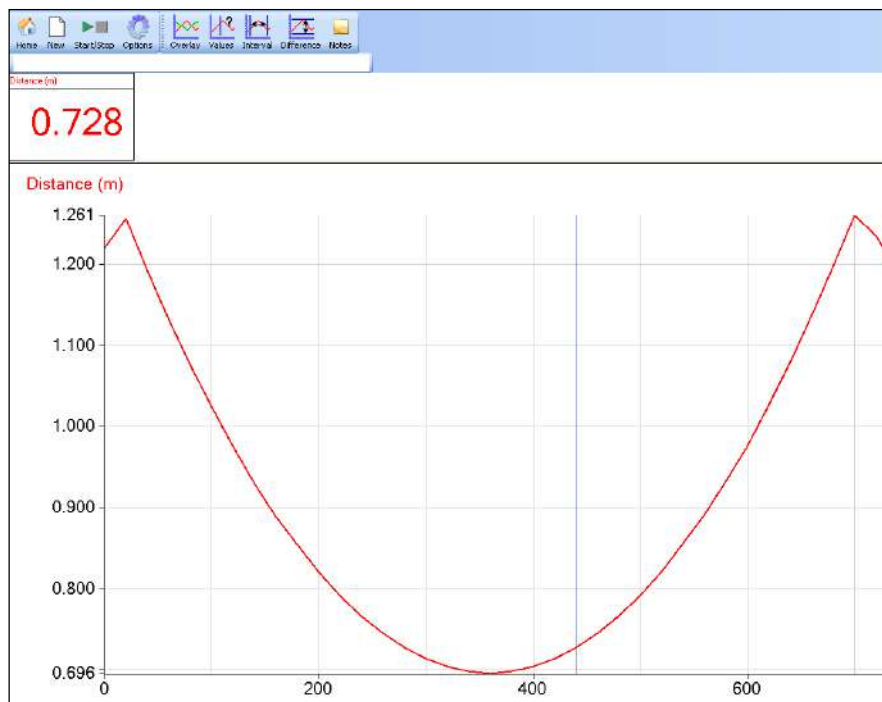


Fig 11.5 A single bounce

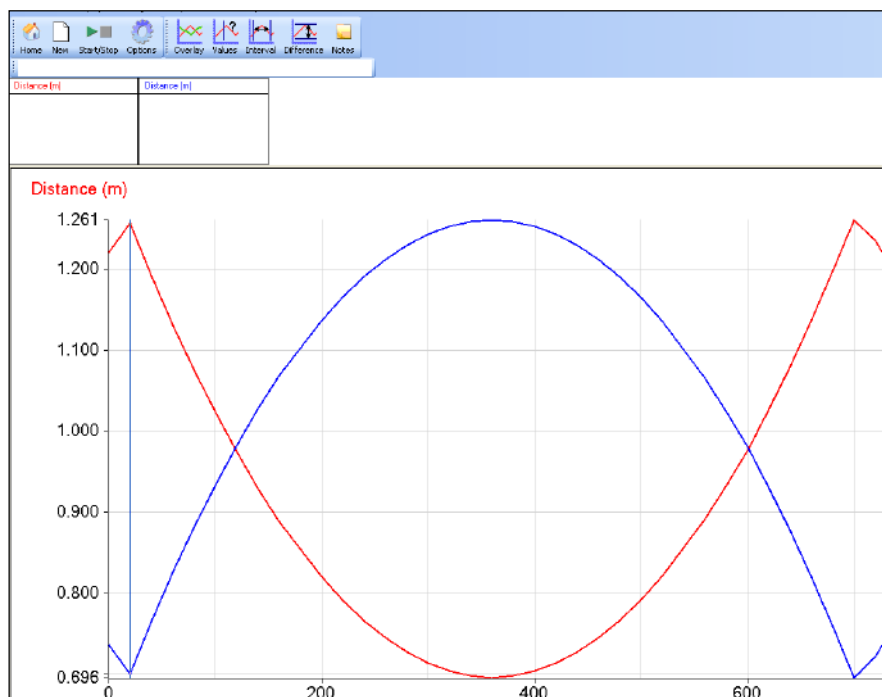


Fig11.6 The data corrected to show distance from floor, using the  $ax^2 + bx + c$  post-log function.  $a = 0$ ,  $b = -1$  (turns the data round)  $c$  = height value at the beginning of the bounce.

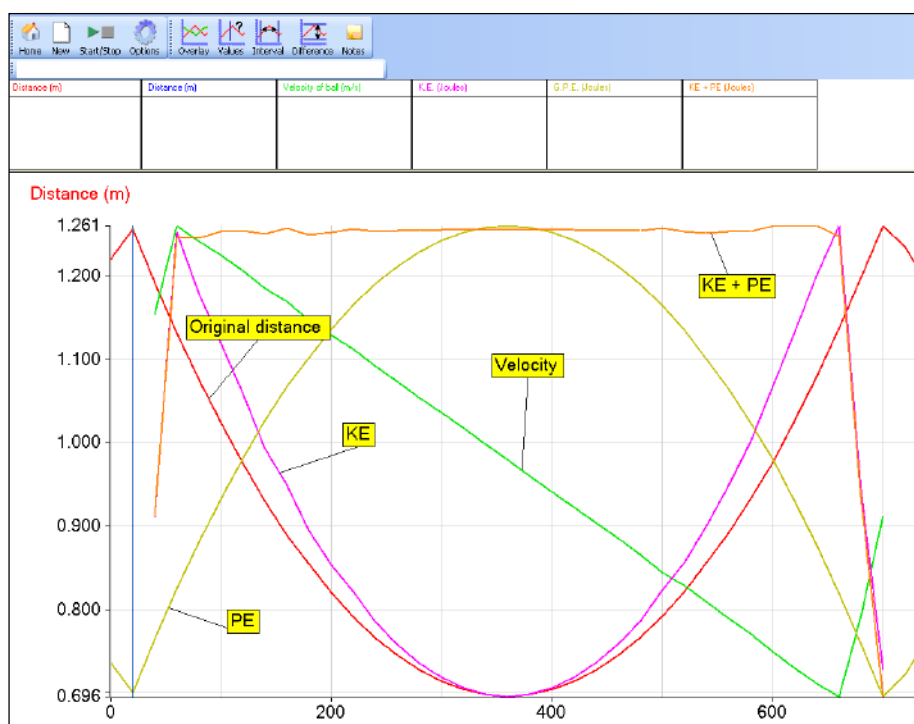


Fig 11.7 The data fully analysed and presented on one graph.

Values obtained from Fig 11.7

Distance from floor (m)	Grav Pot energy, $PE_g$ (J)	Kin Energy, $E_k$ (J)	$PE_g + E_k$ (J)
0.560	3.824	0	3.824
0.489	3.342	0.473	3.815
0.324	2.213	1.595	3.815
0.119	0.810	2.963	3.773

To complete the analysis you need to:

1. Convert the data from showing distance from sensor to distance from floor. To do this use the function  $ax^2 + bx + c$ , where  $a = 0$ ,  $b = -1$  (turns the data round)  $c$  = is the maximum reading of the distance at the beginning of the bounce. The ball is then in contact with the floor.
2. Generate a time velocity graph. Use the Post-log function Motion > Velocity. Select the displacement data as the source data.
3. Generate a kinetic energy graph. Use the Post-log function Energy > Kinetic energy. Enter the mass of the ball in kg, select velocity as the source data.
4. Generate a potential energy graph. Use the Post-log function Energy > Gravitational potential energy (GPE). Select distance dropped as distance data. Enter the mass of the ball in kg.
5. Generate a total energy graph. Use the Post-log function Add 2 channels together. Make the first channel the kinetic energy data and make the second channel the Potential energy channel. Name this new data Total energy.

At the end you may need to select Autoscale to bring all the data to best size to visualise.

## 11. Acceleration due to gravity – by free fall (using a falling ball)

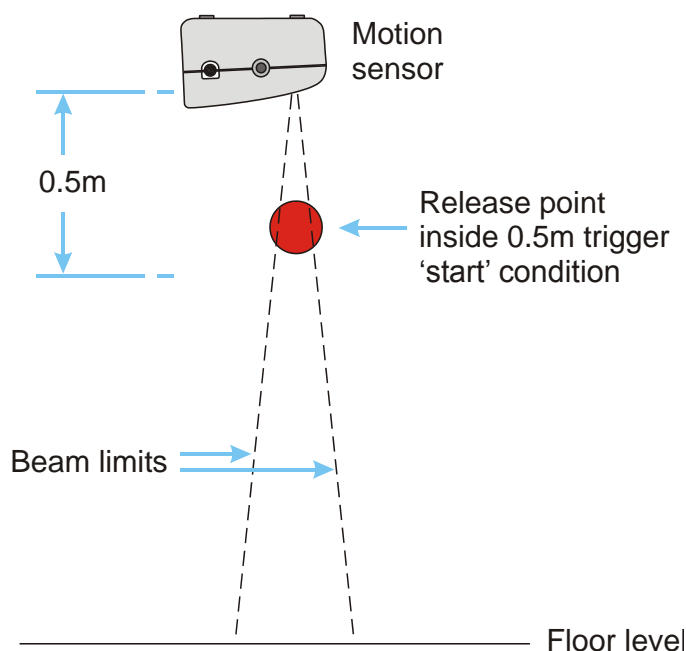
### With analysis of energy changes and conservation of energy (extension)

#### Practical skills AT a, b, k

When you throw a ball vertically upwards, or when it bounces upwards from the ground it will slow down to a stop and then begin to fall. You are going to study how the velocity changes during its motion up and down, and then use this information to measure the acceleration due to gravity. As an extension you can analyse the energy changes and conservation of energy in a single bounce.

To help control the variability in throwing a ball it will be dropped and allowed to bounce.

1. Think about the changes in motion as the ball goes up and down in a single bounce. Write down how you think the following will change during the ball's motion.
  - a. Distance from the start.
  - b. Velocity of the ball.
  - c. Acceleration of the ball.
2. Draw sketch graphs of the Distance vs. Time (s-t), Velocity vs. Time (v-t) and Acceleration vs. Time (v-t) graphs that you would expect to obtain.



### Apparatus

1. Motion sensor with the range set to distance (metres)
2. A large, bouncy ball e.g. a basketball (for extension, mass known in kg)
3. A retort stand, boss and clamp
4. A G clamp or counterweight for the stand
5. Scales



## Method

1. Assemble the apparatus as shown in the diagram. Ensure that there is, at least, 1.5 to 2 meters vertically below the Motion sensor and that the sensor beam is aligned vertically.
2. Measure the mass of the ball.
3. Have a few trial drops to practice. The ball has to stay within the  $12^\circ$  angle of the beam.
4. Set up to record:

Recording method	Recording time	Intersample time	Trigger level
Graph	10 seconds	20 ms	Distance rises above 0.5 m

5. Using Test Mode (Tools menu), check that the Motion sensor will detect the ball during the whole of its' motion.
6. Click on the Start icon to begin logging.
7. Hold the ball close to the sensor and drop it. The logging is triggered at 0.5 m from the sensor. Make sure you move your hands quickly out of the way of the Motion sensor beam after you release the ball.
8. Check the curve to see that it displays a smoothly changing distance, repeat if necessary.
9. Repeat the investigation two or three times (make sure Overlay is selected if you want to record all the results on one graph).

You should get a graph that looks something like the one below. Note how the Motion sensor uses its range to create the axis, this has the effect of making the bounces look small. To make a quick check of the data use Auto scale to maximise the graph trace.

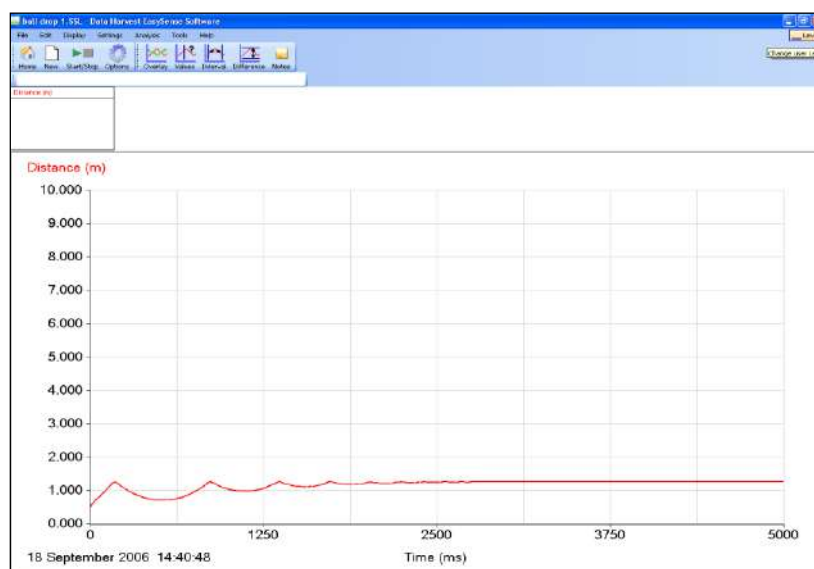


Fig 11.1 The data as collected, showing multiple bounces.

## Results and analysis

Mass of the ball = ..... kg

Each graph is a Distance vs. Time (s-t) graph for the motion, the analysis needs to proceed as follows: -

1. Generate Velocity vs. Time (**v-t**), and Acceleration vs. Time (**a-t**) graphs from the data.
2. Compare the shape of the **s-t**, **v-t**, and **a-t** graphs with your predictions.

3. Measure the acceleration from the graph.

Save the data before starting the detailed analysis.

Select the **first bounce** for more detailed analysis. Click on Edit and select Use Selection. The area you have selected will become the only data on the screen. The first bounce will give a longer time of free fall than the fall from the sensor after you let go of the ball. You can save only this data if you wish before starting the analysis.

### Generation of v-t and a-t graphs

It will be necessary to apply some smoothing to the **v-t** graph before differentiating it.

#### To generate the velocity – time curve from the distance – time curve

1. From the Tools menu select Post-log Function.
2. Select Preset function: Motion, Velocity
3. Source data to be used = Distance.
4. Decimal places = 3
5. Name = Velocity
6. Units = m/s.
7. Click on Finish. Use Smoothing (Tools menu) if necessary.

#### To generate the acceleration – time curve from the distance – time curve

1. From the Tools menu select Post-log Function.
2. Select Preset function: Motion, Acceleration as the second derivative of distance
3. Source data to be used = Distance.
4. Decimal places = 3
5. Name = Acceleration
6. Units = m/s/s.
7. Click on Finish. Use Smoothing (Tools menu) if necessary.

You may need to select an area of the graph to work to remove confusion. The analysis can create a lot of data.

After the analysis you should have a graph that will look something like the one shown below.

Compare each of your graphs with your predictions and describe how each of the quantities '**s**', '**v**', and '**a**' vary with time over the time of one bounce. In particular, is the acceleration constant within experimental error?

### Measurement of 'g'

Using Values in the flat section of the a - t graph, get a range of values for g that indicates the range and the mean value for g. Calculate a mean.

$$g = \dots\dots\dots \text{ m/s}^2$$

Repeat for the other sets of data you have obtained and calculate an overall mean for your results

From the range of values you have obtained estimate the confidence limits in the value for g as measured here.

## Questions

Use the value for acceleration due to gravity  $g = 9.81 \text{ m/s/s}$  in the following questions.

1. A ball is dropped from rest. What is its velocity at the following times: -
  - a. 3 s
  - b. 9 s
  - c. 0.5 s
2. Use the equation  $s = \frac{1}{2}gt^2$  to calculate how far an object falls (when dropped from rest) and fill in the following table, and draw an  $s - t$  graph. You could do this quickly by using an Excel spreadsheet. (note,  $s = ut + \frac{1}{2}at^2$  in this instance,  $u = 0$  and  $a = g$ , hence  $s = \frac{1}{2}gt^2$ )

Time (s)	Distance (m)
0	
2	
4	
6	
8	
10	

3. Maurice Greene's world record for the 100 m was 9.79 s. The average velocity for this race was therefore 10.21 m/s. How far could the sprinter jump upwards if he could launch himself with a vertical velocity of 10.21 m/s?

## Extension

1. Use different balls to see whether the mass and or diameter of the ball have an effect on the value of  $g$  calculated.
2. Use the software to analyse the single bounce data for kinetic, potential and total energy. To complete the analysis you need to:
  - Convert the data from showing distance from sensor to distance from floor. To do this use the Post-log function  $ax^2 + bx + c$ , where  $a = 0$ ,  $b = -1$  (turns the data round)  $c$  = is the maximum reading of the distance at the beginning of the bounce. The ball is then in contact with the floor.
  - Generate a time velocity graph. Use the Post-log function Motion > Velocity. Select the displacement data as the source data.
  - Generate a kinetic energy graph. Use the Post-log function Energy > Kinetic energy. Enter the mass of the ball in kg, select velocity as the source data.
  - Generate a potential energy graph. Use the Post-log function Energy > Gravitational potential energy (GPE). Select distance dropped as distance data. Enter the mass of the ball in kg.
  - Generate a total energy graph. Use Post-log function Add 2 channels together. Make the first channel the kinetic energy data and make the second channel the Potential energy channel. Name this new data Total energy.

At the end you may need to select Autoscale to bring all the data to best size to visualise.

## Teacher's notes

### 12. Time constant for a capacitor - resistor circuit

Practical skills AT a, b, c, f, g, k

#### Theory

The charging and discharging of a capacitor are exponential changes. The following equations represent the way in which the voltage across the capacitor changes during the charge and discharge cycle. The time constant of a resistor - capacitor circuit is a measure of the length of time needed to charge a capacitor to within a percentage of its final maximum value.

$$\text{Discharging } V = V_{\max} e^{-t/CR}$$

$$\text{Charging } V = V_{\max}(1 - e^{-t/CR})$$

The time constant "T" is derived from these equations:

$$T = C \times R$$

Considering the charging cycle, when the time  $t = T = C \times R$ , then the equation becomes:

$$V = V_{\max} e^{-1}$$

$$\therefore V = \frac{V_{\max}}{e}$$

$$e = 2.718$$

$$\therefore V = \frac{V_{\max}}{2.718}$$

$$\therefore V = V_{\max} \times 0.368$$

The time constant T, for charging, is the time taken for the voltage across the capacitor to fall to 0.368 of its maximum value  $V_{\max}$

Conversely, for discharging, the time constant T is the time taken for the voltage to reach 0.632 of the maximum value  $V_{\max}$

When the capacitor is used in timing circuits it will be arranged so that the switching occurs on the steeply rising or steeply falling part of the curve, i.e. somewhere around the time constant.

#### Set up

Use **EasyLog**, this gives the students the visual feedback of the electrical event being studied, while the data is being logged.

#### Apparatus

1. Voltage sensor  $\pm 12$  or 20 V, or 0 - 10 V.
2. Electric circuit kit (Worcester, Snap circuits or Locktronics type) or breadboard.

3. Capacitors and resistors, a 1000  $\mu\text{F}$  capacitor and a 1 k $\Omega$  resistor, are recommended.
4. SPDT switch.
5. d.c. power supply, dry cells in good condition work well. Refer to notes below for fuller advice.
6. Connecting wires and crocodile clips.

A capacitor takes 4 to 8 times the time constant to approach full charge. 30 seconds gives a reasonable time to get two full charge discharge cycles for a time constant of about 1 second.

### Component values and calculated time constants

Capacitance, C ( $\mu\text{F}$ )	Resistance, R ( $\Omega$ )	Time constant, T (s)
10,000	100	1.0
4,700	220	1.03
1,000	1,000	1.0
470	2,200	1.03
330	3,300	1.09
220	4,700	1.03

### Warning

The potential electrical hazards posed by capacitors must be assessed bearing mind both the operating potential (V) and capacity (C), from which the stored energy (E), can be calculated using the relationship  $E = \frac{1}{2} CV^2$ . These precautions may not be required at voltages below 50 V a.c. or 120 V d.c. The discharge of 0.25 J of stored energy to the human body can provide a heavy shock and 10 J can be fatal. Capacitors of hazardous capacity should be individually kept short-circuited with an appropriate resistor during storage.

Care should be taken to avoid the danger of burns from high value capacitors. It is worthwhile calculating the potential energy stored on capacitors being used at the voltages suggested for use in the practical

### Practical notes

#### Alternate circuits

The advantage of using the single resistor is that the resistance during charge and discharge is identical. Any tolerance errors in the resistance are therefore cancelled out. The circuit with 2 resistors, however, may be more easily understood by students.

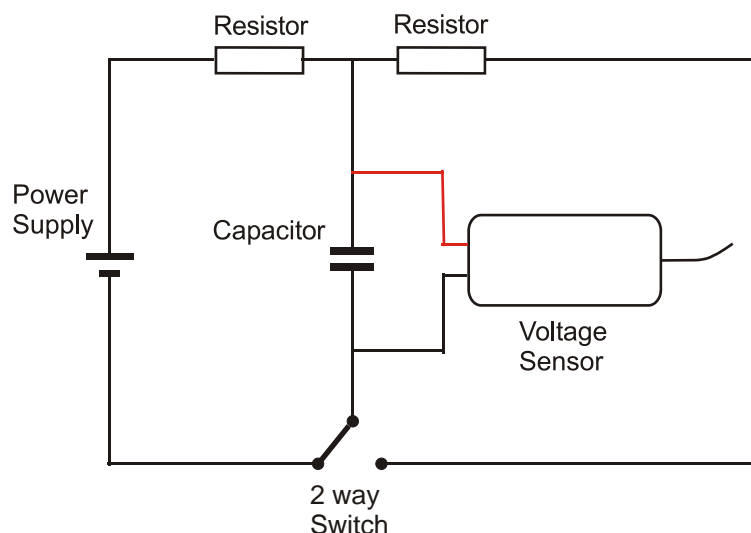
**Using 2 resistors**

Fig 12.1 Circuit with separate charge and discharge resistors

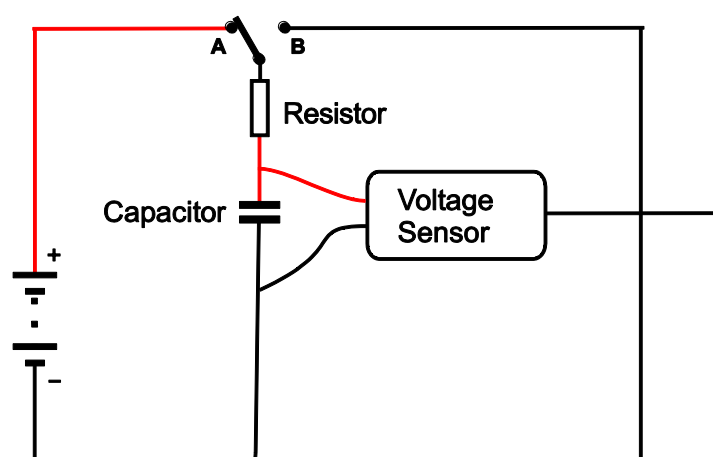
**Using a single resistor**

Fig 12.2 Circuit with a single common charge and discharge resistor

It is important the polarity of electrolytic capacitors is maintained. They are normally marked, but it may be useful to make the polarity more obvious by attaching red / black fly leads.

For power, use dry cells in good condition. Mains power supplies often have a large ripple voltage which will upset results and may cause electrolytic capacitors to overheat. The currents used are very low, and dry cells arranged to give 3 - 9 volts will be adequate for a supply. GCSE circuit kits often provide cell holders that can be used in these experiments. It has also been noticed when testing this work that some power supplies sold as d.c. are in fact unsmoothed half wave rectified a.c, these do not give a true enough d.c voltage for this work.

The Voltage sensors have an internal resistance of 1 Meg ohm. If the load of resistors in the circuit is small compared to this internal resistance then any errors will be very small. It is advised that resistors of less than 10 k $\Omega$  are used to keep errors within 1%. Below is a table showing how the load resistor is linked to errors.

Load resistor $\Omega$	Error in V%
1 k	0.1
10 k	1
100 k	10
1 M	50

The switch used was a two throw On - On switch (SPDT) which allowed quick switching of the circuit, it also reduces the chance of the log picking up the “bounce” that can be feature of some switches. This is when the spring in the contacts can make the contacts bounce back and remake a connection for a very short time, normally you will not notice this but with fast logging you will see an “unusual” voltage spike / dip.

If you do not have a switch you can run a lead from the common line that leads to the capacitor. By linking this to either A or B you can charge and discharge the capacitor. Note that with some combinations the capacitor will start to discharge as the lead is moved. See the sample data set.

An investigation using a 1000  $\mu\text{F}$  capacitor and 100  $\Omega$  resistor with a 9 V power supply gives a time constant of about 1.0 s. This gives enough time for the student to see the charging - discharging profile in real time. A total time span of 30 s for collection of data enables the collection of two complete cycles.

It is possible to make up a small circuit on Vero board using “compression connectors” to allow the students to easily change the components. Provision for the 4 mm connectors the Voltage and Current sensors would make sense.

## Sample results

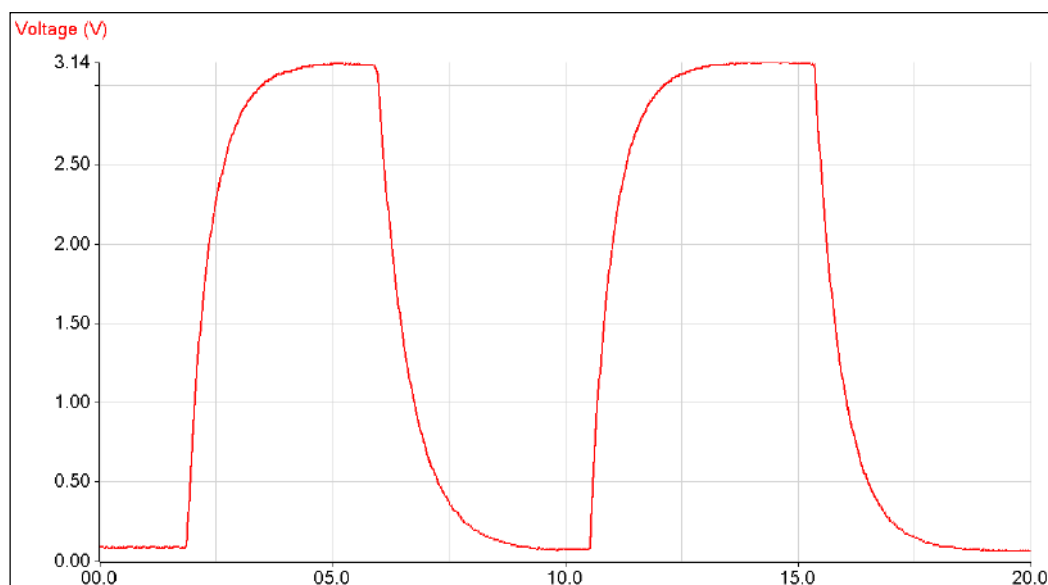


Fig 12.3 Typical result using a 470  $\mu\text{F}$  capacitor and 1 K resistor, using 2 x AAA cells to charge the capacitor

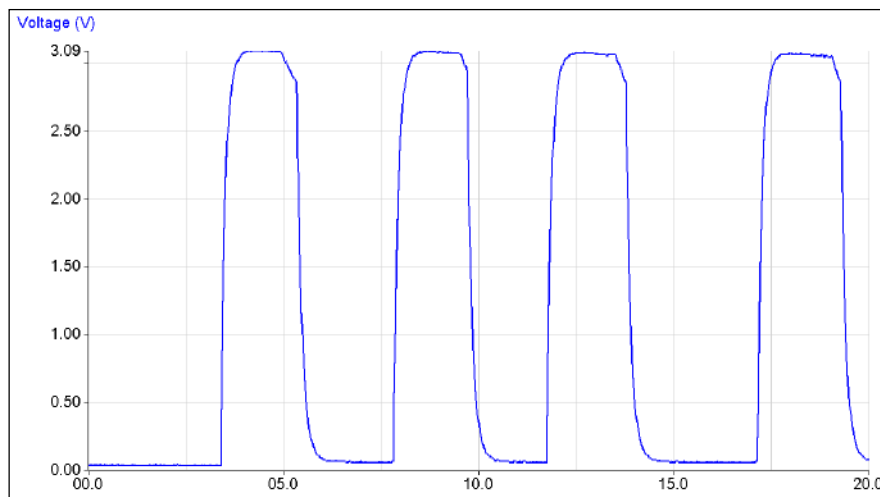


Fig 12.4 Data using a 100  $\mu\text{F}$  capacitor and 1 K resistor. Note how the discharge is taking place before the “short” wire has been connected.

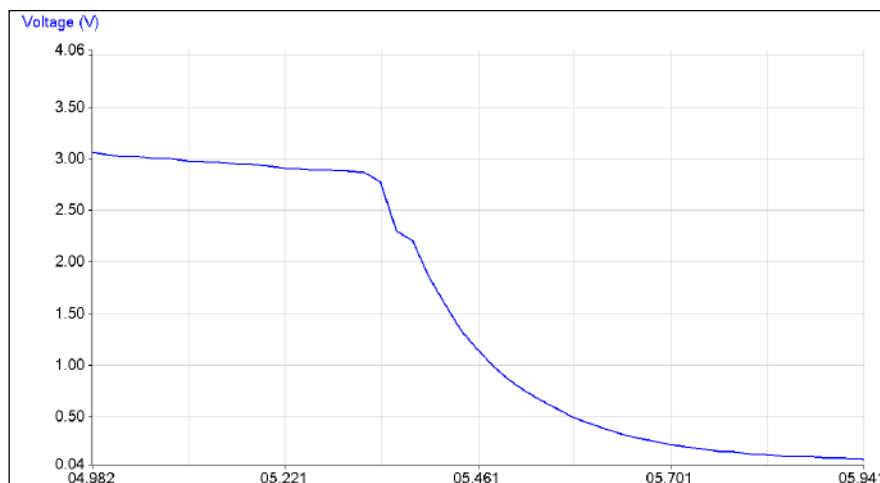


Fig 12.5 Detail of the loss of charge before the “short” wire is connected. This will lead to false time constants, in cases like this a 2 way switch becomes an essential if accurate results are required.

## Extension

### Investigate the effects of (a) resistance (b) capacitance, on the time constant $T$

Data can be collected using the faster logging available with some loggers. The time span selected needs to be long enough to capture the whole trace. The results will be better defined, but the investigator will be “blind” during the data capture if the intersample time is less than 20 ms. A good progression would be to use real time and then move onto fast capture when questions about errors arise.

A typical fast set up would be

1. 20 sec recording time.
2. 10 ms interval between samples.
3. Therefore 2000 samples will be collected
4. **Trigger** when Voltage reaches 0.1 volts (this may need to be changed if there is noise).
5. 25% Pre trigger.
6. Overlay mode



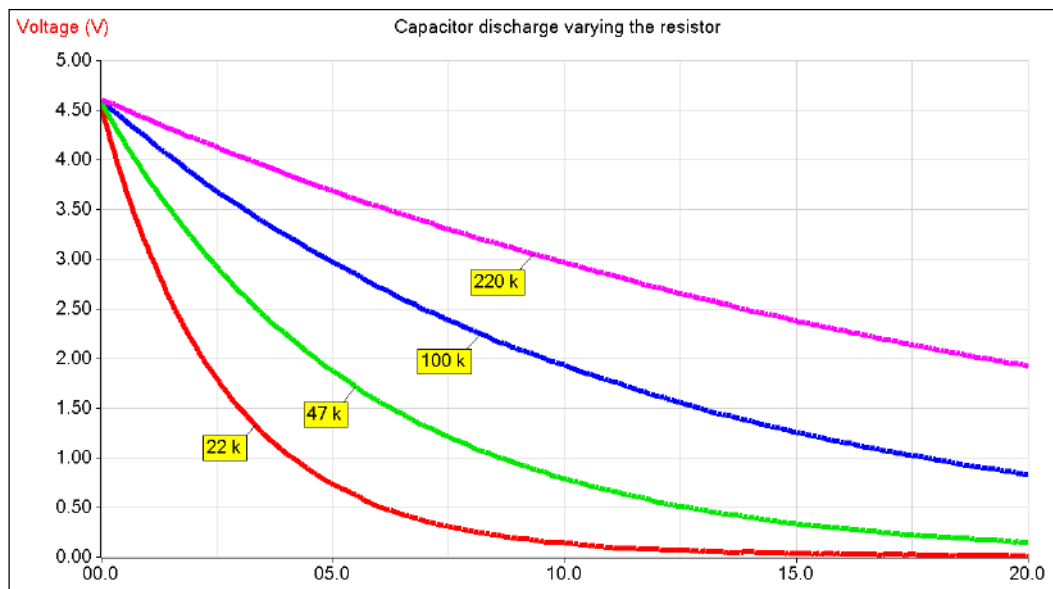


Fig 12.6 Discharge curves of a  $470\ \mu\text{F}$  capacitor with different resistances. 3 x AAA cells used as the power supply.

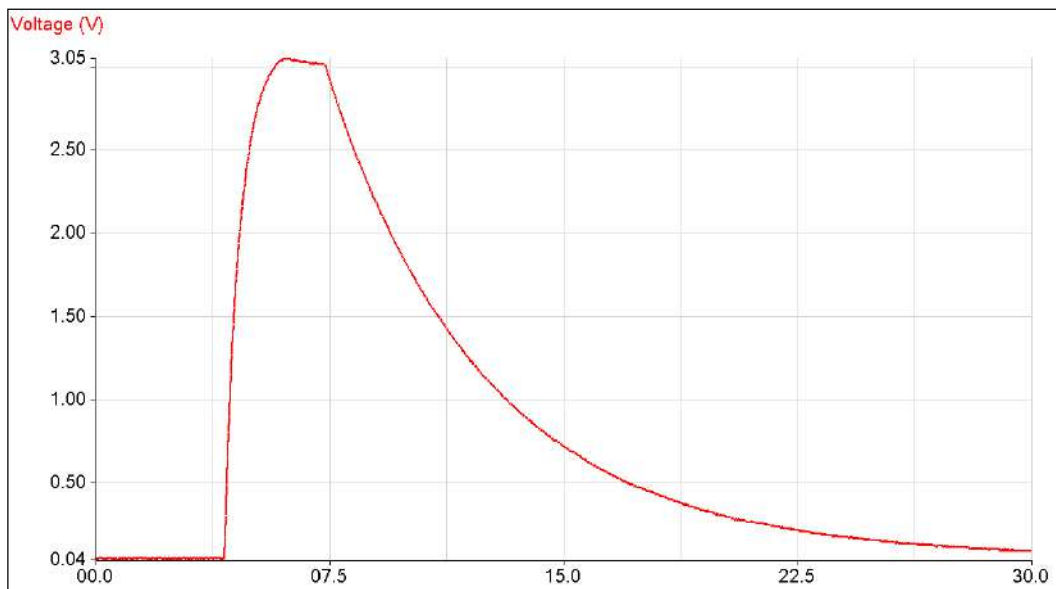


Fig 12.7 Capacitor  $470\ \mu\text{F}$  charge 1 K discharge 10 K resistor.

### Log linear plot to find time constant

In the new key practical skills assessment the “investigation of the charge and discharge of capacitors” requires the log-linear plotting of the data to prove the exponential nature of the charge / discharge curve.

This can be achieved with the EasySense software via the functions.

1. Select out and use a single discharge of the cycle.



Fig 12.8 A single discharge cycle selected

2. Use the function **a loge(bx) + c**. a=1. b=1 and c=0

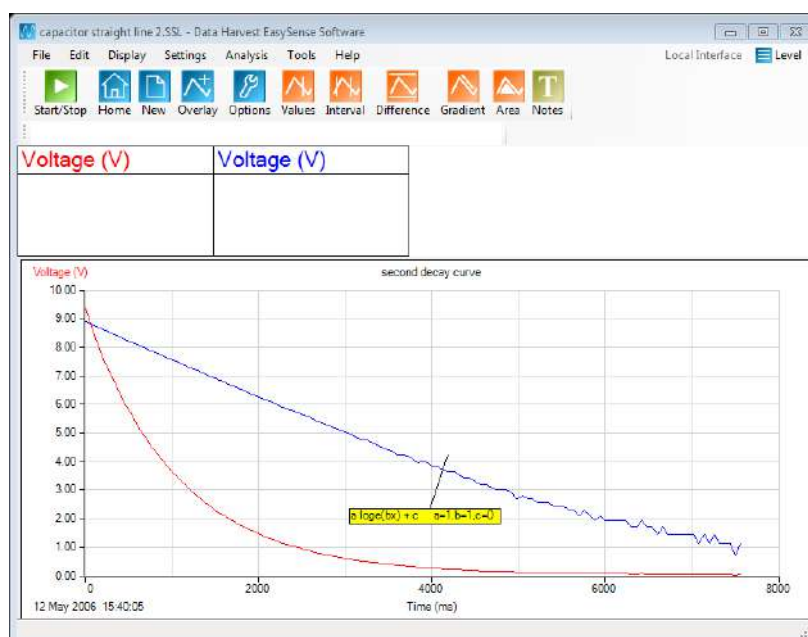


Fig 12.9 The single discharge with the log linear plot

3. You can now use the best fit line to show the gradient line and values.

The time constant is  $1 \div \text{gradient}$ .

**The maths behind the plot are:**

If we use the equation  $V = V_{\max}e^{(-t/CR)}$

Then by taking natural logarithms,  $\log_e$ , we can plot a graph to determine the time-constant.

We use natural logarithms because “e”, the base of natural logarithms, appears in the equation.

$$V = V_{\max}e^{(-t/CR)}$$

By taking logs becomes:

$$\log_e V = \log_e [V_{\max} e^{(-t/CR)}]$$

The logarithm of two numbers (or functions) multiplied together is the same as the sum of their individual logs and algebraically, can be written as

$$\log ab = \log a + \log b$$

therefore

$$\log_e V_{\max} e^{(-t/CR)} = \log_e V_{\max} + \log_e e^{(-t/CR)}$$

and so,

$$\log_e V = \log_e V_{\max} + \log_e e^{(-t/CR)}$$

from the rules of logarithms,  $\log x^n = n \log x$

eg  $\log x^2 = 2 \log x$

$$\log x^{1/2} = \frac{1}{2} \log x$$

$$\log x^{(a/b)} = (a/b) \log x \text{ etc}$$

$$\log_e V_{\max} e^{(-t/CR)} = (-t/CR) \log_e V_{\max}$$

substituting in,  $\log_e V = \log_e V_{\max} + (-t/CR) \log_e e$

(the logarithm of a number of its own base is always 1 eg  $\log_{10} 10 = 1$ ,  $\log_e e = 1$  etc)

$\log_e e = 1$  and substituting in

$$\log_e V = \log_e V_{\max} + (-t/CR) 1$$

as anything multiplied by 1 has the same value anyway

$$\log_e V = \log_e V_{\max} + (-t/CR)$$

removing the brackets we get

$$\log_e V = \log_e V_{\max} - t/CR$$

this arrives at a formulae that follows the  $y=mx+c$  format for a linear line plot,  $c = y$  intercept,  $m=\text{gradient}$ .

## 12. Time constant for a capacitor - resistor circuit

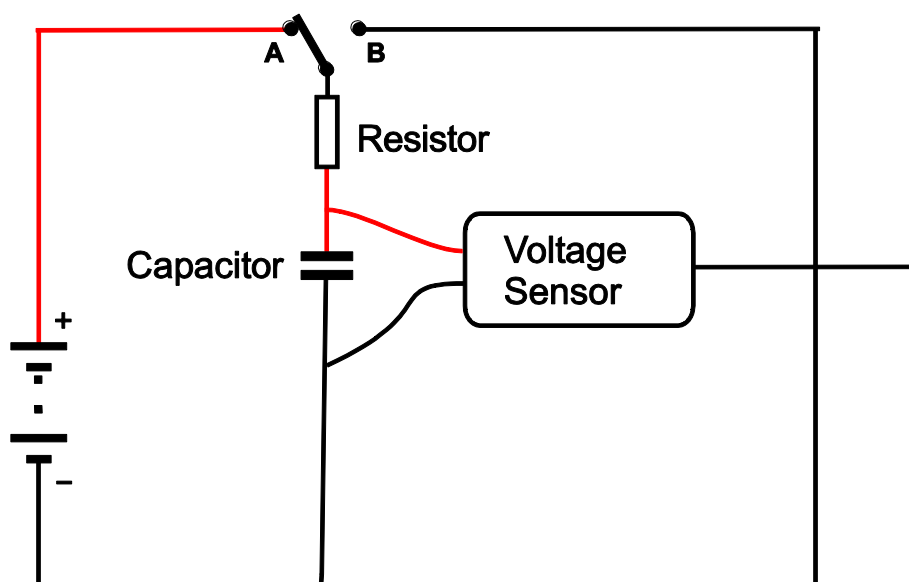
### Practical skills AT a, b, c, f, g, k

Capacitors are devices that can store electric charge; they do not produce the charge. A capacitor was traditionally made from two metal plates separated by an insulating material called a dielectric. They are now made from a wide variety of materials.

When a voltage is applied to a capacitor the potential difference, p.d. across the plates increases as charge flows in. The charge ceases to flow when the p.d. across the plates is equal to the supply voltage, electromotive force, e.m.f. The capacitor in this state is charged. Shorting the terminals of the capacitor will cause it to discharge.

Adding a resistance into the charging circuit increases the time taken to reach a full charge. If a resistance is used to discharge the capacitor, the time taken will also increase.

In this experiment, the time taken for a capacitor to charge and discharge through resistors will be measured and used to determine the time constant of the capacitor - resistor circuit.



### Apparatus

1. Voltage sensor  $\pm 12$  or 20 V, or 0 - 10 V.
2. Electric circuit kit or breadboard.
3. Capacitors and resistors, a 1000  $\mu\text{F}$  capacitor and a 1 k $\Omega$  resistor, are recommended.
4. SPDT switch (2 way).
5. d.c. power supply or dry cells in good condition work well.
6. Connecting wires and crocodile clips.

### Method

If you are using an electrolytic capacitor, make sure that the polarity of the capacitor is followed.

1. Assemble the circuit as shown. Connect to the power supply but do not turn the power on. Connect the Voltage sensor to the data logger.
2. Write down the values of the resistor and capacitor used.
3. Select EasyLog as the recording method.
4. Use Test Mode (Tools menu) to measure the voltage (emf) of the supply with no current flowing. You can do this by temporarily connecting the Voltage sensor across the supply terminals. Replace the sensor into the circuit after taking this measurement.
5. Put the switch in the discharge position (to B) to make sure the capacitor is fully discharged before starting. If necessary finish the discharge by shorting across the terminals of the capacitor with a piece of wire.
6. Click on Start to begin logging.
7. Immediately close the switch (to A) and watch the recording, if the voltage is not rising put the switch into its alternate position.
8. When the line of the graph shows no further change in value, swap the switch to the other position (to A) to discharge the capacitor.
9. Repeat the charge / discharge cycle.
10. Click on Stop to finish logging.
11. If you did not manage to get a complete cycle on the graph, click on Start and repeat.

When you have collected all the data you need, use the switch to make sure the capacitor is discharged fully.

## Results

You will have a plot of voltage (p.d. across the capacitor) against time as series of charge and discharge cycles. Both will be an exponential. The decay will be given by the equation

$$V = V_{\max} e^{(-t/CR)}$$

To confirm this is an exponential, plot the graph of  $\text{Log}_e(V)$  against  $t$ . this will give a straight line with a gradient according to the  $\text{log}_e V = \text{Log}_e V_0 - t \div RC$ .

## Analysis of results

1. Select and use single full discharge cycle.
2. Use the function **a loge(bx) + c**.  $a = 1$ .  $b = 1$  and  $c = 0$ .
3. Find the gradient of the new data set.  $1 \div \text{gradient} (1 \div RC)$  will be the time constant.

## Theory

The time constant of a resistor - capacitor circuit is used as a measure of the length of time needed to charge a capacitor to within a percentage of its final maximum value.

The time constant = **C x R**

R = the value of the charging resistor in  $\Omega$  (ohms)

$C$  = the capacitance of the capacitor in F (Farads)

The time constant is defined as the time taken to reach 63.2% of its final maximum voltage when charging.

When discharging the time constant is the time taken to fall by 63.2% from the maximum value i.e. to fall to 36.8% of the maximum value.

For most purposes the values of 63% and 37% can be used.

### Using the Log – linear plot to find the time constant

If we use the equation  $V = V_{\max}e^{(-t/CR)}$

Then by taking natural logarithms,  $\log_e$ , we can plot a graph to determine the time-constant.

We use natural logarithms because “e”, the base of natural logarithms, appears in the equation.

$$V = V_{\max}e^{(-t/CR)}$$

By taking logs becomes:

$$\log_e V = \log_e [V_{\max} e^{(-t/CR)}]$$

The logarithm of two numbers (or functions) multiplied together is the same as the sum of their individual logs and algebraically, can be written as

$$\log ab = \log a + \log b$$

therefore

$$\log_e V_{\max} e^{(-t/CR)} = \log_e V_{\max} + \log_e e^{(-t/CR)}$$

and so,

$$\log_e V = \log_e V_{\max} + \log_e e^{(-t/CR)}$$

from the rules of logarithms,  $\log x^n = n \log x$

eg  $\log x^2 = 2 \log x$

$$\log x^{1/2} = \frac{1}{2} \log x$$

$$\log x^{(a/b)} = (a/b) \log x \text{ etc}$$

$$V_{\max} e^{(-t/CR)} = (-t/CR) \log_e V_{\max}$$

substituting in,  $\log_e V = \log_e V_{\max} + (-t \div CR) \log_e e$

(the logarithm of a number of its own base is always 1 eg  $\log_{10} 10 = 1$ ,  $\log_e e = 1$  etc)

$\log_e e = 1$  and substituting in

$$\log_e V = \log_e V_{\max} + (-t \div CR) 1$$

as anything multiplied by 1 has the same value anyway

$$\log_e V = \log_e V_{\max} + (-t \div CR)$$

removing the brackets we get

$$\log_e V = \log_e V_{\max} - t \div CR$$
$$\text{or } \log_e V = -t \div CR + \log_e V_{\max}$$

this arrives at a formulae that follows the  $y=mx+c$  format for a linear line plot,  $c = y$  intercept,  $m =$  gradient.  
 $y = \log_e V$ ,  $x = t$ ,  $m = -1 \div CR$  and  $c = \log_e V_{\max}$

## Questions

1. How long did it take the capacitor to reach 95% of its maximum voltage? (Multiply the e.m.f value by 0.95 to calculate the 95% of maximum voltage).
2. How does the value of the time constant relate to the time for reaching 95% of the maximum voltage?
3. If there is unlimited time available, when will the capacitor reach full charge? Explain your reasoning.
4. Where / how could you apply the knowledge of time constants?

## Extension

1. How does increasing
  - a. The value of  $R$
  - b. The value of  $C$
  - c. The supply voltageeffect the time constant?
2. What happens if resistors of different values are used on the charge and discharge sides of the circuit?

## Teacher's notes

### 13. Charge stored on a capacitor

#### Practical skills AT a, b, c, f, g, k

The practical uses the ability of the data logger to record multiple channels and provide analysis of the graphed data. In this case to use the area under the graph function to find the  $I \times t$  (power).

#### Apparatus

1. Current sensor  $\pm 100$  mA or  $\pm 1$  A
2. Voltage sensor  $\pm 12$  or 20 V
3. Electric circuit kit or breadboard
4. Capacitors and resistors; a 10,000  $\mu\text{F}$  capacitor and a 1 k $\Omega$  resistor, are recommended.
5. SPDT switch
6. d.c. power supply, dry cells in good condition work well. Refer to notes below for fuller advice.
7. Connecting wires and crocodile clips

#### Component values

The selection of components is decided on the following criteria:

- Time constant of 0.5 to 1 second.
- Maximum current if 60 to 100 mA, to provide accurate current measurement.
- Readily available components.
- Readily available d.c. low voltage sources.
- Ability to use Real Time or Fast logging.

Voltage, V (V)	Resistor, R ( $\Omega$ )	Capacitance, C ( $\mu\text{F}$ )	Time constant, T (s)
4.5	47	10,000	0.5
9	100	10,000	1.0
6	68	10,000	0.68

#### Warning

The potential electrical hazards posed by capacitors must be assessed bearing mind both the operating potential (V) and capacity (C) from which the stored energy (E) can be calculated using the relationship  $E = \frac{1}{2} CV^2$ . These precautions may not be required at voltages below 50 V a.c. or 120 V d.c. The discharge of 0.25 J of stored energy to the human body can provide a heavy shock and 10 J can be fatal. Capacitors of hazardous capacity should be individually kept short-circuited with an appropriate resistor during storage. Care should be taken to avoid the danger of burns from high value capacitors.

#### Set up

Use EasyLog, this gives the students the visual feedback of the electrical event being studied, while the data is being logged.



## Practical notes

A capacitor takes the 4 to 8 times the time constant to approach full charge.

30 seconds gives enough time to collect two full charge discharge cycles with a time constant of 1 second.

If the components are mounted on a breadboard or in component holders of an electronics kit, substitution of capacitors of different values can be easily done.

Power can be provided by dry cells in good condition, the voltages and currents used are low. GCSE circuit kits often provide holders for cells that can be used as power packs. If low power supply units are used you need to be aware of the effect of ripple voltages. Even good quality units can produce large ripple voltages. Some units described as d.c. are unsmoothed half wave rectified power supplies; they will not be suitable for this exercise.

The switch used was a two pole on - on switch, which allows the circuit to be switched rapidly.

The real time option was used to allow the students to see the curves developing as the logging takes place. Fast logging will give more reliable results, but the logging is unseen and the result not seen until the data is downloaded to the PC.

Errors. There are a number of sources of error in this experiment. All components have a manufacturers' tolerance, typically  $\pm 1$  to 5% for resistors and  $\pm 20\%$  for capacitors. Students need to be aware of these tolerances when comparing measured values and calculated values.

The chemicals used in electrolytic capacitors will take time to return to their original state and there will be energy losses connected with the chemical changes in each charge-discharge cycle. Errors of 5% are not unexpected.

When fully charged, the potential difference across the capacitor plates is the same as that across the battery, so the maximum amount of charge that a capacitor can store is proportional to the battery voltage. By measuring the charge flow into and out of the capacitor, the charge stored can be calculated. The Area function of the software enables the charge flow for the time of charge or discharge to be easily calculated.

The data for the graph below was collected from an investigation using a  $10,000\ \mu\text{F}$  capacitor and  $47\ \Omega$  resistor at 6.27 V.

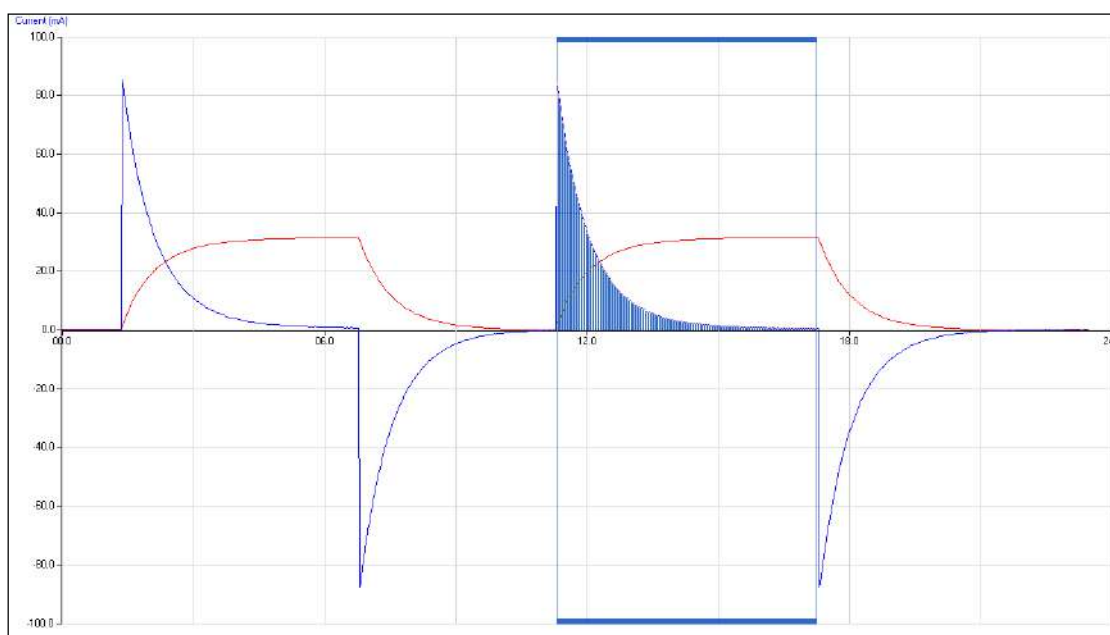


Fig 14.1 Data as collected with **Area** tool being used to find the area under the current curve (mA s).

$$Q = 66.589\ \text{mAs} = 66.589\ \text{mC}$$

by calculation,  $Q = CV$

$$Q = 10000 \mu\text{F} \times 6.27 \text{ V} = 6270 \mu\text{C} = 62.7 \text{ mC}.$$

The difference can be explained in the tolerances of the devices, capacitors are usually at 20%. The value from the area under the graph is the actual value of the device.

Values obtained from the above for the charge flow in the charge-discharge cycles.

Cycle number	Charge flow (mC)	Discharge flow (mC)
1	68.666	65.829
2	67.746	65.936

## Extension

The use of fast logging gives a sampling rate of 100 per second compared to the real time sampling of 20 per second. The extra samples will give greater accuracy on the peak values this is needed if the time constant is low.

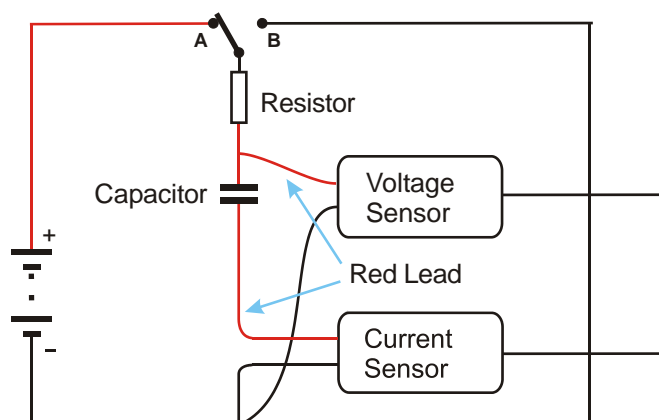
## 13. Charge stored on a capacitor

### Practical skills AT a, b, c, f, g, k

Capacitors are devices that can store electric charge; they do not produce the charge. A capacitor was originally made from two metal plates separated by an insulating material called a dielectric. They are now made from a wide range of materials including ceramics, Mylar, polystyrene, tantalum and aluminium and electrolyte. There are many different types of capacitor available and they come in a variety of shapes and sizes. The unit of capacitance is the farad (F) and values will range from pico-farads ( $10^{-12}$ ) to farads.

Capacitors are used in: timing circuits, energy storage, frequency filters and smoothing voltages.

In this investigation, you are going to measure the charge that a capacitor can store and then deliver when discharged.



Take care with polarity of the wires from the sensors. The red and black in the diagram refers to the colour of the leads from the sensors.

### Apparatus

1. Current sensor  $\pm 100$  mA or  $\pm 1$  A
2. Voltage sensor  $\pm 12$  or 20 V
3. Electric circuit kit or breadboard
4. Capacitors and resistors, a  $10,000 \mu\text{F}$  capacitor and a  $1 \text{ k}\Omega$  resistor, are recommended
5. SPDT switch
6. d.c. power supply, dry cells in good condition
7. Connecting wires and crocodile clips

### Method

1. Assemble the circuit as shown but do not connect the power. If you are using electrolytic capacitors ensure the correct polarity is observed.
2. Connect the Voltage and Current sensor to the data logger.
3. Note down the values of the resistors used and the value of the capacitor
4. Select EasyLog as the recording method.

5. Use Test Mode (Tools menu) to measure the voltage (e.m.f) of the supply with no current flowing. You can do this by temporarily connecting the Voltage sensor across the supply terminals. Replace the sensor into the circuit after taking this measurement.
6. Put the switch in the discharge position to make sure the capacitor is fully discharged before starting. If necessary finish the discharge by shorting across the terminals of the capacitor with a piece of wire.
7. Select Start and immediately close the switch and watch the recording, if the voltage is not rising put the switch into its alternate position.
8. When the line of the graph shows no further change in value, swap the switch to the other position to discharge the capacitor.
9. Repeat the charge / discharge cycle.
10. Click on Stop to finish logging.
11. If you did not manage to get a complete cycle on the graph, click on Start and repeat.
12. When you have collected all the data you need, use the switch to make sure the capacitor is discharged fully.

## Theory

The charge stored on the capacitor is given by the following equation:

$$Q = C \times V$$

$Q$  = the charge in Coulombs,  $C$

$C$  = the capacitance in farads,  $F$

$V$  = the voltage in volts,  $V$

When a capacitor is charged a current flows, the relationship between charge and a steady current is:

$$Q = I \times t$$

$I$  = the current flowing in amps.

If the current is variable, as in this experiment, then the charge flow is the **AREA** under the current time graph.

## Analysis of results

The graphs you obtained are Current and Voltage vs. Time. You will calculate the total charge stored from the Current vs. Time graph.

### Measuring $V_{\max}$

Using Values, measure the maximum voltage in the charge cycle of the voltage-time graph. This is  $V_{\max}$ , write down this value.

### Measuring the charge stored

The charge stored during the charge cycle and the charge delivered during the discharge cycle are found by measuring the area under the current-time graph.

1. Make sure the Current scale is displayed on the y-axis.
2. Select the Area icon.

- Go to the first charge cycle on the graph, click on the point where the current starts to increase, and drag the cursor across to the point where current has fallen back to zero.

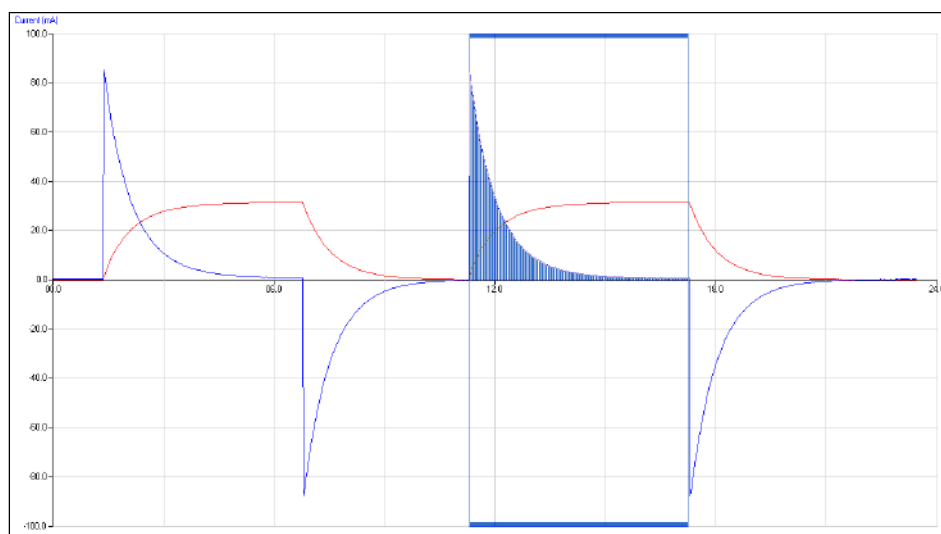


Fig 14.1 Detail showing the use of the area tool to find the area under the current of a single discharge cycle.

- A value will appear in the blue data box showing mAs, i.e. millicoulombs (mC), in the example 66.589 mAs.
- For comparison, the charge on the capacitor can be calculated from  $V_{\max}$  and the farad rating of the capacitor. Charge =  $V \times C$
- Note the error rating of the capacitor; the farad rating can have a 20% tolerance. The result collected from the graph will be the measured value for the device. The value written on the device will be its design value.

## Questions

- Are there any general differences between the charge and discharge values? Explain why this occurs.
- A flash-gun lamp requires a charge of 0.004 coulombs at 6 volts. What sized capacitor (in microfarads) is needed to store this charge?

## Extension

Use fast logging to obtain more reliable results. Use Graph mode, and select a 30 s total recording time with a 10 ms interval; this will be enough for two complete charge-discharge cycles.

Investigate the relationship between:

- Charge vs. Voltage; does the charge stored vary with the charging voltage?
- Charge vs. Capacitance; Measure the charge stored for different values of the capacitance, maintaining the maximum voltage constant

## Teacher's notes

### 14. Energy stored in a capacitor

#### Practical skills AT a, b, c, f, g, k

This investigation allows the student to calculate the energy stored in the capacitor, it is an extension of the work time constant of an RC circuit.

#### Apparatus

1. Current sensor  $\pm 100$  mA
2. Voltage sensor  $\pm 12$  or 20 V
3. Electric circuit kit or breadboard
4. Capacitors: large 4700  $\mu\text{F}$  or 10,000  $\mu\text{F}$  is suggested
5. Resistors: 3 W, 50 – 100  $\Omega$  resistor is suggested
6. SPDT switch
7. Low voltage d.c. Power supply, dry cells in good condition work well. Refer to notes below for fuller advice.
8. Connecting wires and crocodile clips

#### Component values

The selection of components is decided on the following criteria:

- a. Time constant of 0.5 to 1 second.
- b. Maximum current if 60 to 100 mA, to provide accurate current measurement.
- c. Readily available components.
- d. Readily available dc low voltage sources.
- e. Ability to use Real Time or Fast logging.

Voltage, V (V)	Resistor, R ( $\Omega$ )	Capacitance, C ( $\mu\text{F}$ )	Time constant, T (s)
4.5	47	10000	0.5
6	100	10000	1.0
9	68	10000	0.68
6	68	4700	0.5

#### Warning

The potential electrical hazards posed by capacitors must be assessed bearing mind both the operating potential (V) and capacity (C) from which the stored energy (E) can be calculated using the relationship  $E = \frac{1}{2} CV^2$ . These precautions may not be required at voltages below 50 V a.c. or 120 V d.c. The discharge of 0.25 J of stored energy to the human body can provide a heavy shock and 10 J can be fatal. Capacitors of hazardous capacity should be individually kept short-circuited with an appropriate resistor during storage. Care should be taken to avoid the danger of burns from high value capacitors.

## Set up

Use **EasyLog**, this gives the students the visual feedback of the electrical event being studied, while the data is being logged.

## Practical notes

A capacitor takes 4 to 8 times the time constant to approach full charge. The time span of about 30 seconds gives enough time to collect two full charge discharge cycles. Using EasyLog, the intersample time is 30 ms for the first 30 seconds. It is 60 ms for the next 60 sec. It is therefore better to restrict the logging to the first 30 seconds.

If the components are mounted on a breadboard or the component holder of an electronics kit, substitution of capacitors of different values can be easily done.

Power can be provided by dry cells in good condition, the voltages and currents used are low. GCSE circuit kits often provide holders for cells that can be used as power packs. If low voltage mains power supply units are used you need to be aware of the effect of ripple voltages. Even good quality units can produce large ripple voltages which could cause electrolytic capacitors to overheat.

The switch used was a two pole on - on switch which allows the circuit to be switched rapidly.

The real time option is used to allow the students to see the curves developing as the logging takes place on the screen. Fast logging will give more reliable results, but the results will not be seen until the data downloads to the PC.

## Errors

There are a number of sources of error in this experiment. All components have a manufacturer's tolerance, typically  $\pm 1$  to 5% for resistors and  $\pm 20\%$  for capacitors. Students need to be aware of these tolerances when comparing measured values and calculated values.

The chemicals used in electrolytic capacitors will take time to return to their original state and there will be energy losses connected with the chemical changes in each charge - discharge cycle. Errors of 5% are not unexpected.

## Analysis of results

The analysis is carried out in two stages:

1. **Generating the Power vs. Time graph** from the Current and Voltage vs. Time results.
2. **Calculating the energy transfer** by measuring the area under the Power vs. Time graph.

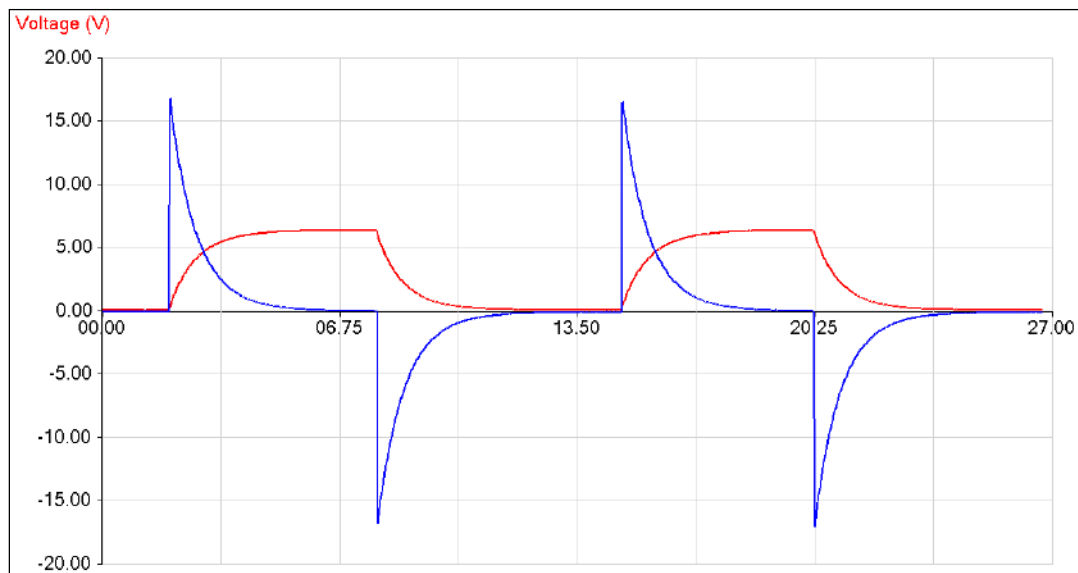


Fig 15.1 Data as collected

### Generating the Power curve

- From the Tools menu select the Post-log Function.
- Select Preset function: Electricity, Power.
- Select the Voltage and Current data channels.
- Type in any changes that are needed to the name, or units. If not, click on **Finish**.

The screen will change back to the Graph screen and the Power curve will be plotted.

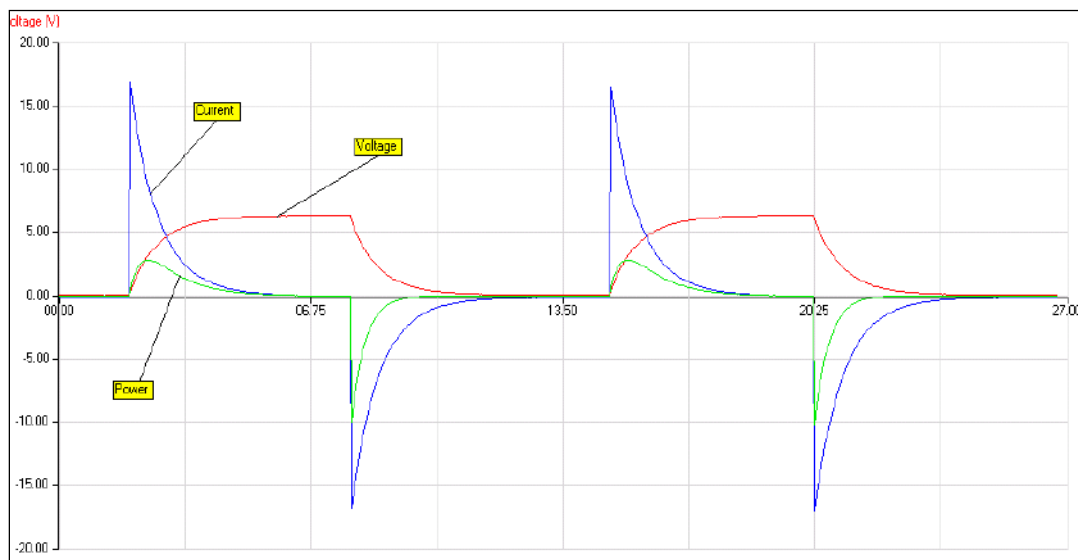


Fig 15.2 shows the Power curve as well as the voltage and current.



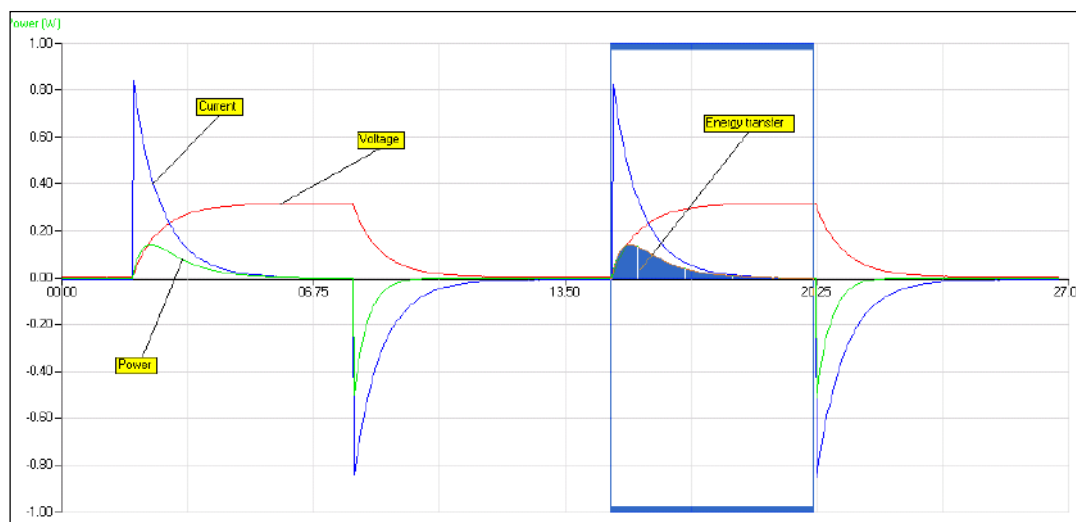


Fig 15.3 shows an area being measured. In the example the area gives a value of 0.205 Ws or 0.205 joules.

Capacitance, C ( $\mu\text{F}$ )	Voltage $V_{\text{max}}$ (V)	Energy IN Charging, $E_{\text{in}}$ (J)	Energy OUT Discharging, $E_{\text{out}}$ (J)	Efficiency % $E_{\text{out}}/E_{\text{in}} \times 100$	Energy Stored Calculated $E = \frac{1}{2}CV^2$ (J)
10,000	6.34	0.208	0.195	94	0.201
10,000	6.34	0.205	0.201	98	0.201

Table 1. Shows the values of energy obtained from the graph, for the two charge – discharge cycles shown.

## Extension

This sample data was obtained using a 10,000  $\mu\text{F}$  capacitor in series with a 6 V 0.05 A lamp.

Fast logging was used to obtain more results around the peaks in the graphs.

A setup similar to the table below was used:

Recording method	Recording time	Intersample time	No. of samples	Trigger
Graph	20 seconds	5 ms	4,000	None

## Practical notes

The intersample time can be made faster, experience will dictate the conditions used, or whether you need to use a trigger for the recording. You could try using **Scope**, and using the faster and slower buttons to find the best recording setup.

The current–time curve is markedly different to that obtained using a standard resistor. In this case the resistance is changing as the lamp filament heats up. This significantly alters the shape of the current–time characteristic.

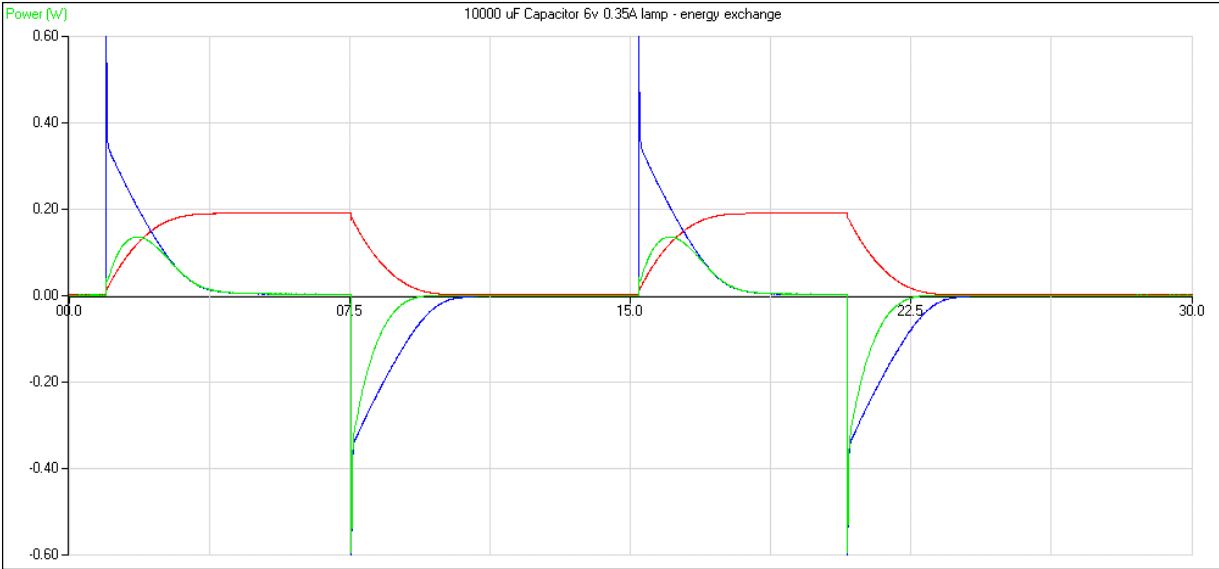


Figure 15.4 Charge and discharge using the resistance of a filament lamp

Capacitance, C (μF)	Voltage, V <sub>max</sub> (V)	Energy IN Charging, E <sub>in</sub> (J)	Energy OUT Discharging, E <sub>out</sub> (J)	Efficiency % E <sub>out</sub> /E <sub>in</sub> × 100	Energy Stored Calculated E=½CV² (J)
10,000	6.33	0.237	0.203	85.7	0.200
10,000	6.33	0.230	0.196	85.2	0.200

Table 2. Comparison of energy in and energy out to estimate efficiency of the energy transfer.

## 14. Energy stored in a capacitor

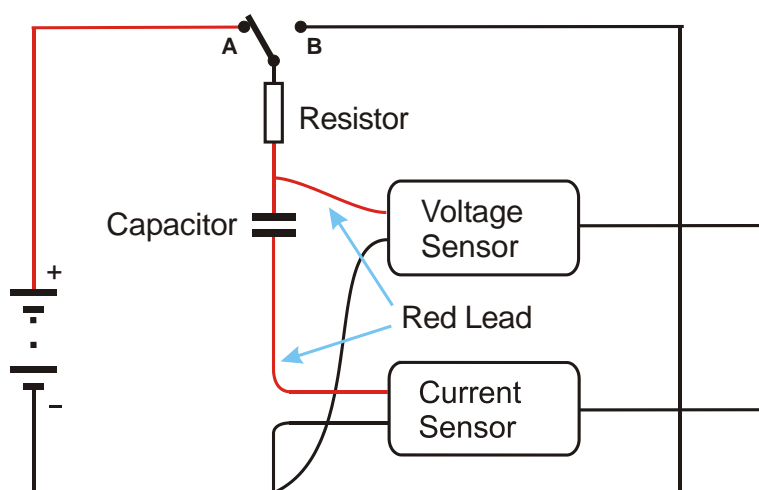
### Practical skills AT a, b, c, f, g, k

Capacitors are devices that can store electric charge. A capacitor was originally made from two metal plates separated by an insulating material. They are now made from a wide range of materials including ceramics, Mylar, polystyrene, tantalum, and aluminium electrolytic. There are many different types of capacitor available and they are used for a variety of different applications. They come in a range of shapes, sizes, and in values from pico farads ( $F \times 10^{-12}$ ) up to farads.

Here are some of the applications, which use capacitors:

- Timing circuits.
- Energy storage e.g. flashguns.
- Selecting frequencies.
- Frequency filters.
- Smoothing fluctuating voltages.

In this investigation you are going to measure the energy stored in a capacitor when it is charged, and then measure how much of that energy can be recovered during the discharge i.e. to find out the efficiency of the capacitor.



### Apparatus

1. Current sensor  $\pm 100$  mA
2. Voltage sensor  $\pm 12$  or  $20$  V
3. Electric circuit kit or breadboard
4. Capacitors: large  $4700 \mu\text{F}$  or  $10,000 \mu\text{F}$  is suggested
5. Resistors:  $3 \text{ W}$ ,  $50 - 100 \Omega$  resistor is suggested
6. SPDT switch
7. Low voltage d.c. power supply or dry cells in good condition.
8. Connecting wires and crocodile clips

## Method

1. Assemble the circuit as shown but do not connect the power. If you are using electrolytic capacitors ensure the correct polarity is observed.
2. Connect the Voltage and the Current sensor to the data logger.
3. Note down the values of the resistors used and the value of the capacitor
4. Select EasyLog as the recording method.
5. Use Test Mode (Tools menu) to measure the voltage (e.m.f) of the supply with no current flowing, You can do this by temporarily connecting the Voltage sensor across the supply terminals. Replace the sensor into the circuit after taking this measurement.
6. Put the switch in the discharge position (switch to B) to make sure the capacitor is fully discharged before starting. If necessary, finish the discharge by shorting across the terminals of the capacitor with a piece of wire.
7. Click on Start to begin recording
8. Immediately close the switch (switch to A) and watch the recording, if the voltage is not rising put the switch into its alternate position.
9. When the line of the graph shows no further change in value, swap the switch to the other position to discharge the capacitor.
10. Repeat the charge / discharge cycle.
11. Click on Stop to finish logging.
12. If you did not manage to get a complete cycle on the graph, click on Start and repeat.

When you have collected all the data you need, use the switch to make sure the capacitor is discharged fully.

## Theory

### Measuring the energy transfer

You can calculate the energy transfer into, and out of, the capacitor from the current and voltage measurements obtained.

The power developed in a component is given by:

$$P = V \times I$$

The energy supplied in a time  $t$  seconds is therefore:

$$E = VI t = P \times t$$

This assumes that  $V$  and  $I$  are constant values. In this experiment, they are changing and therefore the energy is calculated by integrating the above equation.

$$\begin{aligned} E &= \int VI \Delta t \\ &= \int P \Delta t \end{aligned}$$

which is the area under the power–time ( $P$ - $t$ ) graph.

Calculating the possible energy stored

The energy stored by a capacitor may be calculated from the following equation:

$$E = \frac{1}{2}CV^2$$

## Results and analysis

The results you have obtained are curves of current–time and voltage–time. You need to generate a power–time curve before analysis starts.

### Generate the Power curve

1. From the Tools menu select the Post-log Function.
2. Select function: Electricity, Power.
3. Select the Voltage and Current data channels.
4. Type in any changes that are needed to the name, or units. Click on Finish and the Power curve will be plotted.

Using Values read off the maximum value of the voltage across the capacitor. This is  $V_{\max}$ , write it down.

### Measure the area under the power – time graph

1. Make sure Power is selected as the y axis.
2. Select Area.
3. Click and drag with the mouse to select the required area.
4. The values of the area will be displayed in the relevant data box.

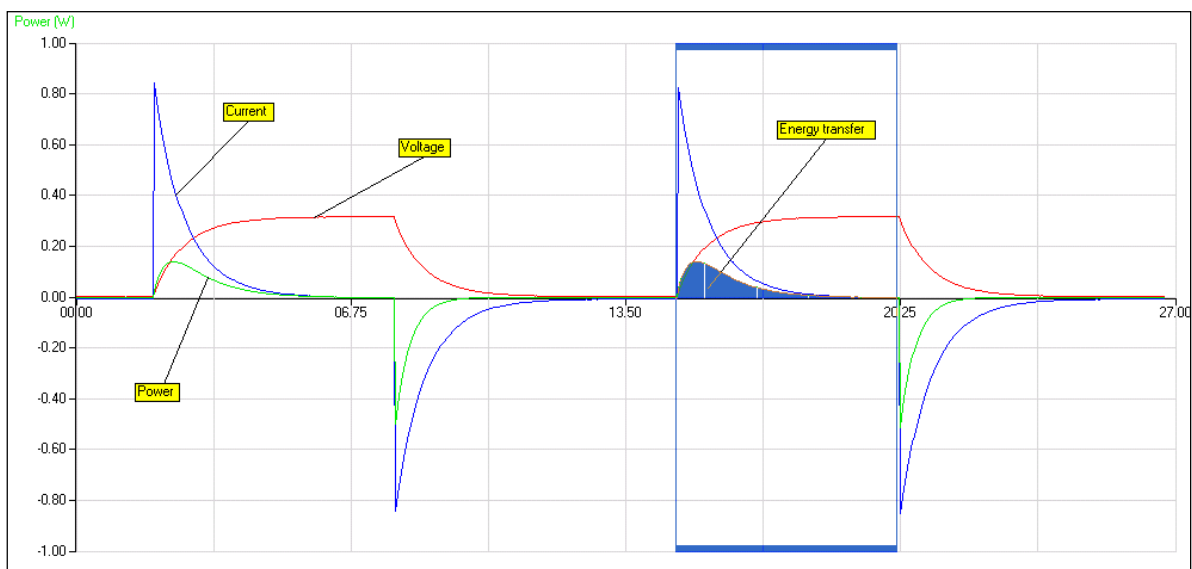


Fig 15.1 An example of the area tool being used to find the area under a power curve.

### Calculation

Calculate the expected energy stored from the equation  $E = \frac{1}{2}CV^2$ , using the stated values of the capacitors.

## Analysis

Fill in the table with the values you have calculated and measured above:

Capacitance, C ( $\mu\text{F}$ )	Voltage, $V_{\text{max}}$ (V)	Energy IN, $E_{\text{in}}$ Charging (J)	Energy OUT, $E_{\text{out}}$ Discharging (J)	Efficiency % $= E_{\text{out}}/E_{\text{in}} \times 100$	Energy Stored Calculated $= \frac{1}{2}CV^2$ (J)

## Questions

- How do you account for the differences between the energy input during charging and the energy output during discharging? Remember the principle of the conservation of energy.
- The calculated and measured amounts of energy will not be exactly the same.
  - What are the sources of error in this experiment?
  - How can you account for the differences between the calculated and measured energies in terms of the experimental errors?
- In a photographic flash unit, a capacitor is used to store the energy to fire the flash tube. A mid-range portable unit requires an energy transfer of about 25 joules. What is the size of the capacitor required if the tube fires at 320 volts?

## Extension

- Measure the energy stored and released when the capacitor is charged and discharged through a low voltage lamp, e.g. a 4.5 V, 0.3 A lamp. It may be necessary to use fast logging for this (5 ms intersample time is suggested).
- Investigate the relationship between the energy stored in a capacitor and the voltage across it.

## Teacher's notes

### 15. Interference in sound waves (using SnapShot)

#### Practical skills AT a, b, c, h, i, k, l

In this investigation the interference between sound waves of identical frequency but emitted from different sources is investigated.

The SnapShot facility of the software is used. The Pre-log function "Asks for Value" is used to prompt the student to enter the distance the Sound sensor has moved.

The investigation is similar to Young's slit experiment for determination of the wavelength of light. The two sound sources represent the two slits and the sound from the speakers the light rays. However the wavelength of sound waves are much greater than light waves, and the geometry of the system is very different. The Young's calculations can give an approximate idea of what is going on, but are only valid for calculations at frequencies above about 4 kHz. Even then only for the central 2 or 3 fringes. At higher frequencies and shorter wavelengths more fringes follow the pattern described in Young's formula.

The SnapShot method produces some good results, to get several central peaks and troughs in the sound level a frequency of above 4000 Hz is required, this may become stressful on hearing. Consideration to hearing and hearing damage should be given.

#### Apparatus

1. Sound sensor set to the dBA range
2. Variable signal generator
3. 2 loud speakers (matched). 8  $\Omega$  0.3 W loudspeakers work well, connected in parallel.
4. Metre rule or straight edge marked in 1 cm (or better) graduations
5. 2 clamps to secure rule / edge to table
6. Retort stand and clamp

#### Practical notes

The loud speakers need to be of identical type; ideally they should be matched from a PC sound system or similar. Depending on the tone used the speaker's response range will affect volume of the sound.

The results will vary according to the distance of separation of the speakers and the position of the Sound sensor from the speaker. If the speaker separation and the distance from the speakers to the Sound sensor are the same, then the central fringe width will be equal to the wavelength of the sound.

$$\Delta x = \frac{\lambda D}{s}$$

Key:

$\Delta x$  = Fringe separation

D = distance from speakers to Sensor

s = Separation of the speakers

$\lambda$  = Wavelength of the sound.

Using a frequency of 4 kHz with  $D = s = 0.5$  m or 1m the fringe separation will be about 8.7cm at 25°C

2 kHz is a particularly intrusive frequency,

Using SnapShot makes the experiment simple. If the separation between snapshot distances can be kept small the accuracy is good. It may pay to do a quick set of results at 1 cm separation to prove the presence of many peaks and then do a small section with finer detail to get measurements

Higher frequencies give more interference spots. Start with a frequency of 8 kHz.

## Set up

Recording method	Pre-log Function	Unit name	Limits
SnapShot	Asks for Value	Distance (set units to the scale of the rule being used)	To the separation of the speakers

## Analysis of the results

The sample data below was collected using a frequency of 8162 Hz

Once the data has been collected and presented as a Sound against Distance graph the students will only need to use the Values tool to collect information about the distance between peaks and lows.

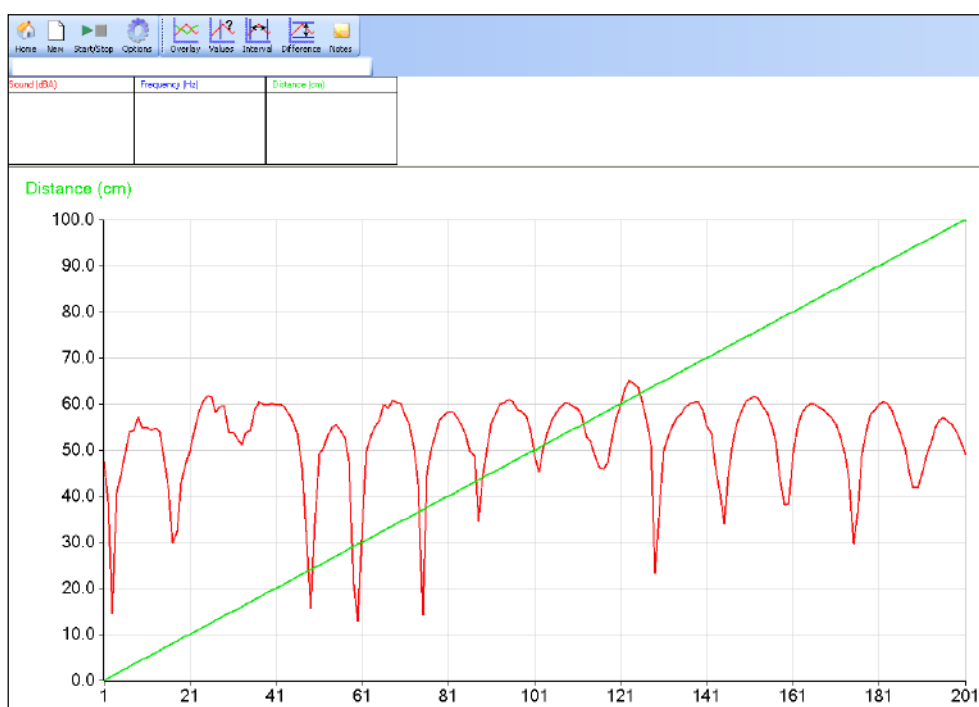


Fig 16.1 Interference in sound waves measured using Snapshot. Graph converted to line form from bar chart.

Useful definitions

**Wavelength (metres)** = Speed of sound (metres per second) / Frequency (Hz)

**Frequency (Hz)** = Speed of sound (metres per second) / Wavelength (metres)

**Speed of sound** is 331.1 metres per second at STP, giving a value of  $346 \text{ ms}^{-1}$  at 25°C



**Example calculations**

Distance between speaker centres = 1.0 m

Distance from speaker centres to sound sensor = 1.56 m

Calculated distance between fringes =  $\lambda D/s$

$$(0.0442 \times 1.56) / 1.00 = 0.0689 \text{ m or } 6.86 \text{ cm}$$

From graph average distance between fringes is 6.9 cm.

**Wavelength from experimental data**

$\lambda = (\text{Fringe separation} \times \text{slit separation}) / \text{distance to fringes.}$

$$= (0.069 \times 1.0) / 1.56$$

$$= 0.0442$$

**Frequency from experimental data**

$F = \text{Speed of sound} / \lambda$

$$= 346 / 0.0442$$

$$= 7834 \text{ Hz}$$

Frequency on the signal generator indicated at 8158 Hz

I.e. a 4% error / difference to be accounted for. Most likely in the speed of sound value and the coarseness of the snapshot to give the inter fringe distance.

**Wavelength from frequency by calculation**

$\lambda = \text{Speed of sound} / \text{Frequency.}$

Speed of sound =  $346 \text{ ms}^{-1}$  at  $24^\circ\text{C}$

Frequency from signal generator = 8162

$$= 346 / 8162$$

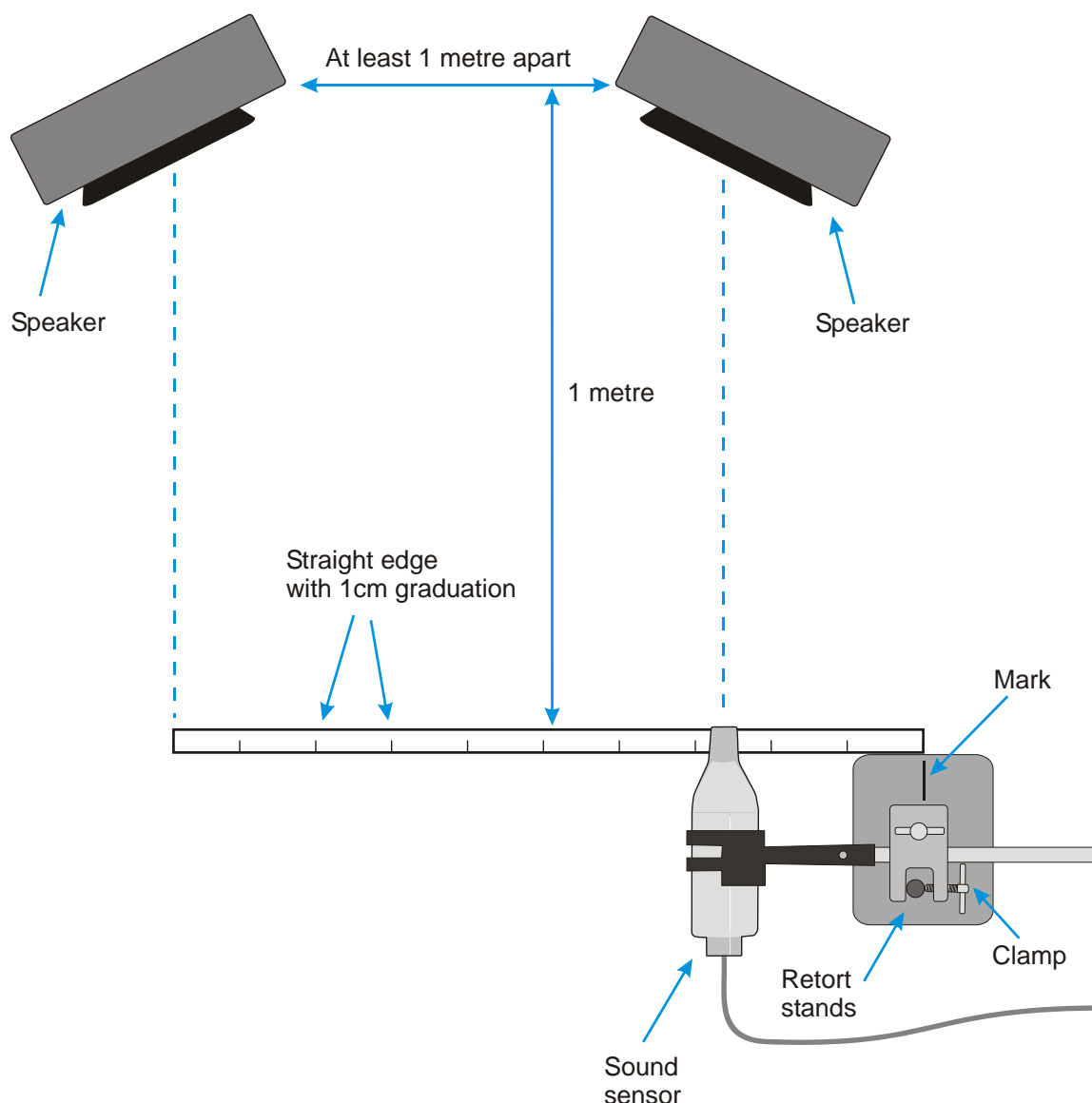
$$= 0.0423$$

## 15. Interference in sound waves (using SnapShot)

### Practical skills AT a, b, c, h, i, k, l

When you set up a stereo or surround sound system, the instructions indicate it is important to position the speakers correctly and to wire them up correctly. One of the reasons for this is that sound waves will interfere with each other and set up constructive and destructive interference patterns. As a listener to a system, you will experience areas of loudness and quiet as you move your head or as you move around the room. On a larger scale, the same can happen with large public address systems as you might find in railway stations or airports, in poorly designed systems the interference can be so bad as to make the spoken information unusable.

In this investigation, you will use two speakers connected to a signal generator. Each speaker will produce the same frequency of sound and with matched speakers the same volume of sound. By moving a sound sensor across the front of the speakers, you will be able to pick up the areas of interference as changes in the amount of sound detected.



## Apparatus

1. Sound sensor set to the dBA range
2. Variable signal generator
3. 2 loud speakers (matched). 8  $\Omega$  0.3 W loudspeakers work well, connected in parallel.
4. Metre rule or straight edge marked in 1 cm (or better) graduations.
5. 2 clamps to secure rule / edge to table.
6. Retort stand and clamp.

## Method

1. Set up the apparatus as show, the speakers should be turned a few degrees to point towards the centre point of the straight edge that the Sound sensor is moved along.
2. The straight edge should have marks on it of at least 0.5 cm separation. A 1 metre rule would act as a good straight edge and would already be marked out.
3. Connect the Sound sensor to the data logger. This sensor should be 1 metre from the line joining the speakers.
4. The straight edge should be running parallel to the line that joins the two speakers.
5. Turn on the signal generator and set it to produce a sine wave at 8 kHz, check both speakers are reproducing the tone.
6. Place the Sound sensor at one end of the straight edge, opposite a speaker. Make sure the Sound sensor is pointing to the centre of the speaker. Make a mark on the retort stand base to be used as a pointer to the cm divisions on the straight edge.
7. Set up to record:

Recording method	Pre-log Function	Unit name	Limits
SnapShot	Asks for Value	Distance	To the separation of the speakers

8. When you are happy that everything is in line, select Start. To record the data click anywhere in the centre area of the graph. As you click the mouse to record data, a small box will appear on the screen asking for a value, this is the distance the sensor has moved along the rule. You should enter the distance the sensor has moved from the beginning, not the distance you just moved sensor by. The first distance should be 0 cm as it's the starting measurement.
9. Move the retort stand along the straight edge until the mark, previously made on the retort stand base, has moved 0.5 cm along the ruler scale, click on the graph screen to record the data, enter the distance. Repeat until you have moved right across the width between the speakers.
10. Turn off the signal generator; select Stop, and save the data.

## Results

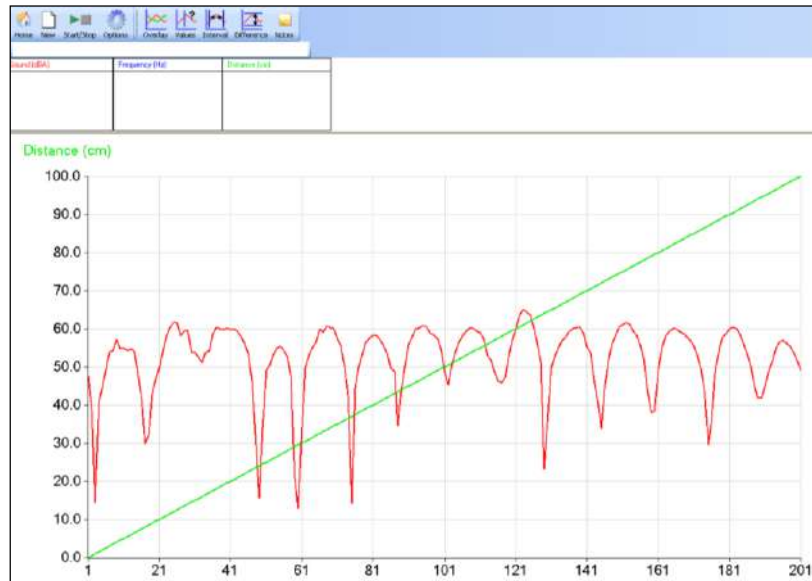


Fig 16.1 Example of collected data

To display the data as sound against distance

1. Select Options, X-Axis.
2. Select Channel and OK.

You should have a graph similar to one below,

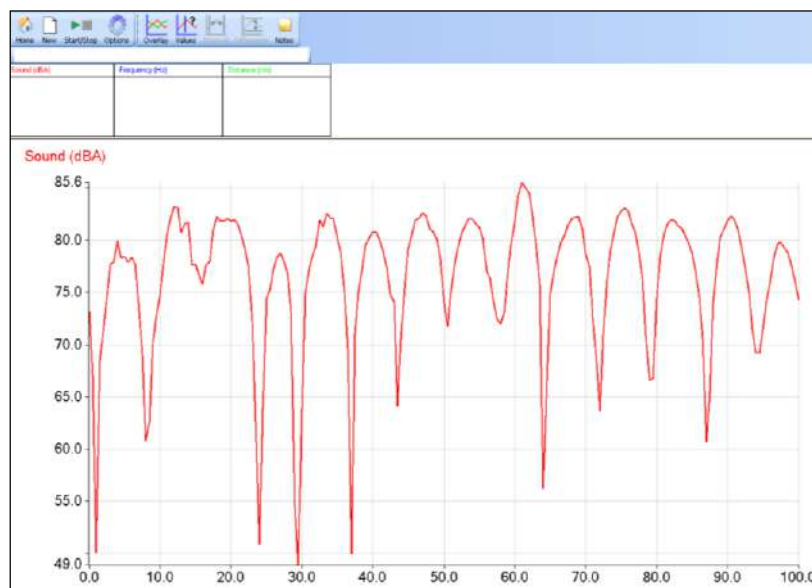


Fig 16.2 example of data plotted as a sound (dBA) against distance.

## Questions

1. What is the distance between the dips in the trace?
2. What is the wavelength of the frequency you selected?
3. What is the relationship between the wavelength and the distance between the peaks/ dips in the recorded trace?

## To check the frequency

1. Select Home, and then Graph.
2. Alter the range of the Sound sensor to mV.
3. Set up to record with a Total recording time of 200 ms and an Intersample time of 50  $\mu$ s, Finish.
4. Turn on the signal generator, after a few moments of “warming up time” select Start. The wave of the frequency being generated should be captured.
5. Use the Interval tool to find the time for one complete cycle, and calculate the frequency.

The frequency is calculated from,

$$\text{Frequency} = \frac{1}{\text{period}}$$

For example for an interval or period of 16.695 ms

$$\text{Frequency} = (1 / 16.695) \times 100 = 60 \text{ Hz}$$

## Extension

What happens if you record the sound level as you move closer to the speakers? Is it a similar pattern to the one recorded?

Can you predict where the null points will be? Select a tone / frequency and try?

## Theory

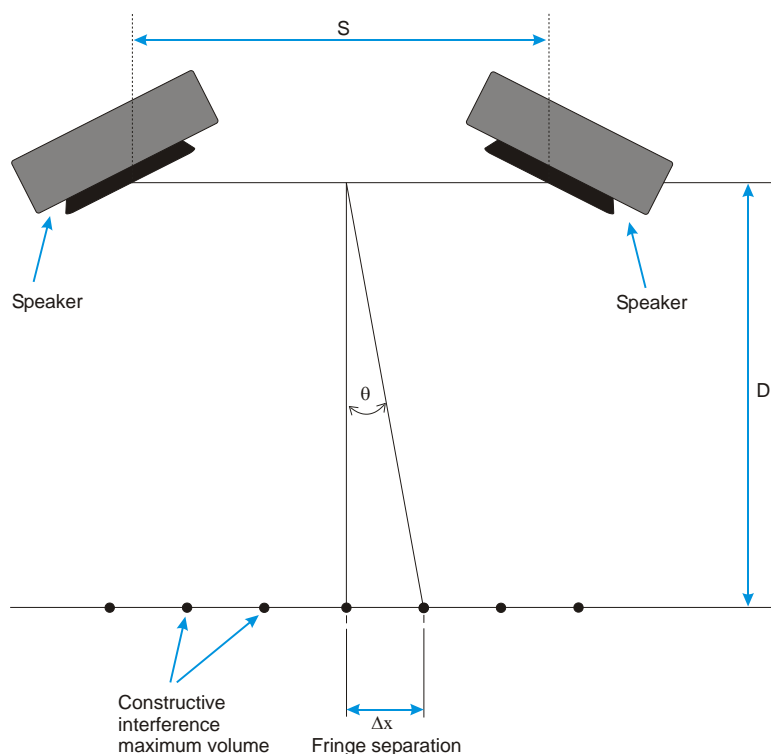


Fig 16.3 Relationship between  $s$  (slit separation) and fringes

The dots in the diagram show the approximate position of constructive interference. The speakers are about 1 m apart and the Sound sensors 1 m in front of them. The position of the minima will be half way between the maxima, and therefore the fringe separation is the same for maxima and minima.

For the first maximum away from the central maximum, there must be a path difference of  $\lambda$ .

The theory for the interference between the two sound sources is approximately the same for two slits in Young's two slit experiments with light, for frequencies of 3 to 4 kHz and above. At these frequencies it is only the central fringes that are predicted by Young's formula. As the frequency rises above 4 kHz, the position of more fringes can be predicted.

Young's Formula for two slit interference is:-

$$\therefore \Delta x = \frac{\lambda D}{s}$$

$\Delta x$  = Fringe width

$\lambda$  = Wavelength

$D$  = Distance from slits/speakers to the sensor

$s$  = distance between the slits/speakers

Young's slits calculation uses small angles so  $\sin\theta = \theta = \tan\theta$ ; it is therefore best practice to confine the analysis to the central section of the fringe pattern.

If you did the extension work you will have found that:

$$\Delta x \propto D$$

for the central fringes above frequencies of 3 to 4 kHz.

## Teacher's notes

### 16. Interference in sound waves (with Motion sensor)

#### Practical skills AT a, b, c, h, i, k, l

In this investigation the interference between sound waves of identical frequency but emitted from different sources is investigated.

A Motion sensor is used to collect the distance information, this has a resolution of 1 mm.

The investigation is similar to Young's slit experiment for determination of the wavelength of light. The two sound sources represent the two slits and the sound from the speakers the light rays. However the wavelength of sound waves are much greater than light waves, and the geometry of the system is very different. The Young's calculations can give an approximate idea of what is going on, but are only valid for calculations at frequencies above about 4 kHz. Even then only for the central 2 or 3 fringes. At higher frequencies and shorter wavelengths more fringes follow the pattern described in Young's formula.

The method produces some good results, to get several central peaks and troughs in the sound level a frequency of above 4000 Hz is required, this may become stressful on hearing. Consideration to hearing and damage should be given.

#### Apparatus

1. Sound sensor set to the dBA range
2. Motion sensor set to a distance range
3. Variable signal generator (ideally with a read out of the frequency)
4. 2 loud speakers (matched). 8  $\Omega$  0.3 W loudspeakers work well, connected in parallel
5. 2 clamps to secure rule / edge to table
6. Retort stand and clamp or clamp to hold Sound sensor and reflector for Motion sensor

#### Set up

Recording method	Recording time	Intersample time
Graph	10 seconds	20 ms

If a trigger is required, use the setup shown below.

Recording method	Total recording	Intersample time	Trigger level
Graph	10 seconds	20 ms	When the Motion sensor rises above 0.2 m

The trigger distance is for when the target on the Sound sensor is moved away from the Motion sensor. Start will start logging but wait for the start condition to be met before the data is recorded. Move the Sound sensor and target away from the Motion sensor and when the trigger is reached the data will record.

#### Practical notes

The loud speakers need to be of identical type; ideally they should be matched from a PC sound system or similar. Simple speakers without crossovers or frequency filters are best.

The results will vary according to the distance of separation of the speakers and the position of the Sound sensor from the speaker. If the speaker separation and the distance from the speakers to the Sound sensor are the same, then the central fringe width will be equal to the wavelength of the sound.

$$\Delta x = \frac{\lambda D}{s}$$

Key:

$\Delta x$  = Fringe separation

D = distance from speakers to sensor

S = Separation of the speakers

$\lambda$  = Wavelength of the sound

Using a frequency of 4 kHz with D = s = 0.5 m or 1m the fringe separation will be about 8.7 cm at 25°C

2 kHz is a particularly intrusive frequency, and should be avoided. Higher frequencies give more interference spots. Start with a frequency of 4 kHz

Using the Motion sensor allows the collection of more data points and produces the distance data directly. It does require a little more skill in moving the Sound sensor towards the Motion sensor. It is recommended that a practice of the technique is undertaken before collecting “live” data. Don’t be surprised if the results are erratic on the first few attempts, once the technique is developed results are very reproducible.

The dial settings on signal generators do not always give a linear response even though the numbering upon them is linear.

If you have the rule / edge clamped to the edge of bench it becomes possible to push or pull the Sound sensor along the edge. This keeps the distance from the Sound sensor to the speakers more constant.

Remember to make sure that there is nothing between the Sound sensor and the Motion sensor or you will simply end up measuring the distance to that object and not to the Sensor.

We found it was simpler, to tape a long rule / rod to the base of the stand the Sound sensor was clamped to and pull the Sound sensor towards the experimenter. Pushing tended to make the Sensor turn in an unpredictable manner, it does work but takes more effort and practice!

The applet on [www.Falstad.com/interference](http://www.Falstad.com/interference) could be of use in showing the interference in sound from 2 points. It allows the user to change the distance between the sound points and the frequency.

### Analysis of the results

The sample data was collected using a frequency of 4055 Hz. This was chosen as it gave a number of dips / peaks and was a frequency that did not annoy the experimenter!

Once the data has been collected and presented as a Sound against Distance graph the students will only need to use the Values tool to collect information about the distance between peaks and lows



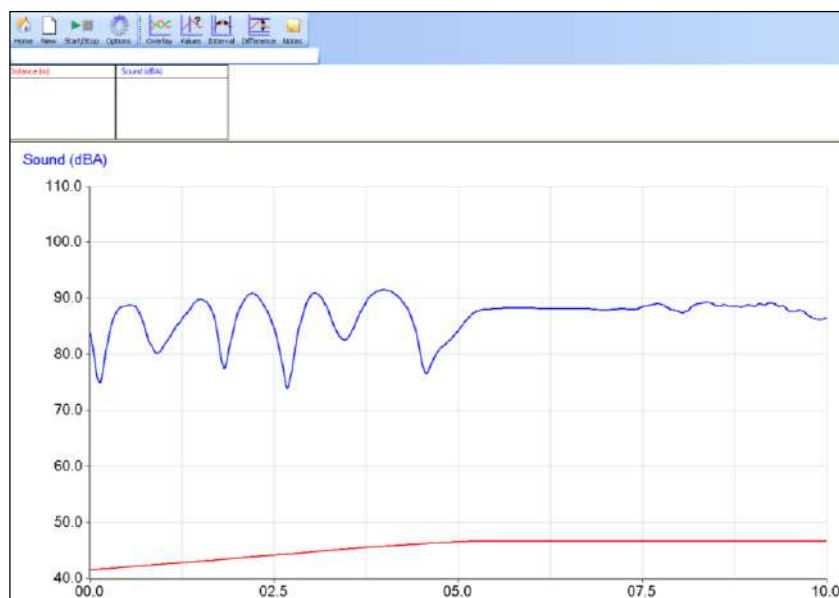


Fig 17.1. Interference in sound waves measured using a Motion sensor to record distance

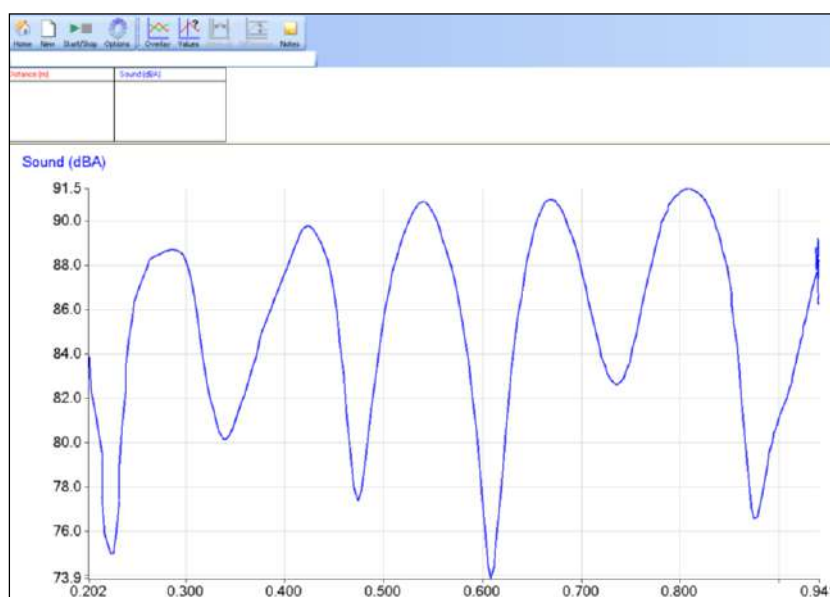


Fig 17.2 The same data plotted as Sound vs. Distance and Auto scale used.

Useful Definitions and formulae

**Wavelength (metres)** = Speed of sound (metres per second) / Frequency (Hz)

**Frequency (Hz)** = Speed of sound (metres per second) / Wavelength (metres)

**Speed of sound** is 331 metres per second at STP, giving a value of  $346 \text{ ms}^{-1}$  at  $25^\circ\text{C}$

### Example calculations

From graph average distance between fringes is 13.5 cm.

Wavelength calculated from fringe separation

**Wavelength** = distance between fringes x distance between speakers / Distance from slits to sound sensor.

$$= (0.135 \times 1) / 1.55$$

$$= 8.7 \text{ cm}$$

Distance between speaker centres = 1.0 m

Distance from speaker centres to Sound sensor = 1.56 m

**Calculated distance between fringes =  $\lambda/s$ .**

$$(0.087 \times 1.55) / 1.00 = 0.1348 \text{ m or } 13.5 \text{ cm}$$

From graph average distance between fringes is 13.5 cm.

**Frequency calculated from experimental data**

$$F = \text{Speed of sound} / \lambda$$

$$= 346 / 0.087$$

$$= 3977 \text{ Hz}$$

Frequency on the signal generator indicated at 4055 Hz

I.e. a 2% error / difference to be accounted for. Most likely in the speed of sound value and the coarseness of the snapshot to give the inter fringe distance.

Wavelength calculated from indicated value of the signal generator

**Wavelength (metres) = Speed of sound (metres per second) / Frequency (Hz)**

$$\lambda = 346 / 4055$$

$$= 0.0853 \text{ m or } 8.5 \text{ cm}$$

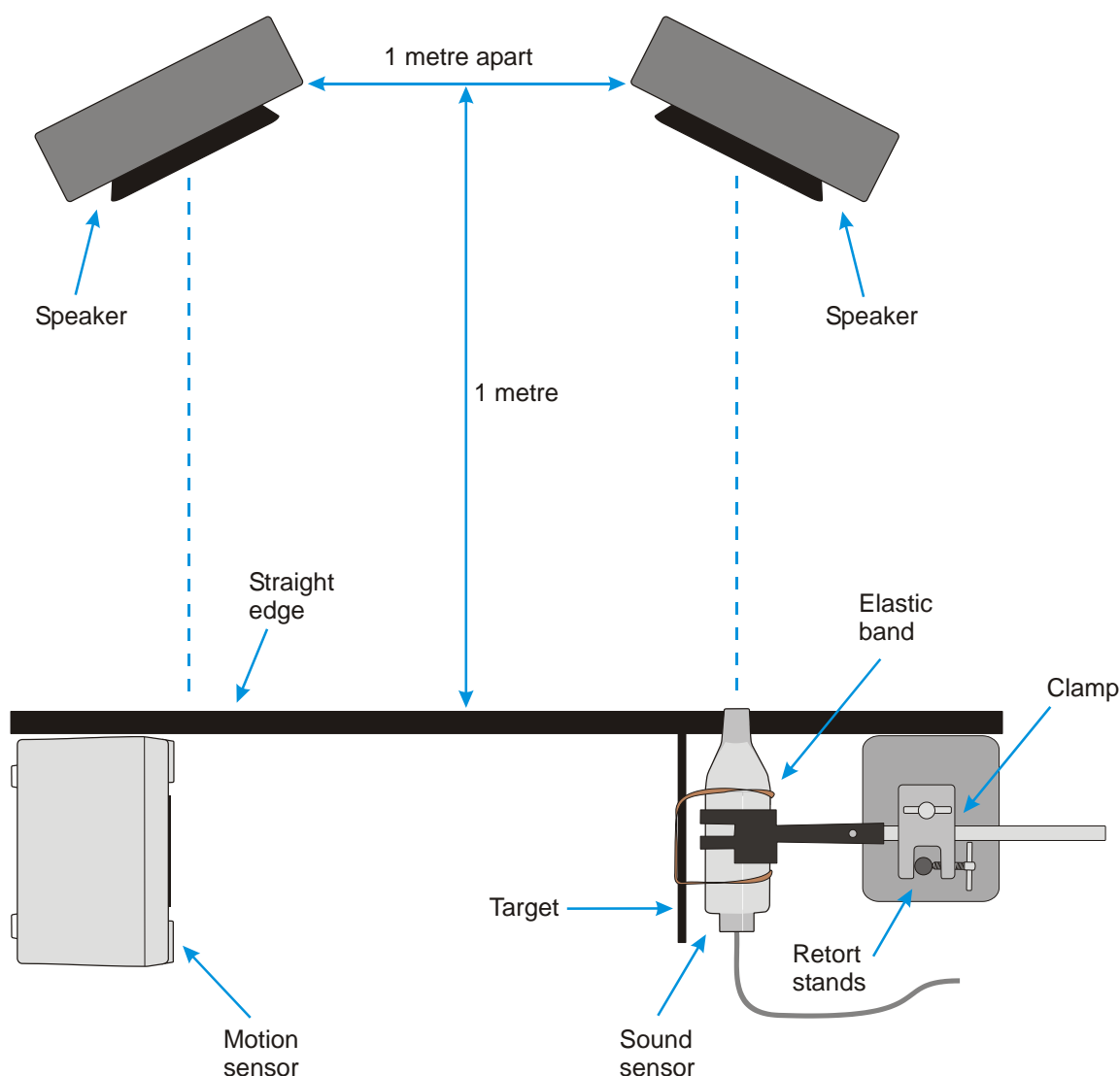
This is in very good agreement with the value calculated from the fringe separation.

## 16. Interference in sound waves (with Motion sensor)

### Practical skills AT a, b, c, h, i, k, l

When you set up a stereo sound system the instructions indicate it is important to position the speakers correctly and to wire them up correctly. One of the reasons for this is that sound waves will interfere with each other and set up constructive and destructive interference patterns. As a listener to a system you will experience areas of loudness and quiet as you move your head or as you move around the room. On a larger scale the same can happen with large public address systems as you might find in railway stations or airports, in poorly designed systems the interference can be so bad as to make the spoken information unusable.

In this investigation you will use two speakers connected to a signal generator. Each speaker will produce the same frequency of sound and with matched speakers the same volume of sound. By moving a Sound sensor across the front of the speakers you will be able to pick up the areas of interference as changes in the amount of sound detected.



## Apparatus

1. Sound sensor set to the dBA range
2. Motion sensor set to a distance range
3. Variable signal generator (ideally with a read out of the frequency)
4. 2 loud speakers (matched). 8 ohm 0.3 W loudspeakers work well, connected in parallel
5. 2 clamps to secure rule / edge to table
6. Retort stand and clamp or clamp to hold Sound sensor and reflector for Motion sensor

## Method

1. Connect the Sound sensor and Motion sensor to the data logger.
2. Set up the apparatus as shown above, the speakers should be turned a few degrees to point towards the centre point of the straight edge that the Sound sensor is moved along.
3. The straight edge should be running parallel to the line that joins the two speakers.
4. The Sound sensor should be at least 1metre from the line joining the speakers.
5. Set up to record:

Recording method	Recording time	Intersample time
Graph	10 seconds	20 ms

6. Turn on the signal generator and set it to produce a sine wave at 4 kHz, check both speakers are reproducing the tone.
7. Select Test Mode (Tools) and move the Sound sensor along the base line across the width of the speakers, to check that a variation in sound is being detected. Depending upon the distance from the speakers and the speaker separation you may get only one dip in sound level.
8. Cancel Test Mode when you are happy you have everything in the correct place.
9. Place the Sound sensor with the target attached at one end of the straight edge; make sure the Sound sensor is pointing to the centre of the speaker it is opposite.
10. Check the Motion sensor is pointing towards the target on the Sound sensor and there are no obstructions between it and the Sound sensor. You may wish to practice pushing the Sound sensor towards the Motion sensor to get the timing correct.
11. When you are happy that everything is set up correctly, select Start.
12. Move the retort stand along the straight edge until the Sound sensor is next to the Motion sensor, try to use the full 10 seconds to do this.
13. Turn off the signal generator, and save the data.

## Results

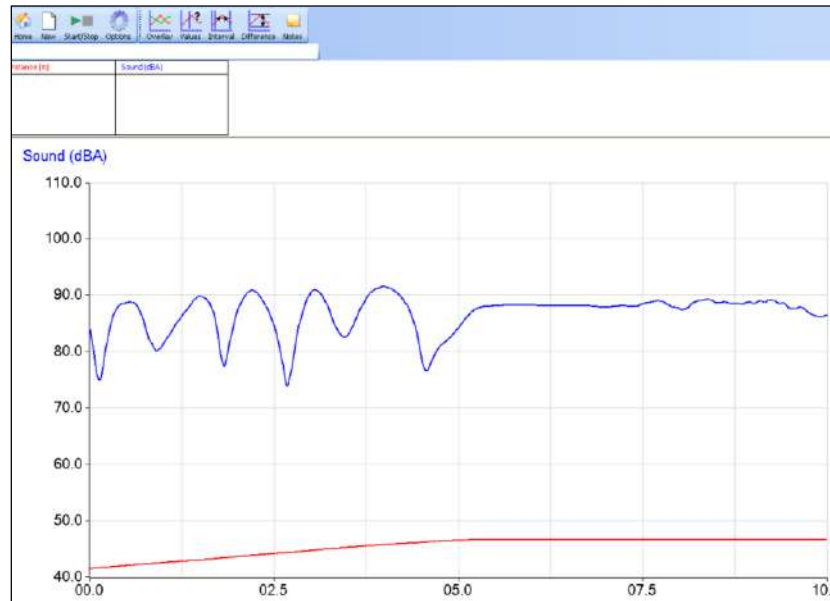


Fig 17.1 Example of the data you should have collected.

In this example the time taken to push the Sound sensor across the width of speakers was not well matched to the recording time. The flat line at the left of the graph is where the Sensor was left stationary until the logging stopped

### Display the data as Sound against Distance

Click on Options, X–Axis and select Channel as the x-axis.

To get Sound on the Y axis and Distance on the X axis, click in the white space outside the graph area. Each time you click the axis label should change, if it does not you are not clicking in the correct place.

You should have a graph similar to one below,

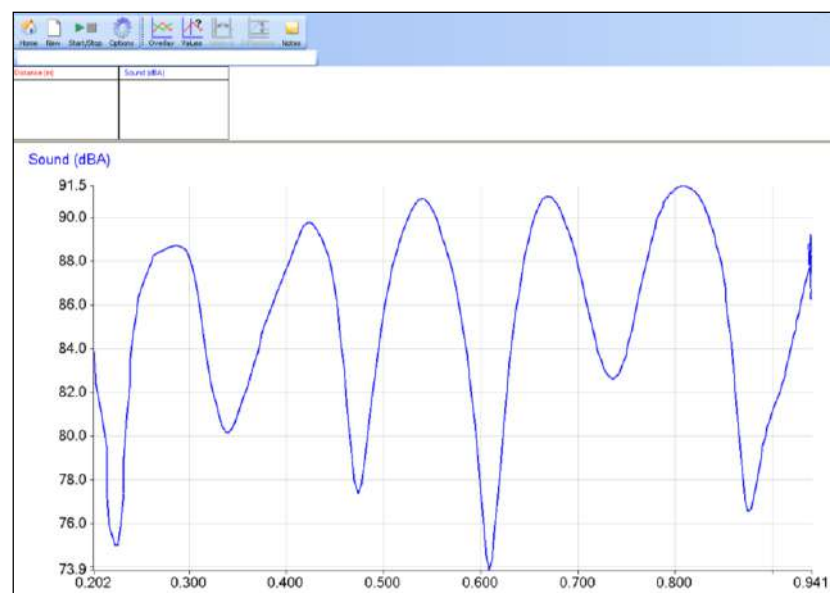


Fig 17.2 Example of the data plotted as intensity of sound against distance

**Calculate:**

1. Wavelength from fringe separation.
2. Theoretical distance between fringes.
3. Frequency of the sound source.
4. Wavelength from sound generator indicator.

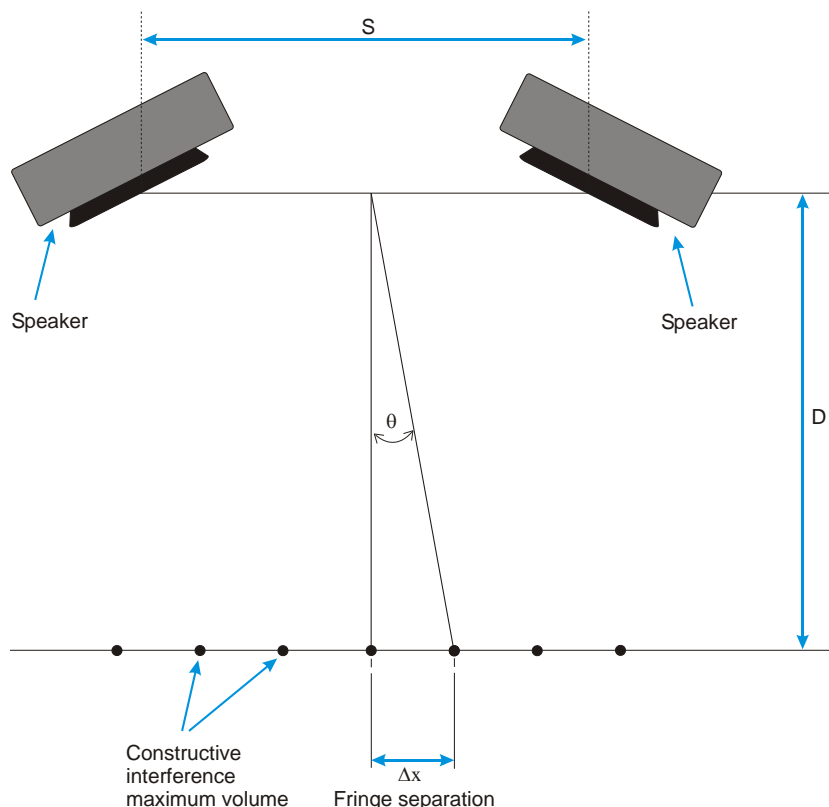
**Questions**

1. What is the distance between the peaks in the trace?
2. What is the wavelength of the tone you selected?
3. What is the relationship between the wavelength and the distance between the peaks/ dips in the recorded trace?
4. How well do the theoretical values agree with values from experimentation?
5. What is the error between theory and practical?
6. What could be the sources of error?

**Extension**

1. What happens if you record the sound level as you move closer to the speakers? Is it a similar pattern to the one recorded?
2. Can you predict where the null points will be? Select a tone / frequency and try.
3. Try different arrangements of speaker patterns to see what happens.
4. If you have access to a second signal generator find out what happens if each speaker is producing a different tone.

## Theory



The dots in the diagram show the approximate position of constructive interference i.e. maximum. The speakers are about 1 m apart and the Sound sensors 1 m in front of them. The position of the minima will be half way between the maxima, and therefore the fringe separation is the same for maxima and minima.

For the first maximum away from the central maximum, there must be a path difference of  $\lambda$ .

The theory for the interference between the two sound sources is approximately the same for two slits in Young's two slit experiments with light, for frequencies of 3 - 4 kHz and above. At these frequencies it is only the central fringes that are predicted by Young's formula. As the frequency rises above 4 kHz, the position of more fringes can be predicted.

Young's formula for two slit interference is:-

$$\therefore \Delta x = \frac{\lambda D}{s}$$

$\Delta x$  = Fringe width

$\lambda$  = Wavelength

$D$  = Distance from slits/speakers to the sensor

$s$  = distance between the slits/speakers

Young's slits calculation uses small angles so  $\sin\theta = \theta = \tan\theta$ ; it is therefore best practice to confine the analysis to the central section of the fringe pattern.

If you did the extension work you will have found that:

$$\Delta x \propto D$$

for the central fringes above frequencies of 3 to 4 kHz.

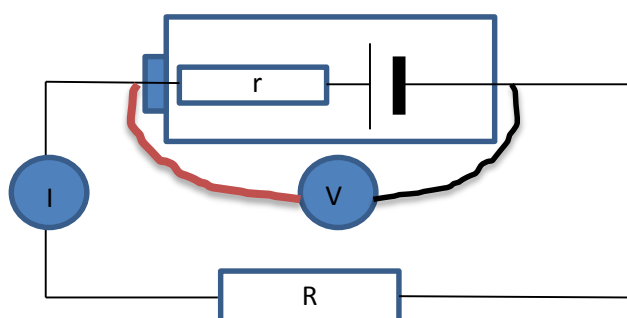
## Teacher's notes

### 17. EMF and internal resistance

#### Practical skills AT a, b, f, k

The internal resistance of a cell can be calculated mathematically, but an experimental determination can be a useful tool when introducing the topic.

The aim is to provide a basis for the derivation and use of the equation that relates e.m.f, potential difference of the cell (measured at the terminals), and the internal resistance.



If we use a Current sensor in series (at I on the diagram) and a Voltage sensor across the cell we can make several measurements of the voltage and current in the circuit with different resistances in place. A switchable resistor module makes life easier, or you could use a variable resistor. The student worksheet makes reference to “measuring the voltage across the cells”, and is attempting to take into account the point of learning / knowledge the student may have when undertaking this work. We should be using the terms p.d. and or e.m.f, unfortunately we are using a Voltage sensor, similarly the circuit diagram uses a circled I to denote the placement of the ammeter. This is a simplistic approach to link the elements used in the theory and mathematics to the practical equipment. Experience has shown that students are not fully adept at swapping terms in and out of equations (regardless of their exposure to advanced mathematics) and the use of “elements” used in equations with consistency does pay dividends.

The data can be used within EasySense, exported to Excel or used to manually plot a graph, this really depends upon the skills you are supporting through this activity.

#### Apparatus

1. Current sensor,  $\pm 100$  mA
2. Voltage sensor  $\pm 12$  or 20 V
3. Good condition cell (new cell fresh from packaging)
4. Poor condition cell (cells that have been used)
5. Cell holder with 4 mm posts (you will need at least 2 cells)
6. 4 mm plug patch cables
7. Resistor selector

#### Set up

Select SnapShot as the recording method.



## Practical notes

The equipment used is fairly basic and can be modified to suit any prep room. Most alternatives to the work described use a rheostat as a variable resistor. The fixed value resistor block offers an alternative and quick way to complete the practical, you could also use discrete resistors but this takes away from the simplicity of the practical.

When using a variable resistor in the circuit you need to be mindful of the fact that you are shorting the cell and the device needs to be able to carry the power, additionally some basic variable resistors can have less than linear resistance and introduce noise. Again in the following discussion use of such apparatus, as long as it does not distract from the purpose, can lead to consideration of the appropriate apparatus for the practical.

We found that the internal resistance of the Voltage and Current sensor were responsible for values different from published values. The Voltage sensor has a mega ohm of internal resistance and the 100 mA current sensor 1.8 ohms.

Using more cells gave better values, the effects of resistance on small currents and readings was reduced. The sensor is not really suitable for measuring single cells.

### Sources of errors / differences:

1. Simple resistance of the apparatus. The quality of the patch leads, connectors, battery end caps all give additional resistance. For example testing the continuity through the connecting pillars to first cell connector of the battery pack showed a resistance of 0.7 ohms.
2. The state of the battery. Reference values are for cells in ideal condition, unused and direct after manufacture. By 90% discharge the internal resistance of a cell will have risen from 0.1 to 1.2 ohms.
3. The formulation of the internal chemistry, budget cells will have a lesser formulation increasing resistance.
4. Battery package. 9 V packages have a large internal resistance over cells linked to form a 9 V battery. AA packages have a different value from the C or D package from the same manufacturer. This can make a good investigation, the method is certainly quick enough to collect the data.
5. Temperature of the cell.

In testing the practical, it is doubtful if any of these were significant alone, but cumulatively they will degrade the final answer.

### Sample data

Snapshot produces the data as a bar chart, your initial results will look similar to the screenshot shown below.

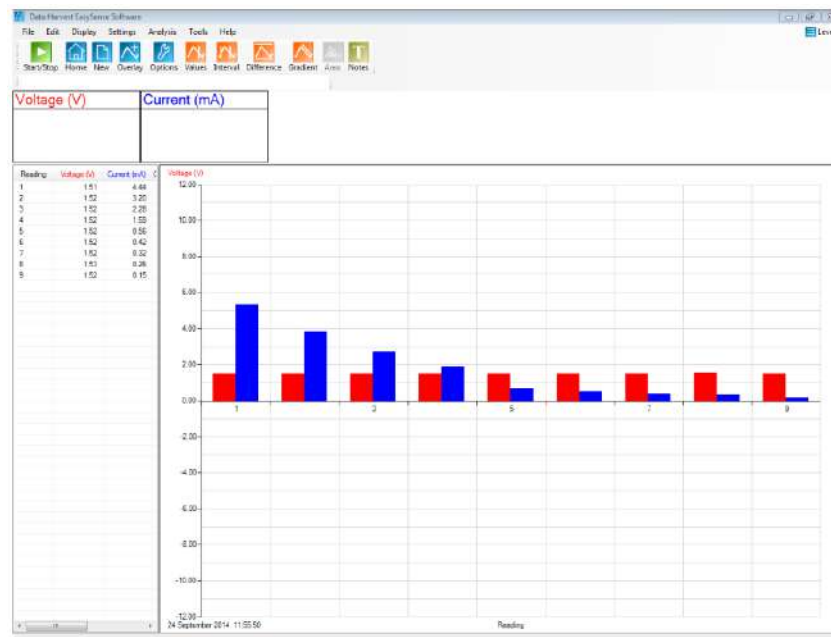


Fig 18.1 Example of data collected, table of data shown.

You have the ability to show the data as a table, refer to the software manual for details of how to reveal the table.

The data will need to be converted to an x-y graph. Use Options, X – Axis and click on Channel.

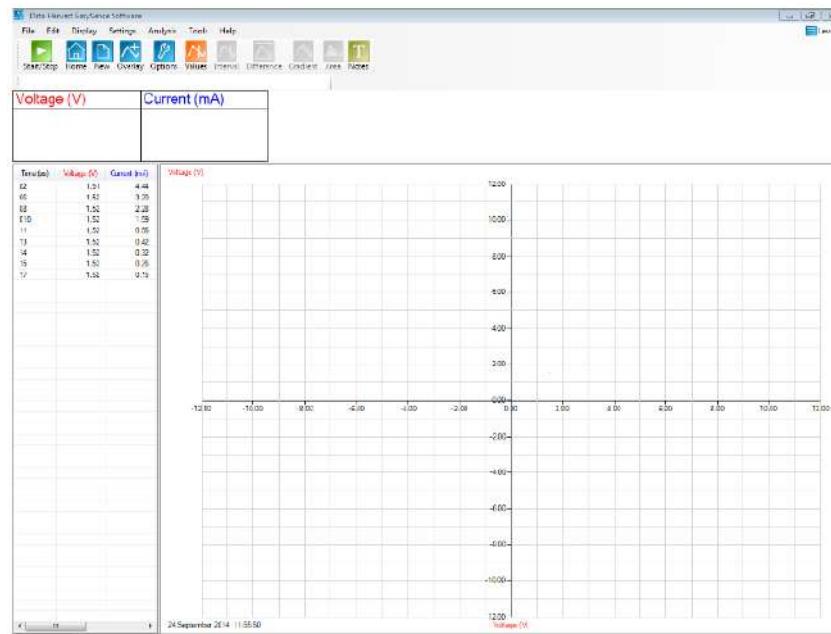
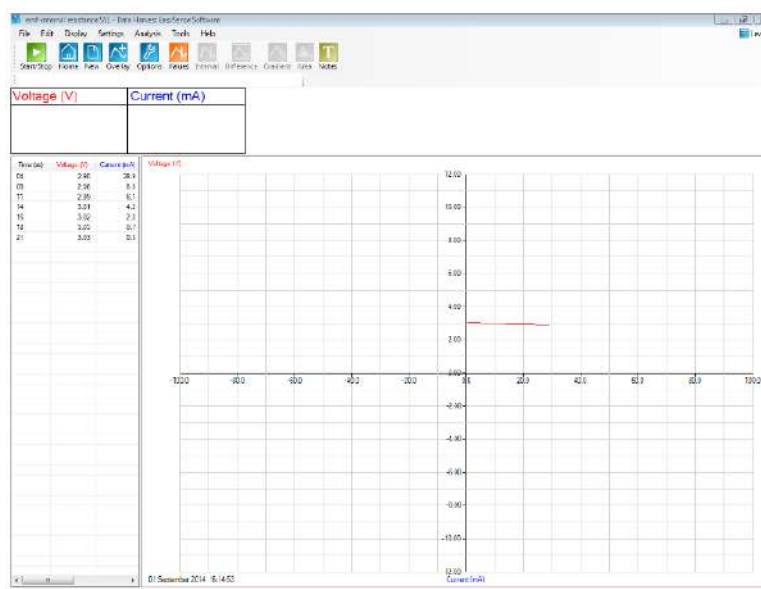


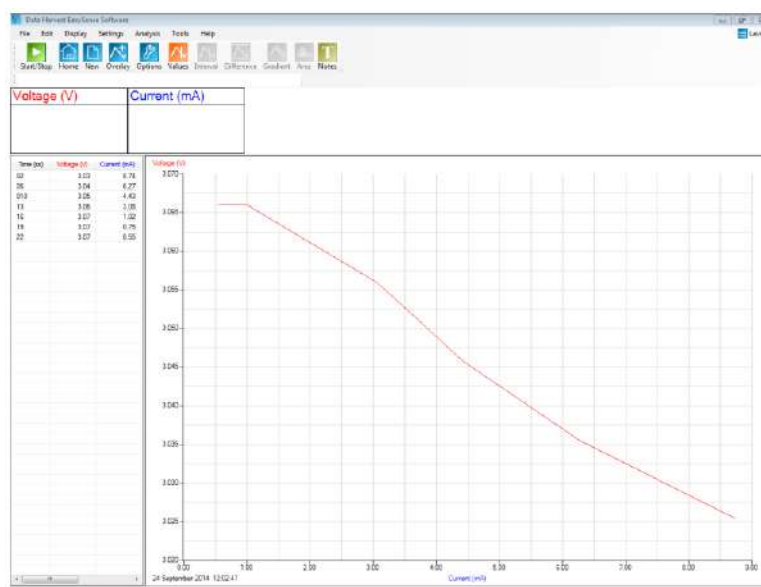
Fig 18.2 How the graph will initially appear with x axis selected as channel.

The graph will appear to show no content, this is because you have not yet defined the x and y axis, by default it plots the data from the first sensor against itself. To get the correct axis click on the scale name / axis label at the bottom centre of the graph, it will cycle through all available sensors data, select Current to the x axis.



18.2 Graph with correct channels selected for x and y axis.

Use Autoscale or Sensor settings to customise the scale for the data limits.

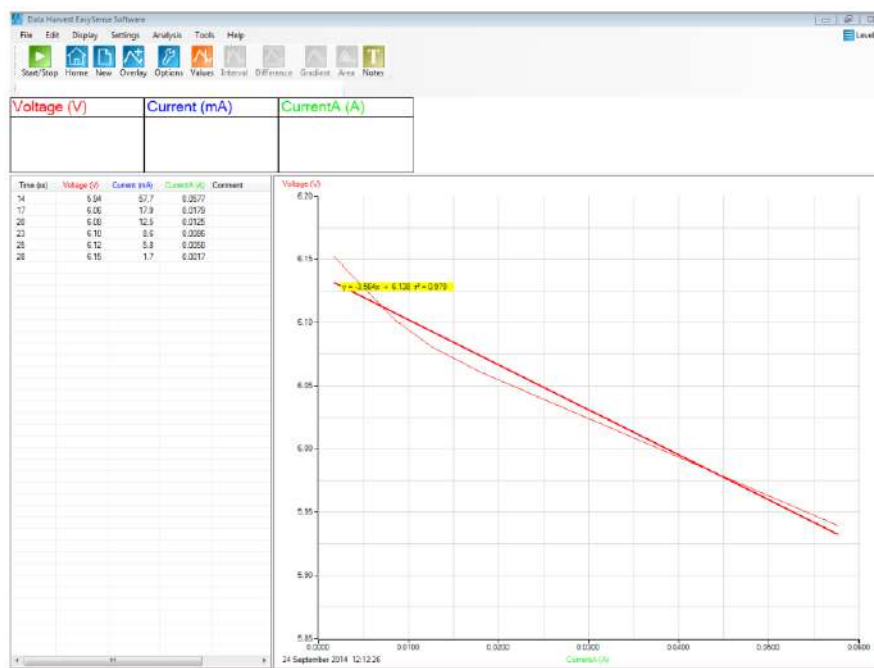


18.3 The final graph shows the linear relationship between voltage and current.

You need to find the gradient of the plotted line which tells you the internal resistance as ohms. This can be derived by traditional x/y calculation or alternatively you can use the software to create a best fit line that will show gradient data.

This will require one additional step to compensate for the current being measured in milliamps. Select Post-log Function (Tools menu), General, Divide by a Constant. Identify the Current channel to apply the constant to, apply a correction of 1000 to convert, change the name to CurrentA in A, and the number of decimals shown to reveal the full number. On the x-y graph, select Voltage as the Y axis and CurrentA as the X axis.

To add the best fit line, select Tools, Best fit. Choose Automatic and select the correct axis for X and Y. The best fit line along with the data for the  $y = mx + c$  format will appear on the line along with a regression value.



## Extension

1. You can repeat the exercise with cells that are near the end of their useful life to see how chemical changes in the cell have affected the internal resistance or use cells made from different architectures to see how the internal resistance is changed.
2. Cells from different manufacturers.
3. Cells that have been subjected to different temperatures.
4. Same voltage cells but different package types e.g. AAA, AA, C, D, etc.

## The mathematics

Several strands of electrical laws are used:

**1. Kirchhoff's 2nd Law: As charge goes around the circuit the sum of EMFs must equal the sum of voltage drops leading to:**

(remember  $V = IR$ ).

$$E = IR + Ir$$

- (E is the EMF)
- (IR is the terminal voltage)
- (Ir is the internal voltage)

The terminal voltage is equal to IR so this can be substituted and the formula rearranged to give:

$$V = E - Ir$$

and interpreted as the terminal voltage = EMF – 'lost volts'

Alternatively;

emf = pd across the Resistor,  $V_R$  + pd across cell,  $V_r$

$$\text{emf} = V_R + V_r$$

Now,  $V = I R$ , so,  $V_r = I r$  and substituting in for  $V_r$  gives

$$\text{emf} = V_R + I r$$

rearranging the equation gives:

$$V_R = \text{emf} - I r$$

So pd across the cell (or Resistor) = emf – ‘lost volts’.

**2. Energy is conserved. Imagine a unit of charge,  $Q$ , moving around the circuit:**

$$Q E = Q I R + Q I r$$

This leads to the same equations as in (1) above.

**3. Use Ohm’s law with  $E$  ‘driving’ current through the combined resistance  $(R + r)$ :**

- $I = E / (R+r)$
- Multiplying throughout by  $(R+r)$  leads to the same equations and conclusions as in (1).

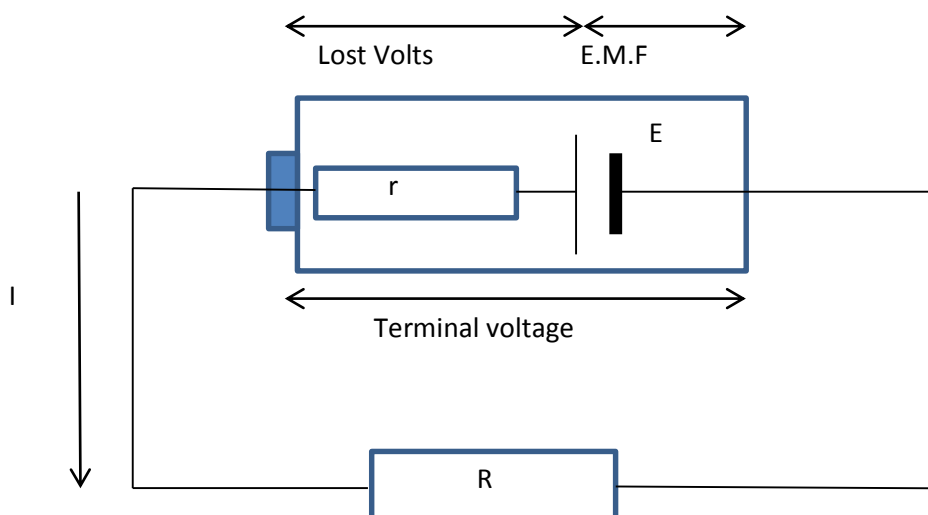
## 17. EMF and internal resistance

### Practical skills AT a, b, f, k

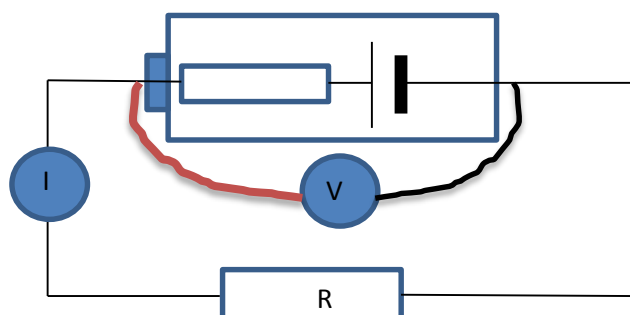
The aim is to provide a basis for the derivation and use of the equation that relates e.m.f, potential difference of the cell (measured at the terminals), and the internal resistance.

Electrochemical cells, as are used in this practical, produce an electrical potential difference through chemical reactions. If the terminals of a chemical cell are connected together through a resistor, a current will flow out of the (more) positive terminal to the (more) negative terminal. At the same time, inside the cell the chemical reaction will attempt to drive a current flow from the more negative region to the more positive region. The molecules involved in the chemical reaction will be subject to various forces that control the rate of reaction, these forces will act as a resistance to current flow. This resistance to current flow inside the cell is known as the internal resistance ( $r$ ).

If the cell has low internal resistance the current flow will be very high, in severe cases the entire charge in the cell will try to transfer across the terminals instantaneously causing the cell to overheat and or explode. Cells with a high internal resistance will deliver current much more slowly. Adding resistance into the circuit will have the same effect as the internal resistance.



To measure the internal resistance a variety of known resistances ( $R$ ) will be inserted into the circuit. The voltage across the cell terminals and the current in the circuit are recorded.



If we use a Current sensor in series (at I on the diagram) and a Voltage sensor across the cell terminals we can make several measurements of the voltage and current in the circuit with different resistances in place. A switchable resistor module makes life easier or you could use a variable resistor.

## Apparatus

1. Current sensor  $\pm 100$  mA
2. Voltage sensor  $\pm 12$  or 20 V
3. Good condition cell (new, fresh from packaging)
4. Poor condition cell (cells that have been used)
5. Cell holder with 4 mm posts (you will need at least 2 cells)
6. 4 mm plug patch cables
7. Resistor selector / variable resistance.

## Method

1. Set up most of the circuit as shown in the circuit diagram, but leave out the resistor.
2. Connect the Voltage and Current sensor to the data logger.
3. Select SnapShot as the recording method.
4. Select Start.
5. Place the lowest value resistance you have into the circuit and complete the circuit, and immediately click in the graph area to collect the snapshot data value.
6. Open the circuit to preserve the cell.
7. Check to make sure both the voltage and current are giving positive values. If one or both are negative swap the sensor leads around and retest. If you had to swap the leads round you will need to restart the recording, click on New to re-start.
8. Swap to the next resistance and take the next reading.
9. Repeat with as many resistances produce a current that can be measured.
10. When you have collected sufficient data (at least 5 values), Stop logging
11. Disconnect the cell and Save the data.
12. Plot a graph of V against I. Draw the best fit line. The gradient will be  $-r$  and the intercept on the y axis is  $\epsilon$ .

Comparative values are available on the internet, not normally brand specific, but for a type of cell (e.g. alkaline, lead acid, Li-ion, etc.).

For example a set of 4 cells was used and a value of 3.56 ohms was determined. This needs to be divided by 4 to give the average resistance per cell, to give 0.89 ohms. A reference value for Alkaline cells is between 0.2 and 0.1 ohms (temperature dependant).

We need to account for the error.

- Consider where additional resistance may exist in the circuit. How you think this would alter the values?
- How could you reduce the errors to get a value closer to the reference value?

You can repeat the exercise with cells that are near the end of their useful life to see how chemical changes in the cell have affected the internal resistance or use cells made from different architectures and compositions to see how the internal resistance is changed.

### The mathematics

Several strands of electrical laws are used:

**Kirchhoff's 2nd Law:** As charge goes around the circuit the sum of EMFs must equal the sum of voltage drops leading to:

(remember  $V = IR$ )

$$E = IR + Ir$$

- (E is the EMF)
- (IR is the terminal voltage)
- (Ir is the internal voltage)

The terminal voltage is equal to IR so this can be substituted and the formula rearranged to give:

$$V = E - Ir$$

and interpreted as the terminal voltage = EMF – 'lost volts'

### Alternatively;

emf = pd across the Resistor,  $V_R$  + pd across cell,  $V_r$

$$\text{emf} = V_R + V_r$$

Now,  $V = IR$ , so,  $V_r = Ir$  and substituting in for  $V_r$  gives

$$\text{emf} = V_R + Ir$$

rearranging the equation gives:

$$V_R = \text{emf} - Ir$$

So p.d. across the cell (or resistor) = emf – 'lost volts'



## Teacher's notes

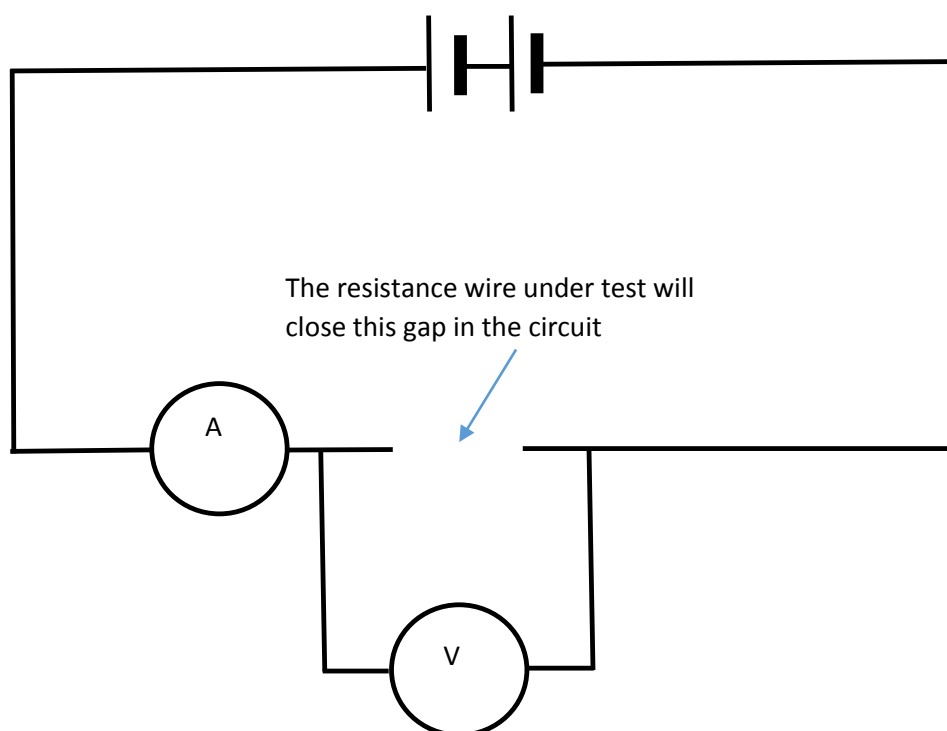
### 18. How does the resistance of a wire depend upon its length?

**Practical skills AT a, b, e, f, g, k**

The practical uses constantan wire which has a known resistance per metre at a given temperature.

#### Apparatus

1. Current sensor  $\pm 1$  A
2. Voltage sensor  $\pm 12$  or 20 V
3. A 1.5 V battery or suitable (smoothed) power supply
4. Two crocodile clips
5. 0.236 mm diameter (34 swg) constantan wire (11.2 ohms/metre)
6. Metre rule
7. 4 mm patch leads
8. Masking tape
9. Vernier calipers or a micrometer gauge



#### Practical notes

The recommended wire 34 SWG constantan gives a reading of just under 1 A at 10 cm with a 1.5 V cell. The current will vary with the condition of the cell being used and the cell technology. On this basis we would recommend instructing the students to go no closer than 20 cm from zero. Data will be a good straight line and a line that passes through 0/0 is easily achievable as a value for the resistance per meter that is within 5% of the given specification for the wire.

The crocodile clip connected to the end of the wire will remain fixed, the other crocodile clip will be used as a jockey along the length of the wire. The position of the jockey relative to the fixed crocodile clip will be the length measurement. It may be necessary to show students and reassure them of the language used to describe the set up and use of the apparatus.

The resistance of the wire is proportional to the length of the wire. Constantan wire has defined values of resistance per metre, the information should be on the spool. You can use a resistance meter to find the ohms / metre value for reference.

## Set up

SnapShot
The user clicks in the graph area to record the currently displayed data

Or:

Meters
Open 2 Numeric sections, one for Voltage, one for Current. Values will need to be copied down into table of results.

For the EasySense software to calculate and display the resistance you will need to collect the data in SnapShot mode, then go to Tools, Pre-log Function, Electricity, Resistance. Make note of the multiplier that is required to correct for mA and mV. When you click on the graph area to record a reading the resistance will be calculated and displayed. Students should adjust the reading for significant figures.

Use the Vernier or micrometer to find the diameter of the wire and hence calculate the cross sectional area.

The resistivity of constantan wire is.

$$P = RA/L$$

The gradient of the graph gives  $R/l$

So

$$\rho = \text{gradient} \times A \text{ in } \Omega\text{m (accepted value is } 4.9 \times 10^{-7} \Omega\text{m)}$$

## Alternative (s)

1. Put a lamp in series with the resistance wire and use the change in brightness of the lamp as an indicator of current. You could use a Light level sensor to give a reading for the lamp brightness.
2. Have preselected wires of the same length but different diameters. Measure and relate diameter to resistance.

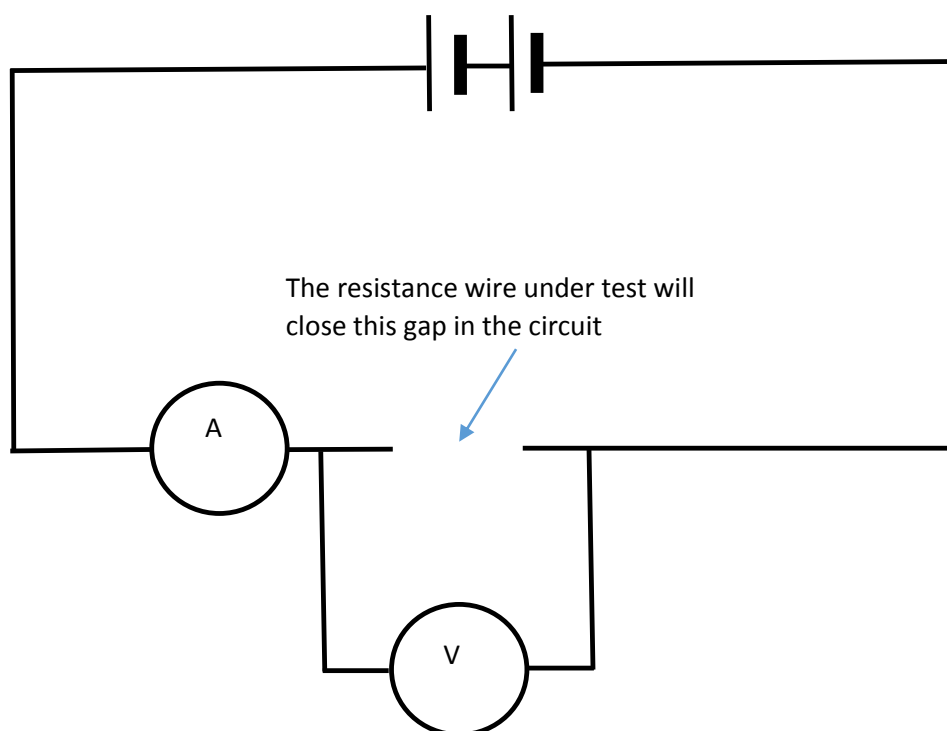
## 18. How does the resistance of a wire depend upon its length?

**Practical skills AT a, b, e, f, g, k**

The practical uses constantan wire which has a known resistance per metre at a given temperature.

### Apparatus

1. Current sensor  $\pm 1$  A
2. Voltage sensor  $\pm 12$  or 20 V
3. A 1.5 V battery or suitable (smoothed) power supply
4. Two crocodile clips
5. 0.236 mm diameter (34 swg) constantan wire (11.2 ohms/metre)
6. Metre rule
7. 4 mm patch leads
8. Masking tape
9. Vernier calipers or micrometer gauge



### Method

1. Make up the circuit as shown in the diagram. The supplied metre stick and wire fills the gap in the circuit as indicated.
2. Connect the Voltage and Current sensors to the data logger.
3. Connect the red lead of the Current sensor (ammeter) to the black lead of the Voltage sensor. Fix a crocodile clip onto the exposed 4 mm plug and clip to the 0 metres end of the metre rule and wire.
4. Fix a crocodile clip to the red lead of the Voltage sensor, this will be the contact to the resistance wire at the measured distances. Do not attach this clip to wire at this stage. This wire is the jockey.

5. Connect the other wires to complete the circuit. Check the pathway of the circuit against the diagram before progressing.
6. Select Meters as the recording method. Open a second Numeric section, set up so Voltage in one section and Current in the other.
7. Check the readings are giving a voltage and current and that the values are positive when the jockey is touched to the resistance wire.
8. Touch the jockey to the 0.900m position on the wire and record the voltage and current. Work quickly to record the data before the wire gets too hot and burns through or damages the metre rule.
9. Wait for 30 s to 1 min between readings to let the wire cool.
10. Repeat for 0.800 to 0.200 m.
11. Disconnect the battery when finished.
12. Transfer the data to a table of results.

Length of wire	Voltage V	Current A	Resistance $\Omega$

## Results

- Calculate the resistance from the voltage and current data for each distance.
- Plot a graph of resistance ( $\Omega$ ) against the length of the wire.
- Draw a line of best fit through the data, it may not go through the 0/0 point. Where would the extra resistance come from?
- Use the Vernier or micrometer to find the diameter of the wire and hence calculate the cross sectional area.

The resistivity of the constantan wire is then.

$$P = RA/L$$

The gradient of the graph gives  $R/l$

So

$$\rho = \text{gradient} \times A \text{ in } \Omega\text{m (accepted value is } 4.9 \times 10^{-7} \Omega\text{m)}$$

## Teacher's notes

### 20. Magnetic field and angle

#### Practical skills AT a, b, f, k

The activity uses a Magnetic field sensor and a coil energised by d.c. Unlike a search coil that has to be energised by an a.c. field, the Magnetic field sensor uses a Hall effect sensor which only has to be aligned at right angles to the field. This simplifies the set up.

The optional Acceleration sensor has an inclinometer range that measures the angle.

The sample data and the student sheet use EasyLog and uses the software to plot the graph. You can use meters or snapshot to record data either to a hand written table or to be saved by the software. Taking the snapshot and meters alternative opens the assessment of graphing.

#### Apparatus

1. Magnetic field sensor  $\pm 10$  mT, set to Radial range
2. Accelerometer sensor Low g 3-Axis set to the Inclinometer range. (optional)
3. A Wire coil (500 turns 32 ohm)
4. 4 mm plug patch cables
5. Smoothed d.c. voltage supply
6. Blu-Tack / modelling clay

#### Set up

Select EasyLog as the recording method.

#### Practical notes

The activity is a close match to the activity in the required skills handbook but it does not use an oscilloscope to record the voltage change in the field probe.

When using the Magnetic field sensor it has two hall sensors, an axial and a radial. Refer to the sensor handbook to make sure you understand how the sensor functions and are orientated. You should use the radial sensor which is at right angles to one of the side surfaces of the sensor. If you look close to the tip of the sensor you should see markings on the plastic case identifying the position and centre line of the hall effect sensor inside. This is not that obvious, a permanent black marker pen is advised to colour the sensor's position.

We used a voltage of 10 V to the coil this gave a current of 0.32 ohms. There was a very slight warming of the coil after 10+ minutes.

The sensors need to be arranged in a specific manner;

1. With the Smart Q label of the Magnetic field sensor facing you the axial field position mark should be on the left of the long sensor housing.
2. Place the Accelerometer against the body of the Magnetic field sensor with the lead connector of the Magnetic field sensor pointing down towards its tip.
3. Rotate the Accelerometer sensor so that the Smart Q label of the sensor is against the body of the Magnetic field sensor. You should see the range label of the Magnetic field sensor on the left side.

4. Use a rubber band or masking tape to bind them together. If you use a rubber band initially you can make changes to the position if necessary.
5. To test, connect both sensors to the logger and use Meters or test mode to show the readings from the sensors. With the Smart Q label of the Magnetic field sensor facing you, slowly rotate the sensors about the tip of the Magnetic field anti clockwise. You should see the angle decrease from 90 to about 10 degrees, the Accelerometer will stop the pair of sensors lying flat.

Dependant on the skills you are testing and the focus of the lesson you may give the sensors out combined or as separate items. The worksheet assumes the sensors have been supplied combined.

## Sample data



Fig 20.1 Easylog data of angle and magnetic field strength.

Convert the graph display make the x axis = Channel and select Inclinator as the x axis and Axial field as the y axis.

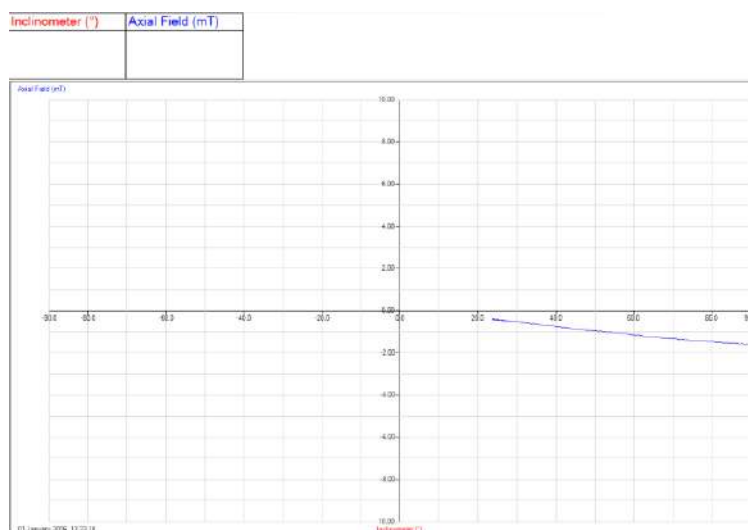


Fig 20.2 Inclinator against Axial field. The linear relationship between angle and strength is clearly seen.

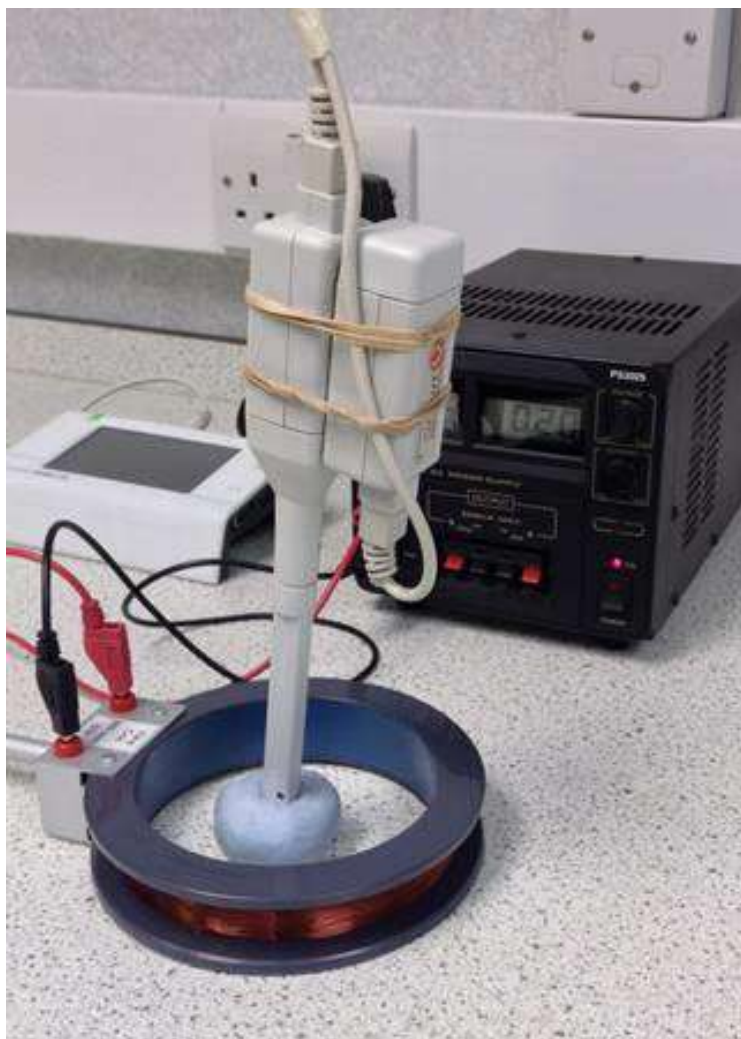
Use Auto scale to expand the graph.

Use manual Best Fit to extrapolate the data back to the origin.

## 19. Magnetic field and angle

### Practical skills AT a, b, f, k

The activity is to study the relationship between magnetic field strength and the angle.



### Apparatus

1. Magnetic field sensor  $\pm 10$  mT, set to the Radial range
2. Accelerometer, Low g 3-Axis, set to the Inclinator range (optional)
3. Wire coil (500 turns 32 ohm)
4. 4 mm plug patch cables
5. Smoothed d.c. voltage supply
6. Blu-Tack / modelling clay

## Method

The exact method and set up for the activity will depend on how the apparatus is presented and the focus of the skills being assessed. There are several alternatives and your teacher will indicate the alternative to use.

1. Place the large coil flat on the workbench.
2. Place a large lump of Blu-Tack or modelling clay in the centre of the coil. Have the height of the Blu-Tack to about half the height of the coil.
3. Connect the large wire coil to the power supply. Set the voltage to the value given by your teacher, this may vary from power supply to power supply.
4. Connect the Magnetic field sensor and Accelerometer to the data logger.
5. Use Meters or Test Mode (Tools menu) to see the readings from the sensors.
6. Start with the Magnetic field sensor upright with the tip of the sensor on the Blu-Tack. The Smart Q label of the sensor should be facing towards you. The spot marking the axial field should be pointing to the left as you look at the Magnetic field sensor. The Accelerometer, which is attached to the Magnetic field sensor should read 90 degrees in this position. As you rotate the Magnetic field sensor, the angle will change from  $90 > 0$  degrees.
7. When you are convinced that rotating the Magnetic field sensor to the left changes both the field strength and the angle set up to record either in:
  - a. EasyLog mode for the software to draw the graph.
  - b. Meters mode if data is to be recorded into a table of results.
  - c. Snapshot mode if the software is to record the data
8. Start logging and move the Magnetic field sensor in 10 degree steps (or smoothly down to 10 degrees if using EasyLog).
9. Record the angle and field strength at every 10 degrees as shown by the Inclinator.
10. Plot a graph of angle against field strength.
11. Draw a best fit line and extend back through the origin.

## Questions

1. What is the relationship between angle and field strength?
2. What is the field strength when the sensor is at 0 degrees to the coil plane?
3. Why might the origin not pass through 0/0?
4. What would happen if the voltage on the coil was reversed?
5. What would happen to the field strength if the
  - voltage was increased?
  - current was increased?
6. If you use a search coil the coil has to be energised with an a.c. current, why?
7. How does the sensor in the magnetic field sensor work with d.c.?



# Maths modelling and functions

## CONTENTS

### Mathematical modelling

Radioactive Decay – Protactinium practical vs. mathematical model .....	2
Simple Harmonic Motion (SHM) from practical vs. a mathematical model .....	6
Capacitor charge, time constant and exponents.....	17

### Mathematical tools

The Function Wizard Guide .....	23
Preset Functions .....	23
Presets detail .....	27
Formula functions.....	30
Examples of use of formula functions .....	31
To convert data from a sensor to a new scale.....	31
To derive velocity and acceleration from a time vs. distance graph .....	32
Calculating Kinetic energy.....	33
Work done in stretching a spring $\frac{1}{2}kx^2$ .....	34
Applying a correction factor .....	34
Investigating $s = ut + \frac{1}{2}at^2$ .....	35
Generating a reference curve in SHM.....	35
Generating a reference decay curve.....	36
To produce a column of identical numbers.....	36
To add two data sets together.....	37
To subtract two data sets from each other or to remove an offset .....	37
Dividing one data set by another.....	38
Multiplying two data sets together .....	38
Two variables are interdependent – but time is not involved.....	39
Creating a log linear plot e.g. for discharge of capacitor to find the time constant.....	39
Creating an absorbance data set from Transmission data .....	39

## Mathematical modelling

The table below lists the guidance and case studies in this section

Document	Outline
Radioactive decay - Protactinium	Using the half-life value of protactinium to create a model decay curve superimposed upon the data from a practical.
SHM vs. a mathematical model	Using values from practical data to produce the theoretical curve and compare the two. Verification of formulae describing sinusoidal motion.
Time constant and exponents	Using data from CR practical work to model exponential curves and time constants. Using functions to produce a log linear plot ( $-1/cr$ )

### Radioactive Decay – Protactinium practical vs. mathematical model

The radiation source that is used in schools for half-life demonstrations is the protactinium-234 generator. Protactinium has several isotopes with different half-lives, the one measured in schools is protactinium 234 with a half-life quoted from 70 s to 80 s. Wikipedia gives a value of 1 m 17 s (77s). Other isotopes have values of 6.75 hours to  $3.276 \times 10^4$  years.

Protactinium generators use Uranium (U238) and the decay products thorium and protactinium, in an acid solution with an organic top layer (usually the top half of the generator bottle). The high acidity lets the protactinium cross into the organic layer. By vigorously shaking the generator for about 15 seconds, the protactinium will cross into the upper organic layer. After shaking the generator is left standing and the organic and aqueous phases separate back to two layers. The count should start when the two layers have separated.

Uranium emits mainly low energy alpha particles which are blocked by the container glass (or plastic with modern sources), the thorium is a beta emitter but with particles of such low energy that the combination of the dense organic layer and the bottle that they are “shielded” from the Geiger Müller (GM) sensor. Some references suggest a lead foil around the lower part of the generator to cover the aqueous layer improves performance.

The GM sensor should be pointed downwards, close to the centre of the organic layer. Although protactinium is beta source the energy of the decay particles are sufficiently low that the protective cap should be removed. Make sure that the venting hole is **uncovered** when you remove the cap. The GM tube’s window is made of a very thin sheet of mica, which is a delicate material, easily destroyed, so replace the cap as soon as you’ve finished.

The number of counts coming from the generator will be low, typically we see 30 -35 counts per second at peak. In some areas background will be significant and could interfere with results. Decay is a random process, you therefore get clusters and pits of decay events. The plot of the counts per second over a time period will show high variation about an ideal exponential decay curve. Another problem is that one half-life will see the count fall from 35 to 17 to 8 to 4. A background count of 4 is not unreasonable in some areas, so you will only get 2 useful half-lives. If you were lucky enough to have more than one GM sensor you could aggregate the counts from additional sensors.

EasySense does not have a best fit to a curve function. There is however a function that will plot the exponential curve using known (data book) values. In this case we know the rate of decay (70 – 80

seconds), and we know the highest value at start. We can plug these values into the function and create an ideal curve which can be compared against the data from practical.

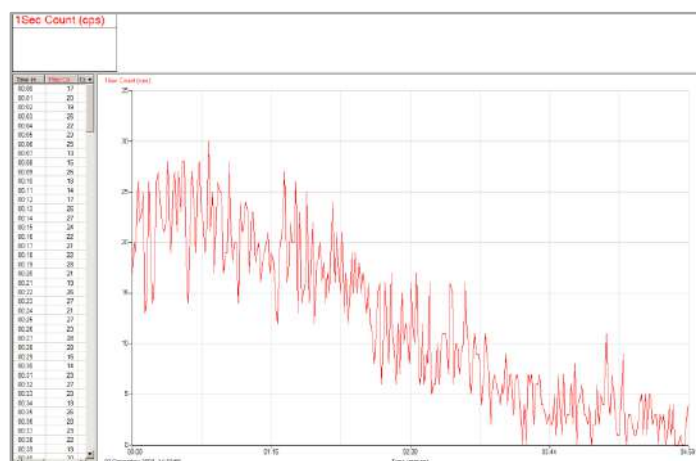
The function is:  **$a \exp(bt) + c$**

$a$  = the largest count value

$b$  = the exponent value, in this case as we are looking a decay of a radioactive species it represents  $1/\lambda$ . Remember to precede this with a –ve sign to get the descending exponential.

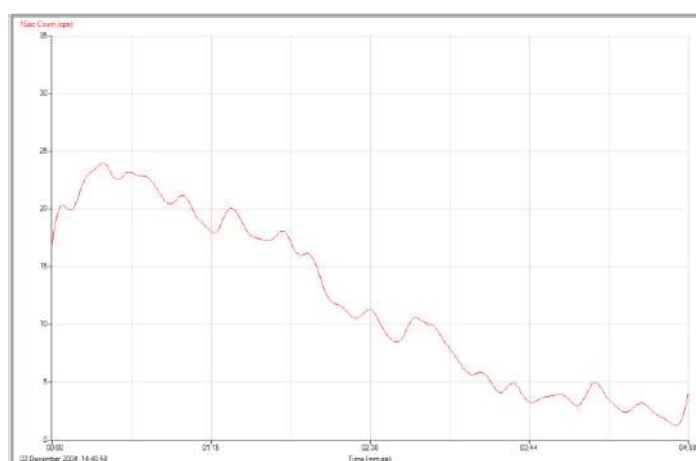
$c$  = an offset value on the y axis e.g. the first number in the table.

Our test data is from a protactinium source that had seen better years. It was giving a start count of 30 -35 counts per second. In the location where we collected data background was in the region of 3 counts per 10 seconds.



Data as collected. Note the depressed values at the start and then a short rise to a maximum value. This initial rate is attributed to starting the count before separation had been completed (while the organic solvent floated to the top).

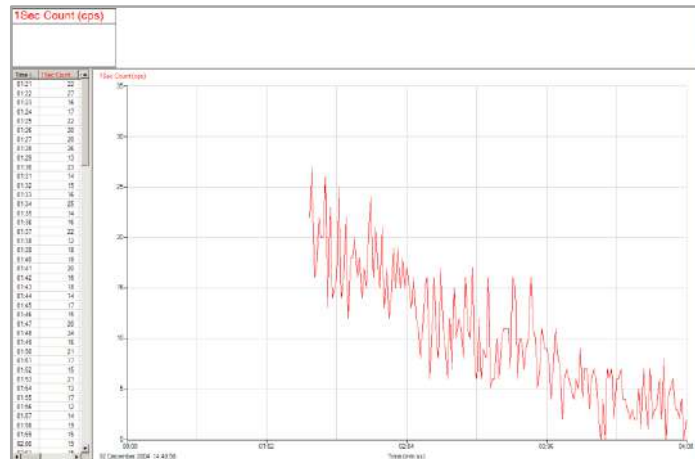
There are tools available to “declutter” the data, smoothing, rolling average, mean or the data could be exported to Excel and one of the more weighted averaging functions used. (This may soothe the soul, but will no doubt leave most learners wondering why? And suspecting a fudge of the data).



Same data after smoothing, still showing bumps and lumps.

## Using a $\exp(bt) + c$

Select then Use selection (Edit menu) to remove the “rising data” (subject to interpretation, but with this data it was until just after the first minute) and the trailing off at the end.



Use the  **$a \exp(bt) + c$**  Post-log exponential Function (Tools menu).

Enter the values for maximum count and  $1 \div \text{lambda}$  (for 77 seconds = -0.012987).

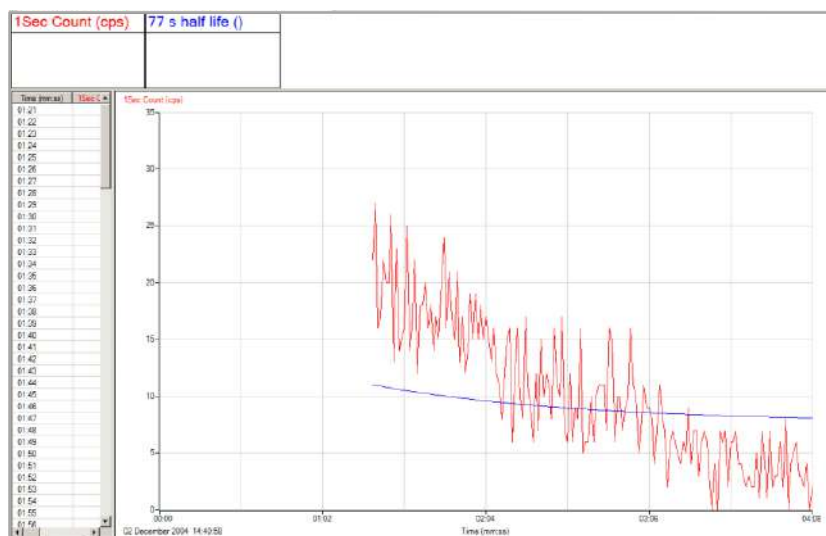
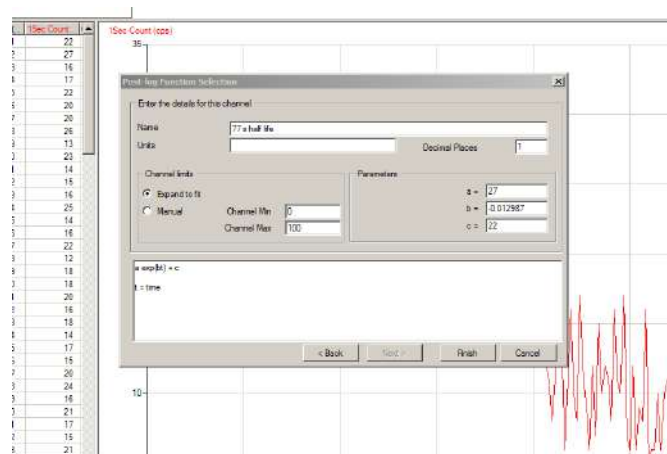
$a$  = the largest count value ( $N_0$ )

$b = 1 \div \lambda$ , the exponent value. Remember to precede this number with a -ve sign to get the descending exponential.

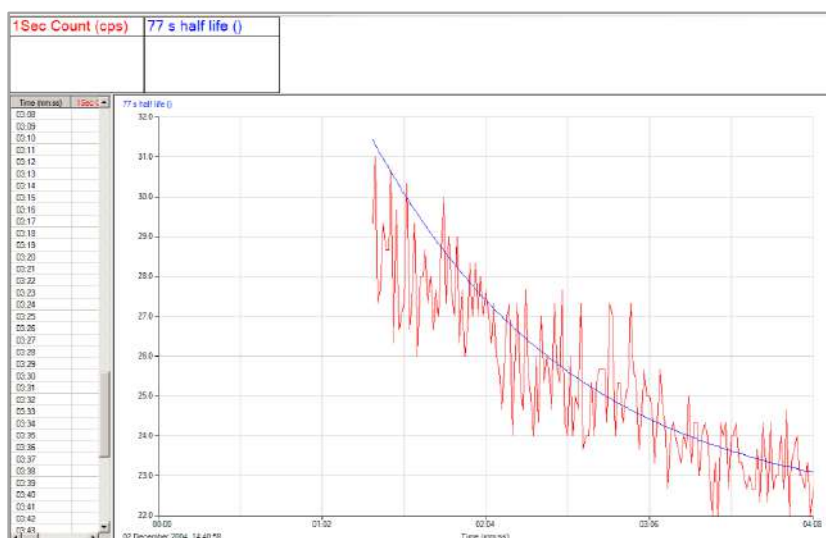
$t$  = time

$c$  = an offset value on the y axis e.g. the first number in the table.

The  **$a \exp(bt) + c$**  formula is the same as  $N(t) = N_0 e^{-\lambda t}$ .



Use Autoscale graph Min Max.

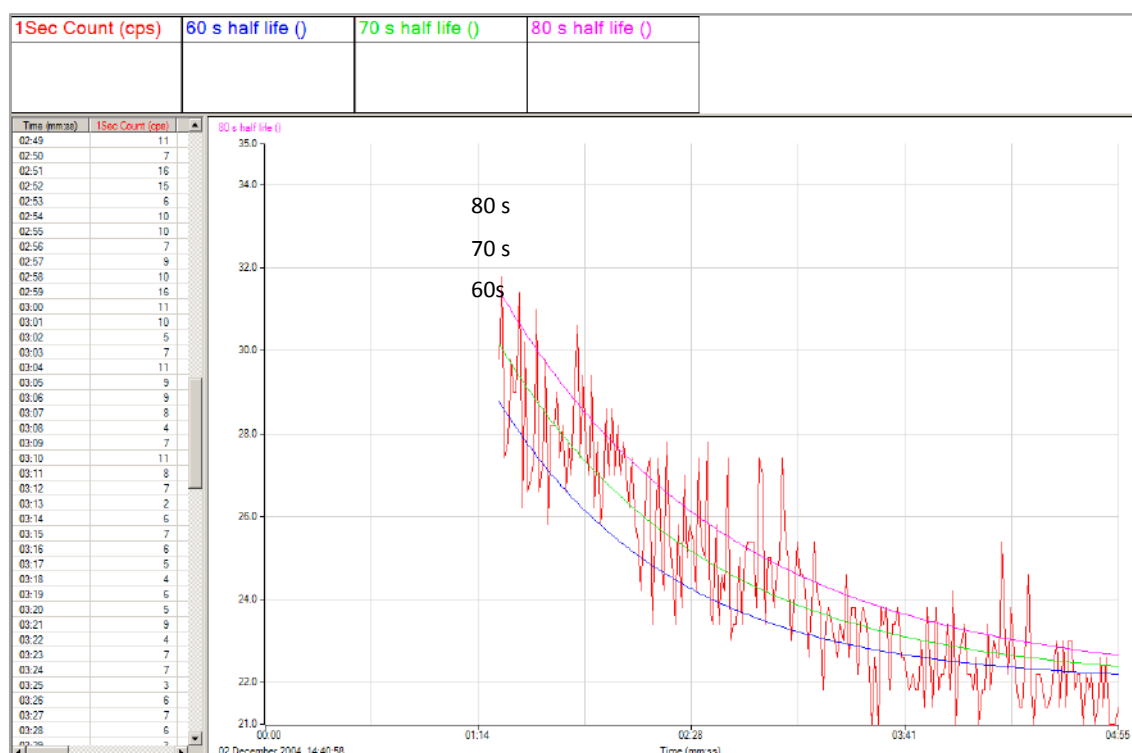


You can re-apply the formula for other half-life times to find the best match.

$$1 \div 60 = -0.0166$$

$$1 \div 70 = 0.0143$$

$$1 \div 80 = -0.0125$$



The modelled lines, representing the ideal decay lines for different half-lives.

The minimum and maximum axis limits for the three half-life data sets were set to all be the same via Sensor settings (Options).

## Simple Harmonic Motion (SHM) from practical vs. a mathematical model

Using a data logger to measure SHM is quick, easy and straightforward. The Data Harvest Physics practical book "L3 Motion and Forces" contains many alternative practical set ups to study SHM.

Collecting the displacement data against time with a data logger and its linked software, allows the sine wave to be shown alongside the physical motion of the mass. The large amount of data collected can be analysed by software, it also shows the complete oscillation not just the point measurements of peaks and oscillation intervals. The result is an expansion of a simple practical to a sophisticated learning project. Without the data logger and the use of ICT you will not be able to access this work.

You will be able to;

- Show the motion of the oscillating mass as a sine wave function.
- Calculate the velocity of the oscillating mass and display the data alongside the displacement data.
- Calculate the acceleration of the oscillating mass and display the data alongside displacement and velocity data.
- Show, and mathematically prove the phase difference between displacement, velocity and acceleration.
- Use the time base of the data collection to model the ideal sine wave for the oscillating mass being used.
- Model the ideal velocity from the ideal sine wave.
- Compare the data modelled from theory against the data from practical investigation.
- Show the Kinetic energy of the oscillation.
- Show the Potential energy of the oscillation and its relationship to kinetic energy and motion of the oscillation.
- Show total energy.
- Find period, amplitude, frequency.
- Show momentum.
- Transfer the data to Excel and use the standard formulae for Oscillations about a fixed point to calculate, velocity and acceleration to encourage understanding about the use of differentials.

This is significant advance from the simple study of period and mass that can be achieved by a stop clock and observer.

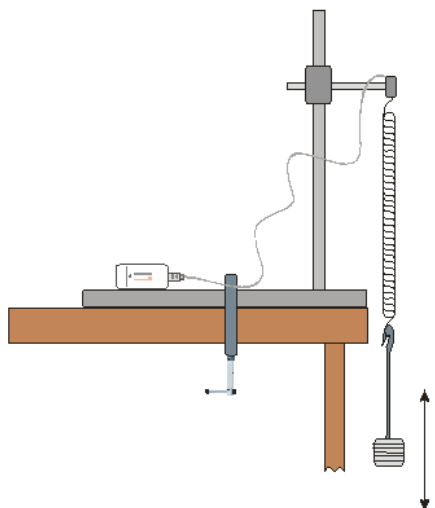
### Methods

1. Collect the displacement vs. time data for a few cycles of the oscillation using the experimental set up that you have chosen.
2. Use the software or a printout to find the period  $T$ , frequency  $1/T$  and the angular change  $\omega$ .
3. These values are then plugged into the formula for a sine wave to create a sine wave by mathematics.
4. Comparison of the curves of live data against the modelled data will confirm the mathematical description of the practical data as a sine function.

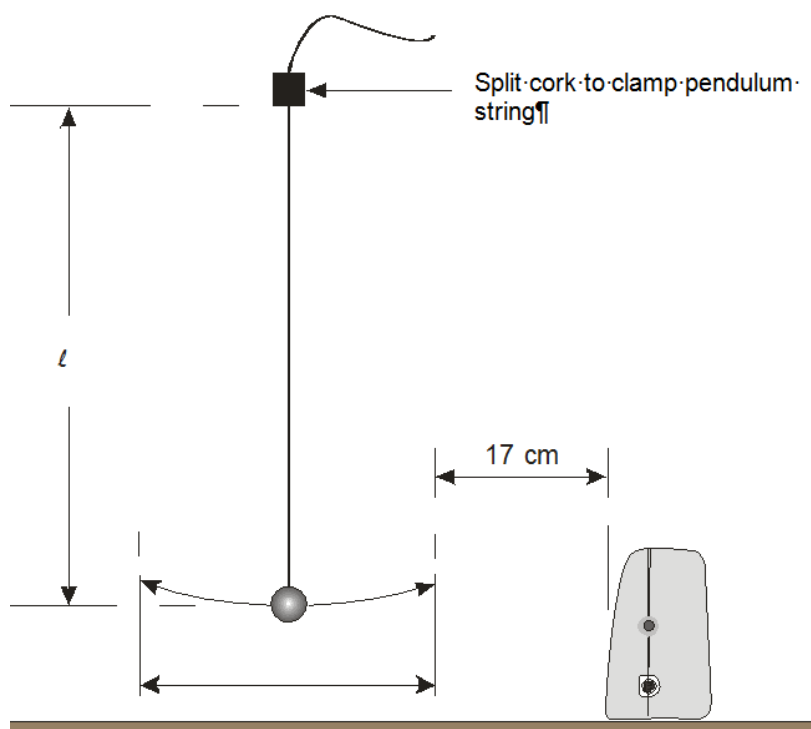
- The process can be taken further, if data is exported to Excel or a similar spreadsheet, the derivatives of the original modelled and real data can be charted again confirming that velocity really is the first derivative and acceleration is the second derivative.

Note: You are collecting and using a large data set to enhance learning and reinforce understanding. Simple collection of period data for SHM or Pendulums would not allow this.

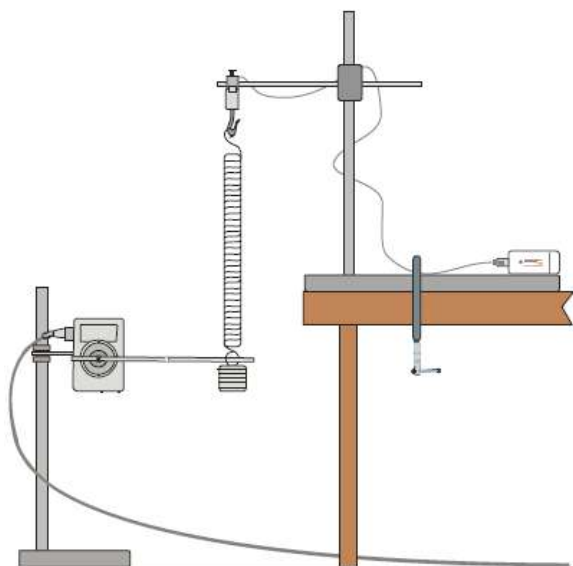
### Example practical set ups for collection of SHM data with a data logger



Ex 1. Data collected as distance vs. time using a Motion sensor. The Motion sensor is protected by a large mesh shield over the sensor.



Ex 2. Using a long pendulum for SHM. Data will be recorded as distance vs. time using a Motion sensor.



Ex 3. The spring is suspended on a Force sensor.

Data collected will be as degrees for motion from the Rotary Motion sensor and Newtons from the Force sensor. You could use a Motion sensor below the mass, as in Ex 1.



Ex 4. Apparatus to show a pendulum swing against time using a Rotary Motion sensor and a rigid pendulum. Data can be recorded as degrees or angular velocity against time.

For simplicity the RMS and pendulum is recommended, but the confusion about whether a pendulum swing represents a true SHM may mean that the extra preparation time to suspend a mass on a spring over a Motion sensor is worth it.

### Data logging settings

In all cases record the data with a 20 ms interval between samples when using the Motion sensor, or 10 ms from the Rotary Motion sensor. Collect for a total recording time of 5 seconds. Once data has been collected select out the data with the start of the oscillation at the maxima of amplitude or when the swing crosses the zero point then from the Edit menu select the Use Selection function.

N.B. Due to the transducer technology the Motion sensor cannot record data at a rate faster than 50 Hz (20 ms interval). At this speed of data collection pre-triggers not available.

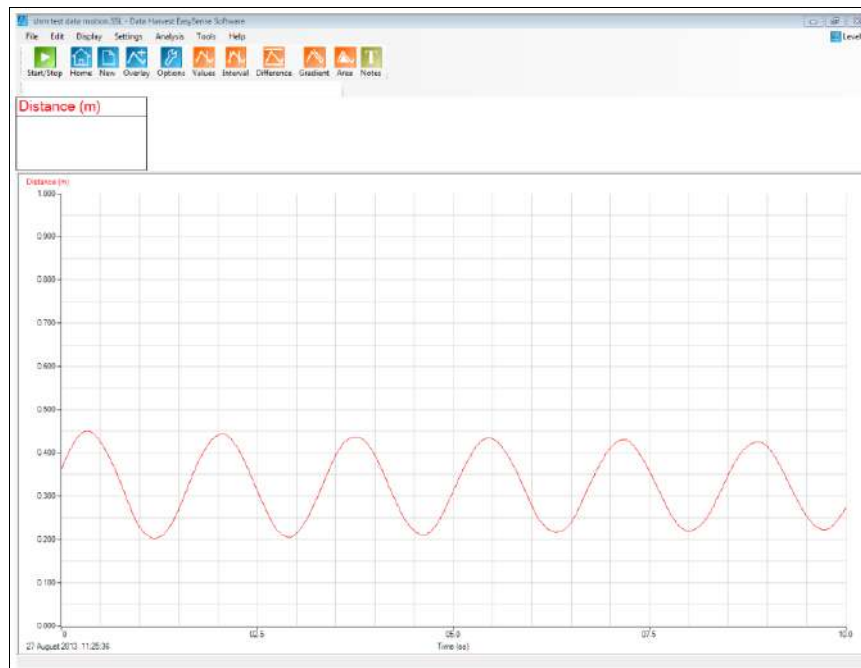
### Sample Data

- To collect the sample data the first apparatus set up (Ex.1) was used, the oscillating mass over a Motion sensor.
- The spring was a section of a slinky spring and the mass used was 30 g.
- The Motion sensor range was set to the distance, 1 metre range.



- A trigger level was set to start data collection, this made it easier to set the mass in motion and then move out of the way while data was being collected.

### The raw data



The post-log Tare function can be used to present the data oscillating about a zero value. It is good practice to Save the original data first.

Use Values to find the maximum and minimum amplitude of the first cycle. Add the values together and divide by 2, this becomes the Tare value.



Data after Tare has been applied, there is now an oscillation around 0. Original data has been deleted. Use Save As to force saving the data under a new name, you don't want to overwrite the original data.



This graph shows the data centred on the graph axis with the maximum axis set to 0.15 and the minimum to -0.15. To alter the axis so the minimum and maximum limits are equal use Options, Sensor settings.

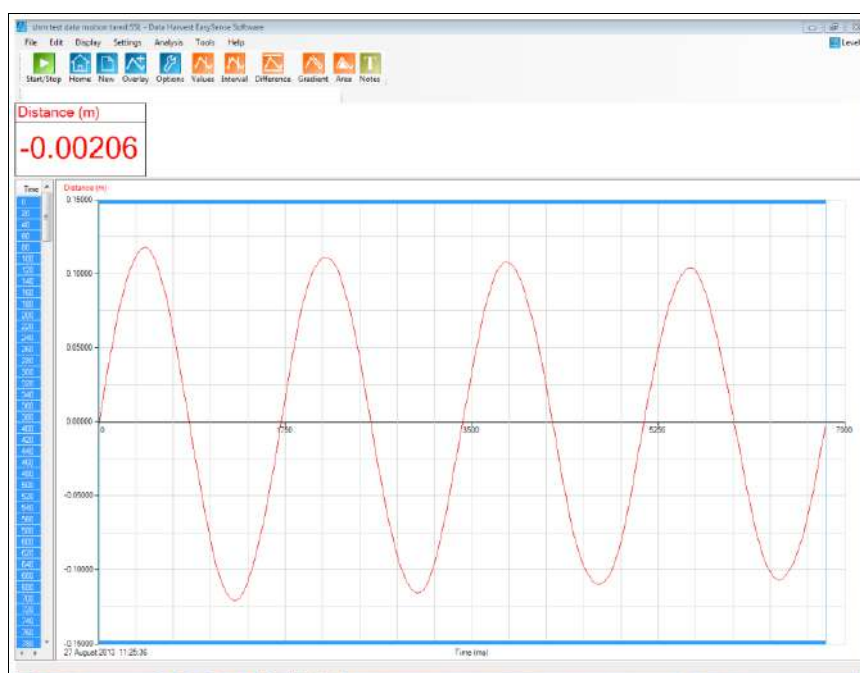
Producing the seed data for the mathematical model

- Use Interval function to find the interval between maxima peaks of one or more cycles.

Find or calculate maximum amplitude  $A$ ,  $T$  (period),  $f$  and  $\omega$ .

$$\omega = \frac{2\pi}{T}$$

- Use the selection tools to make the data start with an oscillation cycle that begins at zero.

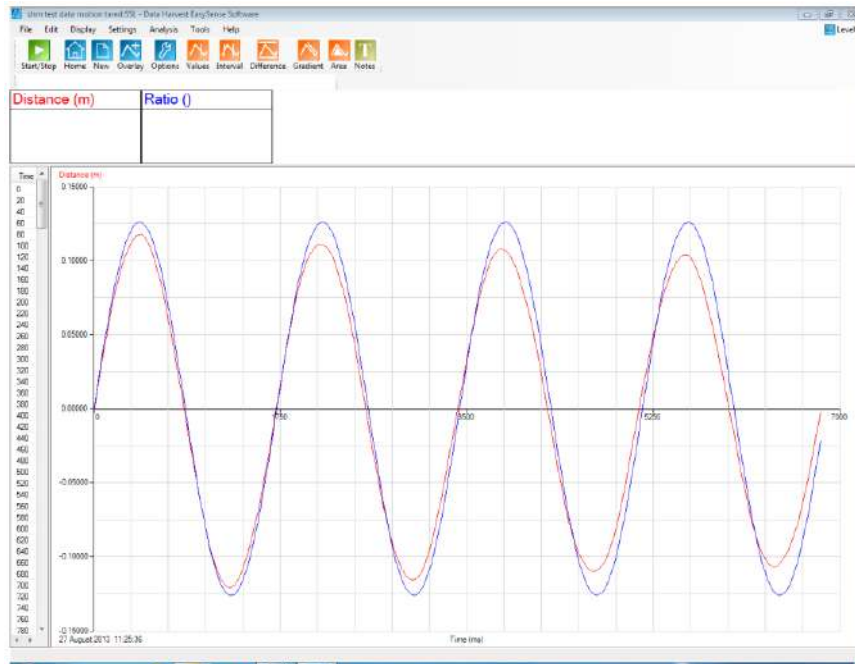
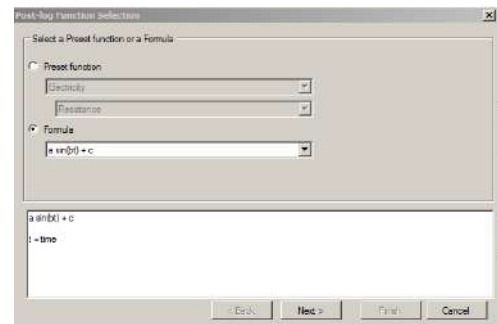


## Creating the mathematical model

Use the Formula function  **$a \sin(bt) + c$**

(This is the same as  $A \sin(\omega t)$ )

- Give the new curve a name (optional)  
e.g. theoretical sine wave.
- $a$  = maximum amplitude.
- $b = \omega$
- $c = 1$
- $t$  = the time data (automatically gained from the time column of the data set)



In the sample curve above, the Ratio () curve is the arithmetically derived curve of  **$A \sin(\omega t)$**  from the T, A and  $\omega$  data extracted from the practical data.

### Notes:

1. It is difficult to get an exact match of the curves due to Y axis scale definitions.
2. The arithmetically derived data will not show the effect of any forces on the oscillations. There is damping of the oscillating mass, and this can be seen as the increasing difference between the peak values between the model and collected data.
3. You may notice a slight creep in relative peak positions, this usually an artefact created by difference in the period data you calculate and the values used by the software. If this is troublesome, restrict the data to no more than 3 cycles.
4. The time period of the practical data varies slightly in measurement, the data is being collected at 50 Hz, the peak value of the displacement may appear between the sample periods. The value of T may have a variance that follows through the calculation.
5. Starting the data at zero produces curves of better comparative look, trying to offset data using the c value in the formula is difficult and can produce some visually unconvincing comparisons.

The arithmetically modelled data and the practical data show very strong similarities and prove the sine wave nature of the experimental data.

You can now use the Functions built into EasySense to develop Velocity and Acceleration curves. The modelling functions of EasySense only allows the first derivative curve to be produced arithmetically, to get the second derivative you would have to apply the function to the first derivative data.

You can transfer the data to Excel and enter the functions below to continue the mathematical modelling.

- $A\sin(\omega t)$

This is the formula to describe a sin wave.

- $\omega A\cos(\omega t)$

This is the equivalent of the “first derivative” as described in EasySense as the function  $dx/dt$

- $-\omega^2 A\sin(\omega t)$

This is the equivalent of the “second derivative” as described in EasySense as the function  $dx/dt$  applied to the curve of  $\omega A\cos(\omega t)$ .

Modelling the data within Excel does make students think about the origin of the components and the correct calculation sequence. Use of brackets to indicate the discrete arithmetical parts is a good exercise to understand the formulae.

The following Excel formulae describe one set of solutions for the calculation in Excel. You would be advised to set a part of the spreadsheet to one side for the constants you would want to use, this will allow testing of the model by “what if”.

Items enclosed in “” are locations of data used in the calculation.

Make sure the correct number of brackets are used in and out of the formula, recent versions of Excel use colour matching, but this can easily be overlooked.

- $A\sin(\omega t)$

Excel formula

=“Location of the value of A”\*(sin(“value for  $\omega$ ”\*“timedata”))

Note the value of A and  $\omega$  will need an absolute address e.g. \$A\$12.

- $\omega A\cos(\omega t)$

Excel formula

=(((“location calculated value of  $\omega A$ ”)\*(cos(“location of  $\omega$ ”\*“location of time”))))

Note values of  $\omega$ ,  $\omega A$ , A will need an absolute address.

- $-\omega^2 A\sin(\omega t)$

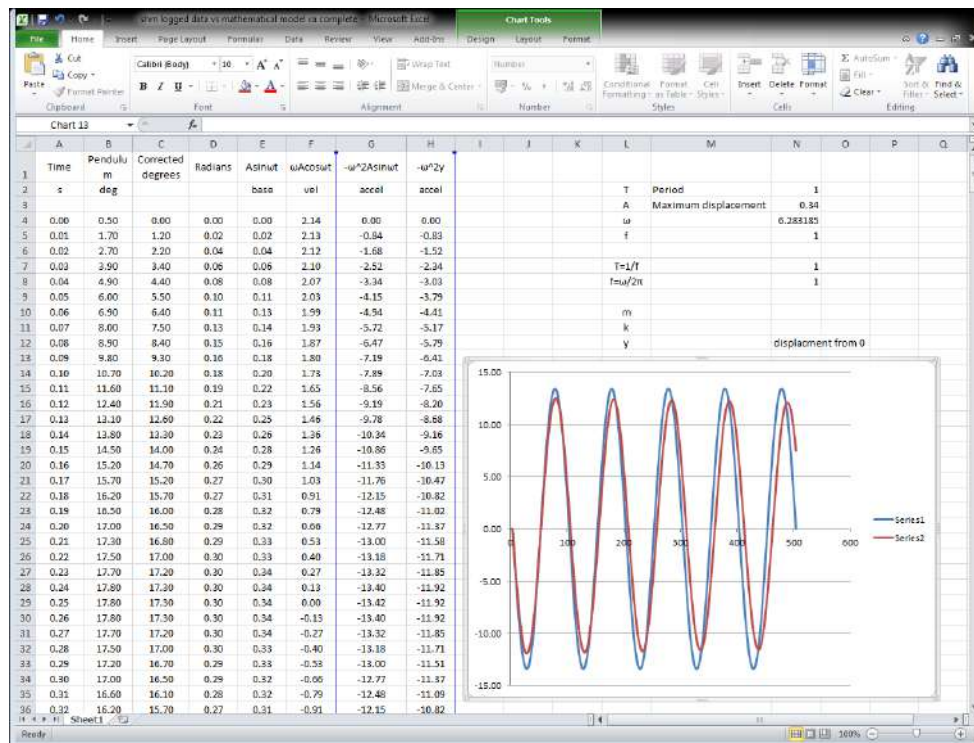
Excel formula

=-((location calculated value of  $\omega A$ )^2\*“value of max displacement”)\*sin((value of  $\omega$ )\*“location of time”).

Alternatively this can be  $-\omega^2 y$ , where y is equal to the displacement data.

You can enter the absolute values of “variables” direct into the formula, but this will make chasing mistakes, modelling difficult.

An example of an Excel treatment of data, in this case the data had been collected from a Rotary Motion position sensor using the degrees range. The data was converted to radians from degrees.



Note the section to the top right, where the various constants used in the formulae are entered and calculated.

### Further extension

If the mas is known then,

- Kinetic energy
- Potential energy (gravitational)
- Momentum
- Total energy
- Spring constant

Can all be calculated both in theory and from the practical data.

### Finding the spring constant and energy

Note: When working on this project, it was noticed that the mathematical derivation of the spring constant from an oscillating mass and the derivation from the same spring via added mass and measured extension gave wildly different answers. An automatic assumption was that the wrong calculations / formulae were being used. Rigorous checking of the re-arrangements of basic formulae continued to produce an error / difference. Returning to the practical and checking the extension for mass added revealed the cause of the error.

Commercial springs do not obey Hooke's law! (sic). The process of making an extension spring by winding coils of wire builds in tension that holds the spring closed. This inherent tension needs to be neutralised to get to the true characteristic of the spring. With some of the springs being used in this project, this meant

preloading with 400 g to just open the coils. Now when you added the additional masses, the extension per mass unit was a perfect example of Hooke's law. Suddenly  $k$  by practical, SHM and maths was comparable. Errors due to arithmetic now became important.

### Teaching point

When learning you doubt the new and feel secure in the old. In this case the doubt was in the various formulae that had not been used previously (and were familiar) and, additionally, the new symbols used in the formulae. The real eye opener was how so much effort was spent on checking the new, unfamiliar knowledge to the point that an obvious flaw in the original data had been missed. There was the assumption that the reason for the failure to get comparison was due to mistakes in the unfamiliar mathematics. The question has to be raised, how much failure of understanding is due to faulty, poor quality apparatus not supporting the new knowledge? How often as a practical teacher do you check the apparatus before using it to remove the uncertainty that can create deviation in learning? Or do you expect the students to understand the "corrections" you make from the position of many years of experience.

### Finding $k$ , calculating energy changes

To determine energy changes, the appropriate formulae required a use of  $k$ , the spring constant. Within the spirit of modelling and verifying between practical and theory it was decided to calculate  $k$  from;

$$\omega = \sqrt{\frac{k}{m}}$$

Analysis of the SHM data had given  $\omega$ ,  $T$ ,  $m$ .

Re-arrangement led to

$$\omega^2 = \frac{k}{m}$$

The answer could be tested by a quick Hooke's law test

$$k = \frac{-F}{x}$$

The two values should be very close to each other, one would hope the same, but errors in data collection and rounding will give a slight variance, and perhaps should be explained.

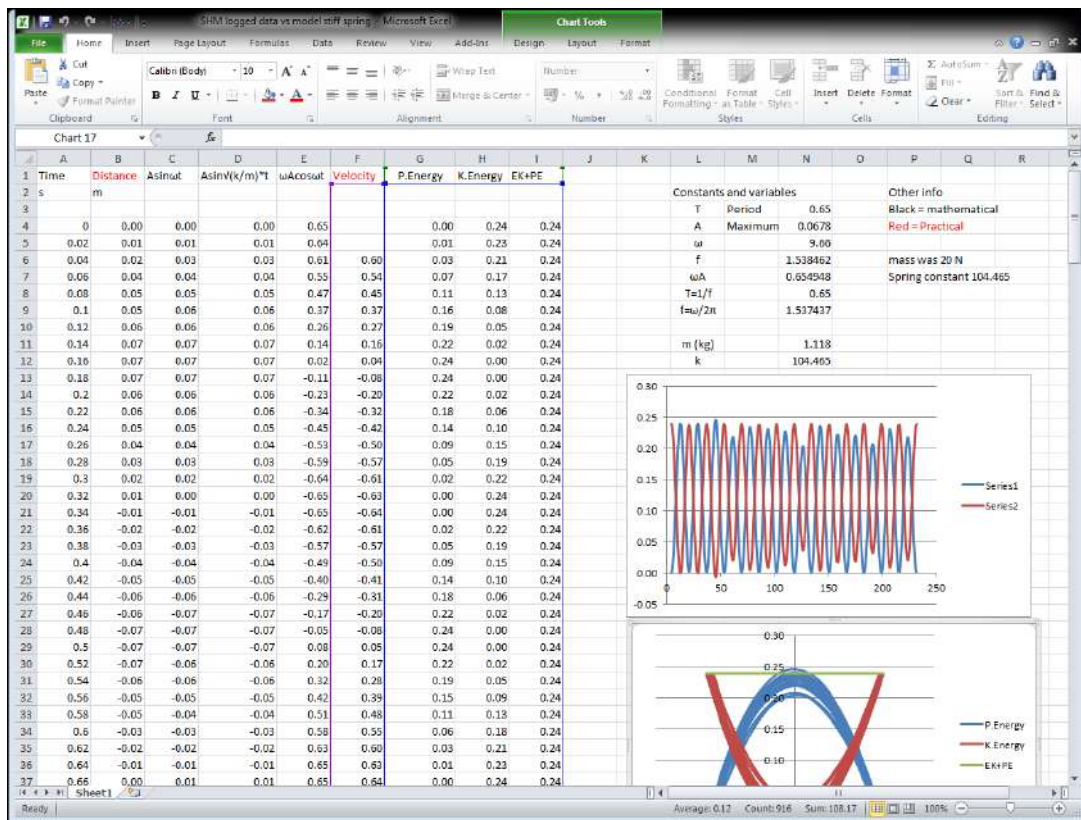
In the end, for the spring mass system being used;

- Hooke's law approach gave a value of  $k$  of 106.90 N/m.
- SHM data gave a value of 104.47 N/m was calculated.

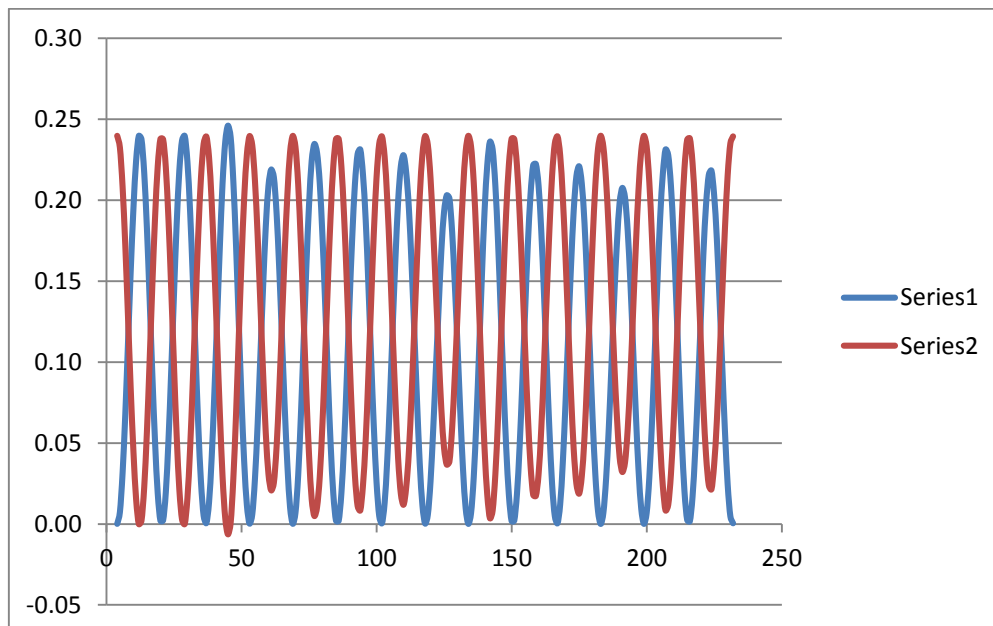
This was considered close enough for proof (3% difference).

The  $k$  value for the SHM data could now be used for energy calculations.

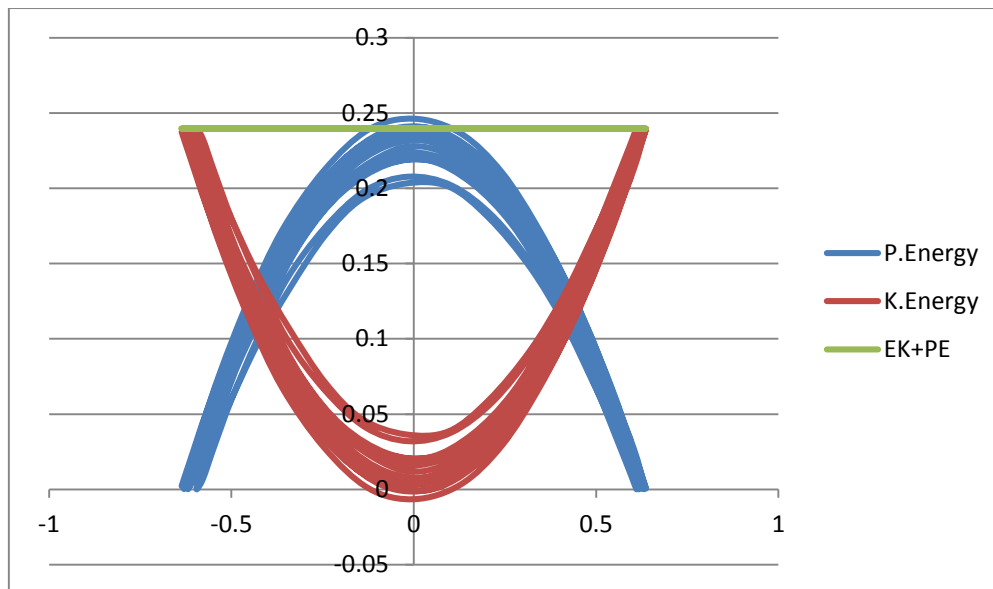




Excel spreadsheet showing displacement data from practical and velocity derived by software from practical alongside the mathematical model of the sine curve, first derivative and second derivative, potential energy, kinetic energy and total energy.



Plot of Kinetic energy and potential energy showing the phase relationship, all variables used to produce the data came from the practical.



Text book plot of PE, KE and Total energy in SHM. The whole data set was charted, hence the wide energy hoops, not every oscillation had the same amplitude. Why?

Final thoughts:

- At the end of the exercise we have a full analysis of the data from the practical alongside a mathematical proof.
- In the process of producing the model in the spreadsheet formulae used have had to be converted to excel formulae.
- The terms inside the formulae, and where they came from has been better understood.
- A better learning route has been followed for the student.

Total time to complete the project was about 2 hours, including modelling in both EasySense and the spreadsheet.

To understand the variance of  $k$  by the two methods took a full “school day and more”, time wasted by not having the apparatus correctly explained, there is little reference to this “spring tension” in most of the help sites. Sadly once found out, asking the correct question revealed it as common knowledge. In published example practicals this information was not passed on! Imagine a student meeting this on an “assessed practical” having only seen the teachers “perfect demo”?



## Capacitor charge, time constant and exponents

The capacitor – resistor circuit (CR) is universal in schools as a practical. There are many ways to use and incorporate the practical into class teaching;

1. Experimental confirmation of the time constant.
2. Experimentation with the time constant e.g. calculate a constant and then test by practical.
3. Explanation of the exponential, symbolism and even as a model for radioactive decay.
4. As part of the description of the characteristics of a capacitor.
5. Energy and charge storage devices.

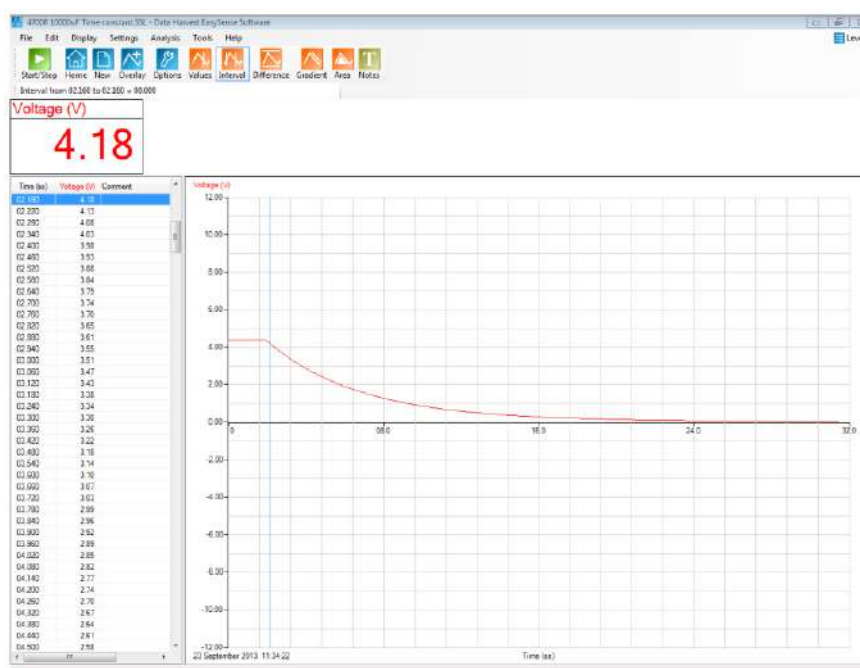
It is acknowledged that capacitors have wide tolerances, 20% variance from value is the norm. 10% variance from indicated value is considered high quality. In practical work the theoretical product may be disappointingly different from the practical, whichever way you feed into the work (i.e. use values to predict or use experiment data to find out).

With this exercise it is intended to show how and understanding of the exponent function in EasySense can be used to model, test or verify data from practical investigation.

- The student will need to find the time constant, this can be from calculation using  $C \times R$  (capacitance in farads multiplied by resistance in ohms) or from the accepted value of 63.2% of the final asymptotic value. The time constant is in seconds.
- They will also need the maximum voltage or current.
- They will need to separate out one discharge cycle to work on using the selection tools.

### Example

Using a capacitor of 10,000  $\mu\text{F}$  and a resistor of 4700 ohms, we have a calculated / theoretical CR value of 4.7 seconds.

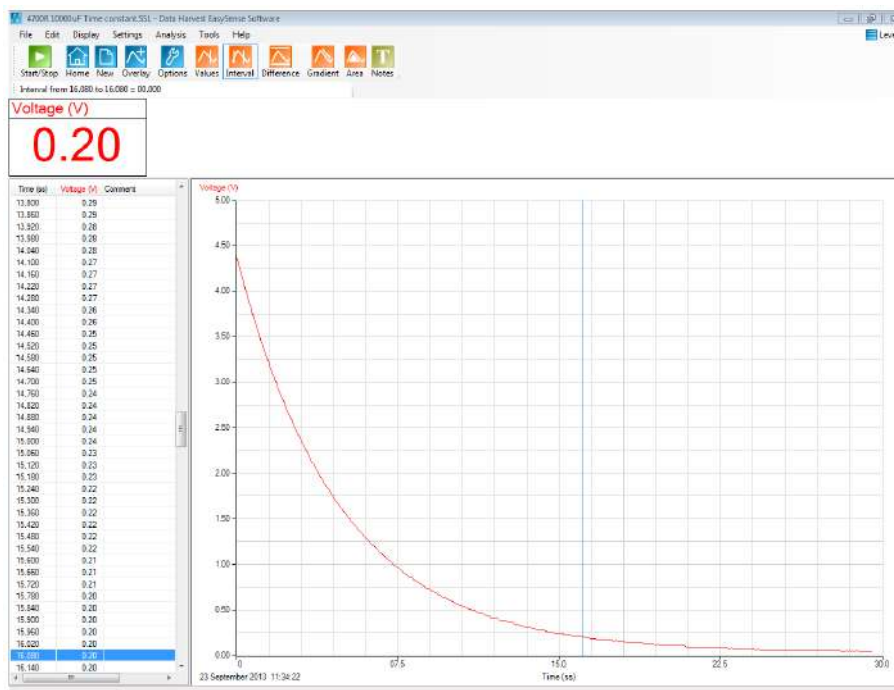


Graph of a discharge cycle of the CR circuit, 10,000  $\mu\text{F}$ , 4700 ohms.

There needs to be a bit of tidying of the data to remove the –ve voltages on the y axis and to remove the steady voltage shown before the discharge switch was thrown.

If you use Autoscale to remove the negative voltages be prepared to repeat, some actions in manipulating the data will bring them back. The better alternative is to use Sensor settings (Options) and edit the y axis range.

Use the Edit, Use Selection tool to remove the data before the discharge started.



Data after rescaling, and removal of the unwanted data.

The maths.

### Values

- $C = 10,000 \text{ uf}$
- $R = 4700 \text{ ohms}$
- $V_0 = 4.35$
- $t_0 = 0.00 \text{ s}$

For this system the CR value is 4.7 seconds from the values of R and C on the components.

### To extract data from the graph:

The voltage when 63.2% of the voltage has been discharged is found by  $0.368 \times 4.35$

This is 1.66 volts

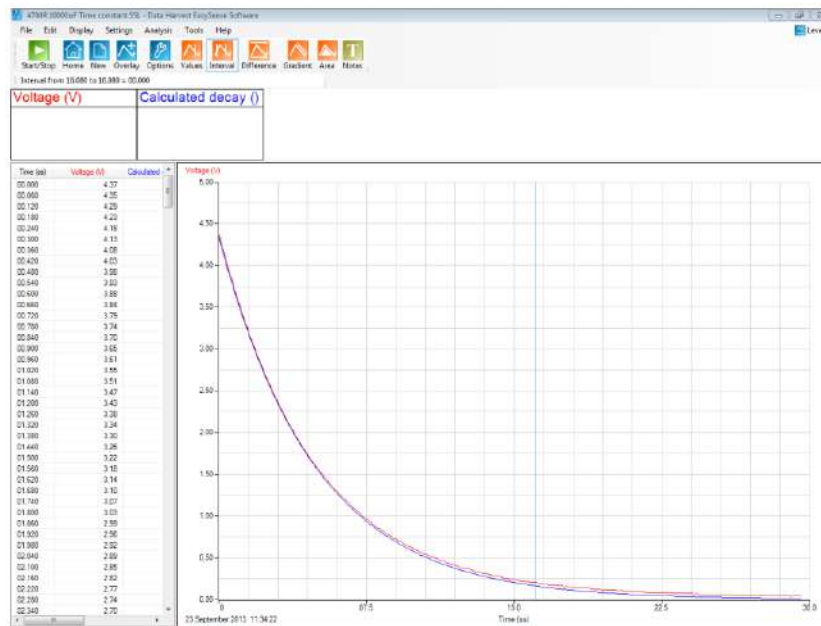
Time at 1.66 volts is read of the graph to be 4.86 seconds.

- Note how close the 'from graph' and calculated values are, approx. 4% different. Almost certainly from the tolerance in the capacitor.

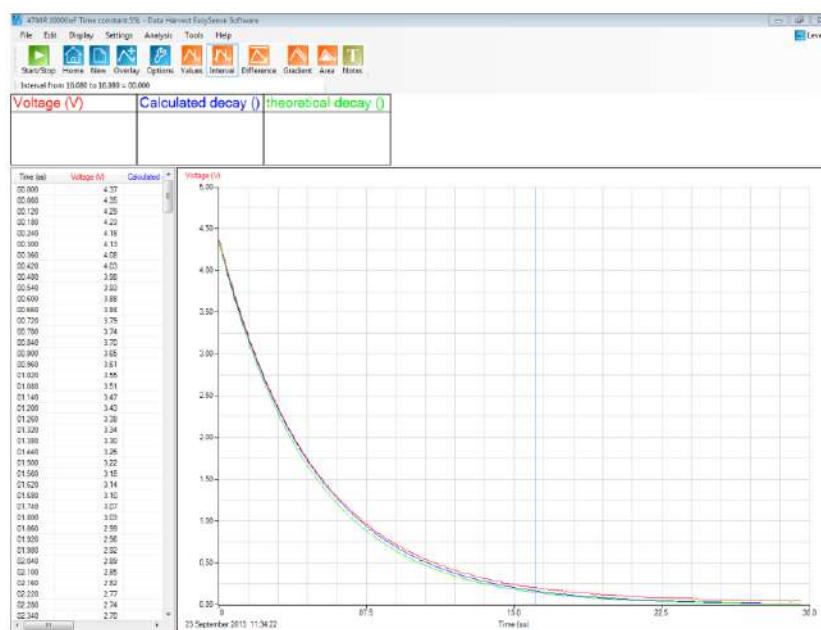
$$-1 \div cr = -1 \div 4.86 = 0.205.$$

This should give us access to all the numbers we require,

- In EasySense select Post-log Function (Tools menu).
- Select Formula and scan down the list find **a exp(bt) + c**, make sure you don't select a exp(bx) + c.
- Change the name, then enter the Parameters
  - $a = V_0$  (in this worked example = 4.35)
  - $b = -1/cr$  (in this worked example = -0.205)
  - $c = 0$
  - Channel max = the maximum of the y axis scale.



Practical data and calculated data on the same graph.



Decay curve using the exponent from the CR value calculated from the component values. It is very close, but slightly depressed.

The point of the exercise is;

- To show how the elements of the decay curve formulae link back to practical.
- To create practice of reading off the values of the CR on the practical data, and finding the critical data points for modelling.
- To show how theory can correctly model practical data.
- To provide a tool for advanced modelling of CR circuits.

### Creating a Log linear plot to find the time constant

To confirm that the discharge decay curve is an exponential, plot a graph of  $\log_{10}(V)$  on the y axis against time . This will (if the decay is exponential) give a straight line graph with a negative gradient.

EasySense has the ability to produce this graph.

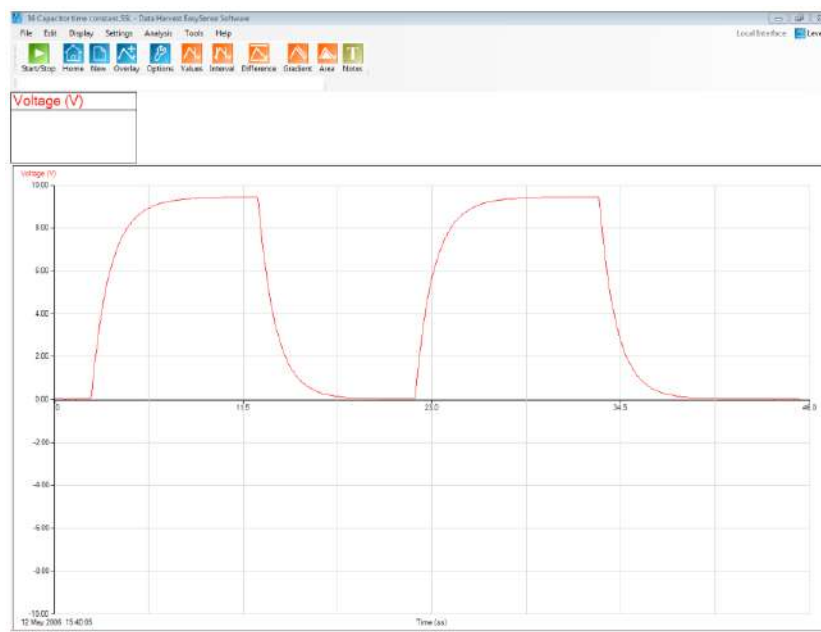
Among the Post-log Functions, in the Formula section there are several log based formula. If we use:

$$a \log_{10}(bx) + c$$

We will create a  $\log_{10}$  data set from the discharge data. The slope of this curve is the  $-1/RC$ .

If the value of R (resistance) is known then the value of C can also be found.

To produce the new data set you need the discharge section of the data collected.



Example data of several charge and discharge cycles of a CR circuit.

First step is to isolate out, a discharge cycle.



One discharge section isolated out from the whole data.

Next step is to make this the used selection (Use Selection from the Edit menu).

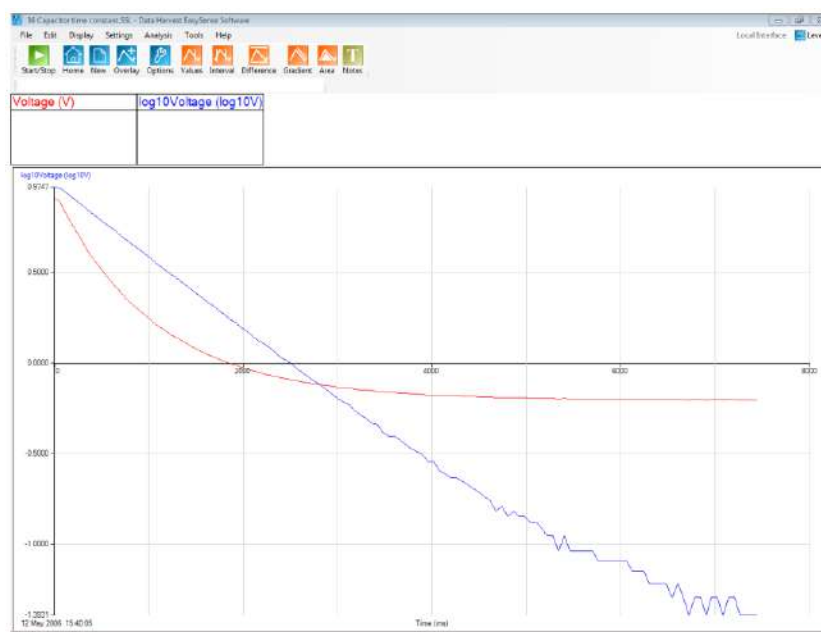


The selection made as the entire graph

Now we select the function ' $a \log_{10}(bx) + c$ '

Using 1 and zero to negate the effect of a, b, c or simply to pass on the data unchanged.

1.  $a = 1$
2.  $b = 1$
3.  $x$  = the original voltage data
4.  $c = 0$  (we have no constant to add on)

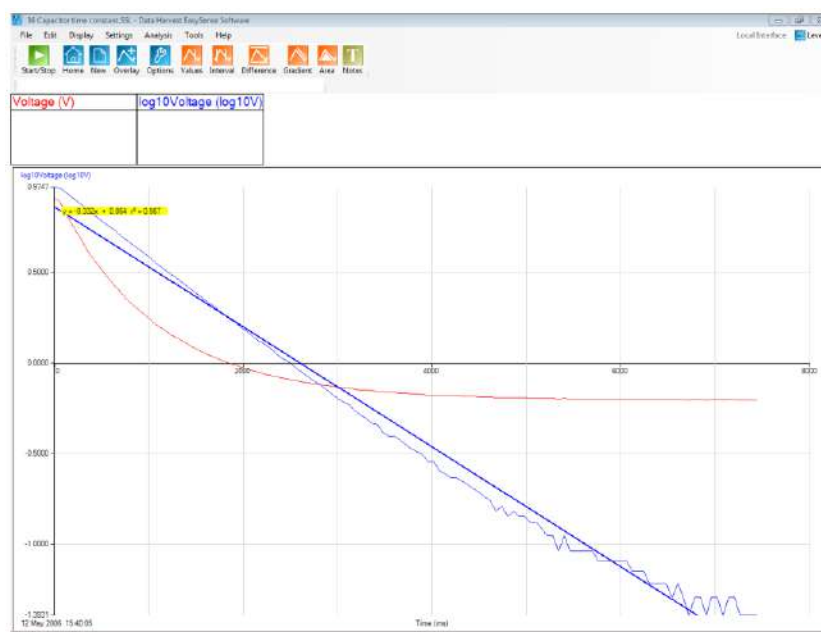


Log<sub>10</sub>(v) against time plot

At this point you can either

- Mathematically calculate the gradient
- Use the Gradient tool
- Use the best line fit to give the  $y=mx+c$  data

Which is chosen will depend on the focus of the lesson, learning outcomes and skill of the user.



Automatically drawn and calculated best fit line, showing the  $y=mx+c$  data and  $r$  value.

## The Function Wizard Guide

Functions are mathematical operations that can be applied to the data. This guide is based upon the PC version of EasySense. Other platforms may not have all of the features described, refer to software guides.

Functions can be applied to the data as it is being collected (Pre-log Function), or after the data has been collected (Post-log Function).

The functions in EasySense are also described as Preset or Formula functions. Both will produce the same results, Preset functions are however described in words and not in terms of mathematical symbols. This does allow students to gain access to the powerful analysis feature of EasySense that could otherwise be beyond their mathematical skill.

The EasySense software needs to be set to Level 2 or higher for Functions to be available.



With the exception of the SnapShot, Asks for a value, and Spirometer, Volume drift correction functions, all functions can be applied to act on data as it is being collected, or on data after has been collected.

When a function has been applied as a Pre-log function, there may be a slight delay between collection of data and the presenting of the data on the screen. The delay will be very slight, and in most cases, unseen. When collecting distance vs. time data, for example, you may wish to show velocity or acceleration. The calculation of both of these values will need a collection of some data before calculations can take place. Velocity needs three data points before calculation can commence and acceleration needs five data points. An adjustment of the data may take place at the end of the logging period to make sure the data is correctly aligned with its original source.

## Preset Functions

The use of the Preset function is the same when it is used as a Pre-log Function as it is when used as a Post-log Function.

Preset functions are arranged by subject area and sensor.

In many cases the unit names and limits are predefined by the function, they can always be overwritten if they are not considered appropriate.

Subject topic area	Functions	Data channels / sensors/other information that is needed
Electricity	Calculate Resistance	Current, Voltage
	Calculate Power	Current, Voltage

Motion	Velocity	Distance, position
	Acceleration from distance	Distance, position
	Acceleration from velocity	Velocity
	Angular Acceleration	Angular velocity
	Displacement	Distance value of reference point
	Pendulum – linear displacement	Angular displacement in radians
	Displacement from velocity	Velocity

<b>Energy</b>	Gravitational Potential Energy (G.P.E.)	Reference Distance, acceleration (g), mass of object
	Kinetic energy	Velocity, mass of object
	Pendulum – Potential Energy	Angular displacement
	Spring – Elastic Potential Energy	Displacement, Restoring Force

<b>General</b>	Tare	
	Ask for a value (SnapShot only)	
	Manual Entry	
	Add a Constant	
	Subtract a constant	
	Multiply by a constant	
	Divide by a constant	
	Moving Average (simple)	
	Mean (x,a)	
	Average of 2 data channels	
	Average of 3 data channels	

<b>Titration</b>	First derivative of pH	pH
	Asks for volume added (SnapShot only)	
	Convert Drops to volume	Drops, Bubbles

<b>Spirometer</b>	Spirometer Air Flow to Volume	Air Flow
	Spirometer Volume drift correction (Post-log function only)	Derived volume from flow

<b>Channel</b>	Multiply Channel by Channel	
	Divide Channel by Channel	
	Subtract Channel from Channel	
	Add two Channels together	

<b>Oxygen</b>	% Saturation to mg/L	Oxygen % saturation, Air pressure, and Temperature of water
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<b>Conversions</b>	Convert degrees(angles) to radians	Angle in degrees
	Convert radians to degrees	Angle in radians
	Convert Celsius to Fahrenheit	Temperature in Celsius
	Convert Fahrenheit to Celsius	Temperature in Fahrenheit
	Convert Celsius to Kelvin	Temperature in Celsius



### To select a Preset function

- Select from the Tools menu either Pre-log or Post-log Function. For post-log functions, you will need some data present before the function will work.
- Select the **Preset function** radio button

**Pre-log Function Selection**

Select a Preset function or a Formula

☒ Preset function

Electricity

Calculate Resistance

☐ Formula

$ax^2 + bx + c$

Resistance, calculates resistance from Voltage and Current data.  
 When Current is A and Volts is V, make Multiplier = 1.  
 When Current is A and Volts is mV, make Multiplier = 0.001.  
 When Current is mA and Volts is V, make Multiplier = 1000.  
 When Current is mA and Volts is mV, make Multiplier = 1

< Back   Next >   Finish   Cancel

1. The top line indicates the subject / topic area. Click on the down arrow to list all the options available.
  2. The second line indicates the function(s) available within that topic area; click on the down arrow to reveal the options available.
  3. The larger panel is the information box that describes what the function will be calculating and what additional information will be needed for the calculation.
- Click on Next to select which channels of data are going to be used,

**Pre-log Function Selection**

Select the Source Channels

Select the Voltage Channel to use

Voltage

Select the Current Channel to use

Current

Resistance, calculates resistance from Voltage and Current data.  
 When Current is A and Volts is V, make Multiplier = 1.  
 When Current is A and Volts is mV, make Multiplier = 0.001.  
 When Current is mA and Volts is V, make Multiplier = 1000.  
 When Current is mA and Volts is mV, make Multiplier = 1

< Back   Next >   Finish   Cancel

The text indicates which data channel is to be chosen. Click on the down arrow to reveal the list of sensors connected. The list is presented in the order of the connected sensor ports and lists the sensors by name. In Post-log Functions, the list will include any derived data channels. Take care to ensure that the correct channel has been selected, especially if you have many sensors of the same type.

You may wish to rename the channels before starting to use functions to make it easier to identify the channels you will be using. To do this go into Options, Sensor settings, double click on the name you wish to change. Type in the new name, and confirm the change by clicking the Enter key on your keyboard. The new name will have an asterisk.

- Click on Next to select the units, channel limits and any constants used in the calculation.

**Pre-log Function Selection**

Enter the details for this channel

Name: Resistance

Units: Ohms

Decimal Places: 2

**Channel limits**

☒ Expand to fit

☐ Manual

Channel Min: -20

Channel Max: 20

**Parameters**

Enter the multiplier: 1000

Calculates resistance from Voltage and Current data. For low resistances set decimal places to 3.  
 When Current is A and Volts is V, make Multiplier = 1.  
 When Current is A and Volts is mV, make Multiplier = 0.001.  
 When Current is mA and Volts is V, make Multiplier = 1000.  
 When Current is mA and Volts is mV, make Multiplier = 1

< Back   Next >   Finish   Cancel

**Name** = the name of the new data. A default name is suggested.

**Units** = the name of units of the new data. A default unit is suggested

**Decimal places** = how many decimals are to be shown, 0 = no decimals, 1 = 1 decimal, 2 = 2 decimals, etc.

**Select the Minimum and Maximum** = setting the limits of the axis on the displayed data. Default values will be based around the default limits of the sensors used. In the example above a  $\pm 20$  V Voltage sensor and a 1000 mA Current sensor were used.

**Expand to fit** = If the data generated is larger than the channel limits the scale will automatically expand to accommodate the larger range.

**Manual** = the channel limits entered by the user will be used, regardless of the values of the numbers generated by the function. Additional manual re-scaling may be required.

**Parameters** = enter any parameters required for the calculation e.g. constant (can be negative or positive, the action of the constant is indicated in the text).

## Presets detail

Preset functions are grouped into curriculum areas, or groups of similarity.

### Electricity

Topic area	Function	Data required
Electricity	Calculate Resistance	Current, Voltage
	Calculate Power	Current, Voltage

The presets use the relationship between voltage and current to calculate power and resistance. Watch out for the correction factors (multiplier) needed when current values are in mA and voltages are mV. Read the comments in the information box to get the correct multiplier.

### Motion

Topic	Function	Data required
Motion	Velocity	Distance, position
	Acceleration	Distance, position
	Acceleration	Velocity
	Angular Acceleration	Angular velocity
	Displacement	Distance value of reference point
	Pendulum – linear displacement	Angular displacement in radians
	Displacement from velocity	Velocity

Velocity is calculated as the differential  $\frac{dx}{dt}$  and acceleration is calculated as the differentials  $\frac{dv}{dt}$  and  $\frac{d^2x}{dt^2}$

where x is the distance data and t is the time data. Care needs to be taken, to ensure the correct units are created. A guide to the units is in the information box. There is also a chance to change the unit name to match the units used on the input data. Units are ?/s or ?/s/s. The ? is to be substituted with the units the distance was recorded in.

Some sensors (e.g. Rotary Motion) produce data as a velocity. This is why there is a choice of calculation of acceleration. Acceleration from velocity data is  $\frac{dv}{dt}$ . It is advisable to apply at least one level of smoothing before calculation. The calculation tends to exaggerate small differences, which can be distracting for the naive user.

### Energy

Topic area	Function	Data required
Energy	Gravitational Potential Energy (G.P.E.)	Reference Distance data, acceleration (g), mass of object (kg)
	Kinetic energy	Velocity, mass of object
	Pendulum – Potential Energy	Angular displacement in radians

	Spring – Elastic Potential Energy	Displacement, Restoring Force
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Gravitational Potential Energy (G.P.E). is a simple calculation of the mass x acceleration (g) x height. You will need to decide where the zero of the height is, and if necessary use a formula function to calculate an appropriate 'distance' channel. For example, it is necessary to calculate the distance from the floor when calculating the value of the GPE for a bouncing ball. Usually it will be a relative height measured from one point in the experiment to another point in the experiment.

Kinetic energy uses  $\frac{1}{2}mv^2$ . The velocity is a linear velocity calculated from one of the Presets in the Motion section above.

### General

Topic area	Function	Data required
General	Tare	
	Ask for Value	
	Manual Entry	
	Add a constant	
	Subtract a constant	
	Multiply by a constant	
	Divide by a constant	
	Moving Average (simple)	
	Mean (x,a)	
	Average of 2 data channels	
	Average of 3 data channels	

General functions are functions that conduct a simple mathematical operation on the data.

**Tare** is used to remove a value from all the data i.e. to change the zero of the data. Use it as you would the tare on scales. Remember a tare is usually a subtraction, entering a positive value will add to the data – this may be what you wish. Tare can also be used to make all sensors start at the same point, e.g. remove a temperature difference from a pair of Temperature sensors.

**Asks for Value** will only be available if you are working on functions in SnapShot mode. This is a powerful function, that when applied, asks for a variable that is not coming from a sensor. E.g. volume of solution added, or the distance of a light sensor from a lamp.

The constant is any value you wish the data to be treated with, e.g. half the mass of a cart to create an energy data set or times 0.5 to half the number.

**Moving Average (simple)** takes the average of a fixed number of data points. E.g. if there are 10 data points, and a = 5, then the averages of data points 1 to 5, 2 to 6, 3 to 7 .... will be taken. This is, in effect a smoothing function.

**Mean (x,a)** takes the mean of successive groups of data points. E.g. if a = 5 in a data sequence of 20 points. Then the means of data points 1 to 5, 6 to 10, 11 to 15 and 16 to 20 will be calculated. This allows the means of successive sets of repeated readings to be taken.

**Average of channels** allows you to take data from repeats of the same experiment and create an average column. It simply adds the data in the columns and divides by either 2 or 3, depending upon the selection made.

### Titration

Topic area	Function	Data required
Titration	First derivative of pH	pH
	Asks for the Volume added (SnapShot mode only)	
	Drops to Volume	Drops, Bubbles

### Spirometer

Topic area	Function	Data required
Spirometer	Spirometer Air Flow to Volume	Air Flow
Post-log functions only	Spirometer Volume drift correction	Derived volume from flow

The spirometer measures flow. Most spirometer investigations require volume. Spirometer volume will calculate volume of air that has passed through the spirometer by integration of the flow (e.g. multiplication of the flow by the time interval). Problems occur with the sensor not always giving zero with no flow. This means that drift can take place. This is normal with this type of pressure difference flow sensor.

Spirometer drift correction applies a filter to the data and tries to make the volume data become centred around zero. It will only correct for data that is good but shows a slight drift. Poor data will not be corrected very well.

### Channel

Topic area	Function	Data required
Channel	Multiply Channel by Channel	
	Divide Channel by Channel	
	Subtract Channel from Channel	
	Add two Channels together	

Channel functions allow you to use the data in separate channels as the sources for a mathematical function. E.g. a channel of control data can be removed from real data to reveal the true changes, or sine waves could be added together to show superposition of waves. Use it as  $a \times b$ ,  $a - b$ , etc.

### Oxygen

Topic area	Function	Data required
Oxygen	% Saturation to mg/L	Oxygen % saturation. Air pressure and temperature of water.

## Conversions

Topic area	Function	Data required
<b>Conversions</b>	Convert Degrees(angles) to Radians	Angle in degrees
	Convert Radians to Degrees	Angle in radians
	Convert Celsius to Fahrenheit	Temperature in Celsius
	Convert Fahrenheit to Celsius	Temperature in Fahrenheit
	Convert Celsius to Kelvin	Temperature in Celsius

## Formula functions

**Formula functions** are intended for users who are confident in maths and are able to manipulate formulae. The formulae provide a powerful set of mathematical functions.

**Formula functions** work in the same way as **Preset Functions** and can be applied as **Post** or **Pre-log functions**.

The available functions are

<b>a</b>	<b>Mean (x,a)</b>	<b><math>a/(x^b) + c</math></b>	<b><math>a \exp(bt) + c</math></b>
<b><math>ax + by</math></b>	<b><math>ax^2</math></b>	<b><math>atx + b</math></b>	<b><math>a \log_{10}(bx) + c</math></b>
<b><math>ax - by</math></b>	<b><math>a/x^2 + c</math></b>	<b><math>at/x + c</math></b>	<b><math>a \log_e(bx) + c</math></b>
<b><math>axy</math></b>	<b><math>ax^2 + bx + c</math></b>	<b><math>a \sin(bx) + c</math></b>	<b><math>a \log_{10}(bt) + c</math></b>
<b><math>ax/y</math></b>	<b><math>at^2 + bt + c</math></b>	<b><math>a \cos(bx) + c</math></b>	<b><math>a \log_e(bt) + c</math></b>
<b><math>a/x + c</math></b>	<b><math>a \, dy/dx</math></b>	<b><math>a \exp(bx) + c</math></b>	
<b><math>(x-a)/b</math></b>	<b><math>a \, dx/dt</math></b>	<b><math>a \sin(bt) + c</math></b>	
<b>Moving Average (simple)</b>	<b><math>ax^b + c</math></b>	<b><math>a \cos(bt) + c</math></b>	

**x** and **y** are either data from a sensor or a data calculated by a logging functions.

**a**, **b** and **c** are constants entered by the user.

**t** is the time base used in collecting the data

### Using constants a, b or c:

- Any number multiplied by 1 gives the same number.
- Any number multiplied by zero = 0.
- A negative number multiplied by a positive number creates a negative.
- A negative number multiplied by a negative number creates a positive.

Using the value 0 in the place of the constants **a** or **b** allows us to effectively remove that part of the function.

**Example 1. Adding information from two data sets together**

When adding two data sets there is no function  $x + y$  (add data set  $x$  to data set  $y$ ), the closest is  **$ax + by$** .

- **a** is set to 1
- **b** is set to 1

$$ax + by = 1x + 1y = x + y$$

**Example 2. Multiplying a dataset by a constant**

When multiplying a dataset by a constant there is no function  **$ax$**  (multiply **a** by **x**). The function  **$ax + by$**  can be altered to produce the same result.

- **b** is set to 0

**$ax + 0y = ax$** . Remember any number multiplied by 0 = 0, so 0 multiplied by  $y$  gives 0.

**To summarise,**

If there is a part of the function not required, then making the constant number zero will remove that part from the function.

If there is value in the data set that is to be left unchanged by the calculation then the value of **a** or **b** should equal one

The examples given show the functions most commonly seen or used to achieve a solution, it is not suggested this is the best or only way to achieve a particular solution.

**Examples of use of Formula functions****To convert data from a sensor to a new scale**

**Example 1:** You have recorded the pressure change in an investigation in kilopascals and you need to change the data to atmospheres

$$P_{atm} = \frac{PKpa}{101.3}$$

Use the function  **$(x-a)/b$**

- **x** is the data set you wish to convert
- **a** is set to zero to cancel out its effect
- **b** is the correction / conversion factor

Open Post-log function from the Tools menu.

Select the formula function  **$(x-a)/b$**

**x** = Gas Pressure kPa data set

**a** = zero (0) (this removes the **a** from the calculation leaving  **$x/b$** )

**b** = 101.3

**Name** = Atmospheres

**Units** = atm

The new data set produced will show a graph of Atmospheres vs. Time.

This is also useful if someone has not selected the correct range before starting an experiment and needs to correct the data to the appropriate units.

**Example 2:** You are using a change in linear distance to indirectly record a volume increase in a gas syringe experiment and you need to present the results as a volume change.

In rates of reaction experiments, you may need Volume of Gas produced vs. Time.

A Rotary Motion sensor using the 9 mm pulley range was used to record the movement of a gas syringe plunger; the data collected gives a distance against time graph. You need to plot the volume against time and not distance, as recorded, against time.

Measure the distance along the gas syringe from the graduation for 0 cm<sup>3</sup> to the graduation for 100 cm<sup>3</sup> in mm. This can be done with a ruler, callipers, or using the Rotary Motion sensor. Use the Meters programme or Test Mode (in Graph) to find out the distance recorded per 100 cm<sup>3</sup> of volume on the syringe. It is advisable to repeat three times and calculate an average.

E.g. L = 90 mm.

Then distance moved per cm<sup>3</sup> = 0.9 mm

Use the function **(x-a)/b**

- **x** is the data set you wish to convert.
- **a** is set to zero to cancel out its effect.
- **b** is the correction / conversion factor.

Open Post-log function from the Tools menu.

Select the formula function **(x-a)/b**

**x** = 9 mm Pulley data set

**a** = zero (0) (this removes the **a** from the calculation leaving **x/b**)

**b** = 0.9

**Name** = Volume

**Units** = cm<sup>3</sup>

The new data set produced will show a graph of Volume vs. Time for the rate of reaction experiment.

Note: This method could be used if a Motion sensor is used to record movement of a spirometer. The volume of the spirometer can be calibrated for distance (e.g. 1 litre of gas gives a 50 cm movement of the spirometer) and the calibration used to create a volume against time curve.

## To derive velocity and acceleration from a time vs. distance graph

Data logging in kinematics usually creates a graph of distance vs. time. The Post-log function allows us to convert the distance data to a velocity vs. time data set. The function used is **a dx/dt**. The original data will need smoothing slightly before use. The application of the function exaggerates small differences in the original data.

**Example 1:** A cart has been allowed to run down a slope and the distance it has moved has been recorded using a Motion sensor. The data collected is therefore a distance vs. time graph.



Use Smoothing (Tools menu) to remove any “noise” from the original data. One level of smoothing is normally adequate.

Open Post-log Function from the Tools menu.

Select the formula function **a dx/dt**

- **a** = 1
- **x** = Distance data
- **Name** = Velocity
- **Units** = m/s

The new data set will show how the velocity varies over time. The advantage of using the Motion sensor over Light gates is that the velocity of the cart is shown over the whole run and not just at two points.

To create the acceleration data set the same function is used but applied to the velocity data set. The resultant data set is acceleration.

Open Post-log function from the Tools menu.

Select the formula function **a dx/dt**

- **a** = 1
- **x** = Velocity
- **Name** = Acceleration
- **Units** = m/s/s

## Calculating Kinetic energy

Once velocity has been calculated you may wish to calculate the kinetic energy of the moving object in the investigation. There is no direct formula function to make this calculation but the function **ax<sup>2</sup> + bx + c** can be modified to produce the desired function

### Kinetic Energy – calculating $\frac{1}{2}mv^2$

Open Post-log Function from the Tools menu.

Select the formula function **ax<sup>2</sup> + bx + c**

- **a** = half the mass of the object, for example if a 1 kg trolley was being used the value of **a** would equal 0.5
- **b** = 0
- **c** = 0 so the function effectively becomes **ax<sup>2</sup>**.
- **x** = Velocity\*
- **Name** = Kinetic energy
- **Units** = joules

*\*Note: This will work as long as velocity has already been calculated and it is present as a data set.*

## Work done in stretching a spring $\frac{1}{2}kx^2$

Where  $k$  = spring constant, and  $x$  = extension of the spring.

$k$  is the gradient of the Force vs. Extension graph for the spring.

Open Post-log Function from the Tools menu.

Select the formula function  **$ax^2 + bx + c$**

- **$a = 0.5 k$**  ( $k$  = the spring constant)\*
- **$b = 0$**
- **$c = 0$**  so the function effectively becomes  $ax^2$
- **$x$**  = Extension of the spring (m)\*\*
- **Name** = Work
- **Units** = joules

*This will work as long as:-*

*\* Extension has already been calculated and is present as a data set.*

*\*\*The Force Extension graph has been generated, it is a straight line, and its gradient has been measured to calculate  $k$ .*

## Applying a correction factor

Sometimes two sensors of the same type will show a slight difference in reading when placed in the identical condition e.g. two Temperature sensors in iced water may read 0 degrees and 0.4 degrees. This difference can be removed from the data set, which will allow the direct comparison of information.

Open Post-log function from the Tools menu. The  **$ax^2$**  part of the calculation needs to be removed. The addition of  **$c$**  is the correction factor.

Select the formula function  **$ax^2 + bx + c$**

**$x$**  = the data set being changed

**$a = 0$**  (this removes the  **$ax^2$**  function)

**$b = 1$**  (this leaves the value of  **$x$**  unchanged)

**$c$**  = the correction factor (use a positive number to add a correction and negative number to take away a correction).

**Name** = the name of the data set being altered

**Unit** = the units used for the data set being altered

This can also be used to remove an offset from a data set.

**Example 1:** The temperature of two containers of hot water is being measured over time, it is noticed that the sensors read 1.1 degrees different to each other in water of the same temperature. To compare the data it is decided to correct the sensor readings (the correction factor is to be added to the lower reading).

Open Post-log Function from the Tools menu.

Select the formula function  **$ax^2 + bx + c$**

**x** = Temperature 1

**a** = 0

**b** = 1

**c** = 1.1 (the correction value, note it is positive value as it is being added to the data)

**Name** = Temperature

**Unit** = Celsius

This will add 1.1 degrees to every data point of the “low” reading sensor.

If the reading is to be taken away then use  $c = -1.1$  (note negative sign).

*Note: This method only works when the “error” is constant across the whole range.*

**Investigating**  $s = ut + \frac{1}{2}at^2$

A cart is logged going down a track with a Motion sensor or a spoked pulley. The data will be displayed as a distance time ( $s - t$ ) graph. A velocity time ( $v - t$ ) graph can be generated from the distance – time data. Measure the gradient of the graph. This will give you the acceleration  $a$ .

Select the data between two points on the  $v - t$  graph, from the Edit menu select **Use Selection**. Note down the velocities  $u$  and  $v$ .

Use **Interval** to measure the time between the selected points.

Open Post-log Function from the Tools menu

Select the formula function  **$at^2 + bt + c$**

**t** = time (from time data selected above)

**Name** = Distance

**Units** = metres

**a** =  $0.5a$  (where  $a$  = acceleration measured above)

**b** =  $u$  (measured above)

**c** = 0

This will give a distance – time curve matching the original  $s-t$  curve.

A similar curve could be easily generated to model the  $s - t$  curve of a ball dropping under gravity. All the equations of motion curves could be modelled in this way.

## Generating a reference curve in SHM

In some experiments, a reference curve may be needed to check the validity of collected data, and to demonstrate that the curves of displacement vs. time, velocity vs. time, etc. are in fact sinusoidal curves. For example in pendulum experiments, it may prove useful to compare the sine wave generated from a pendulum swing to a mathematically generated sine curve.

Open Post-log Function from the Tools menu.

Select the formula function  **$a \sin(bt) + c$**

**a** = the maximum displacement – choose the appropriate quantity and units i.e. linear or angular displacement in degrees, radians or metres.

**b** = angular velocity ' $\omega$ ' N.B. this is not the angular velocity of the pendulum. It is calculated from the formula  $T = \frac{2\pi}{\omega}$  where T = the period of the pendulum in seconds.  $\omega$  will be in rad/sec.

**c** = 0 if the sine curve starts a cycle at time  $t = 0$

**Name** = Reference curve

This curve can be used to compare the derived curve with the experimental data.

N.B. if the first half cycle of the experimental data of displacement is negative then a cos curve should be modelled.

## Generating a reference decay curve

We can model the discharge curve of a capacitor, and use this curve to show that the capacitor does have an exponential discharge curve.

In this case we will be using the functions to model the equation:

$$V = V_0 e^{-\frac{t}{CR}} + c$$

You could use the stated values of C and R. However, many capacitors have a large error, so it is advisable to use the measured value of the Time Constant CR. You can measure the time constant from your discharge curve. It is the time it takes for the value of the voltage to fall to 0.37 of its maximum value.

If you have several charge / discharge cycles, select one discharge cycle and from the Edit menu select **Use Selection**. The time '**t**' will then be zero at the beginning of the discharge and the value of **c** will be zero.

At time  $t = 0$   $V = V_0$  the max value of the voltage.

Open Post-log Function from the Tools menu.

Select the formula function **a exp(bt) + c**

**a** =  $V_0$  = the maximum value of V

**b** =  $-1/CR = -1/(\text{time constant})$

**c** = 0 if you have selected the data appropriately.

## To produce a column of identical numbers

You may wish to show the constant being applied in a calculation or the correction factor being used. This is appropriate in experimental reports where the examiner will wish to see where all the numbers came from. The column of numbers can then be used to feed into a further function.

Open the Post-log Function from the Tools menu.

Select the formula function **a**

**a** = the value you want to appear in the table.

**Name** = name of the number e.g. Gas constant,  $\text{Log}^e$ , gravity constant etc.

**Units** = the name of the unit if appropriate

**Decimal places** - type the appropriate number of decimal places

## To add two data sets together

It may be necessary to add two sets of data to find the total change that has taken place over an experiment. For example in an investigation looking at changes in energy in trolley moving down a ramp you can calculate the potential energy of the cart and the kinetic energy of the cart. It would be useful to see what the total energy of the cart was.

**Example:** When using dynamics carts you may have produced graphs of kinetic and potential energy in the system. The data from these two graphs could be added to produce a graph of total energy.

Open Post-log Function from the Tools menu.

Select the formula function **ax +by**

**x** = 1<sup>st</sup> data set to be added (e.g. kinetic energy)

**y** = 2<sup>nd</sup> dataset to be added (e.g. potential energy)

**a** = 1

**b** = 1

**Name** = Total energy

**Units** = joules

The new graph will give the total energy in the system in Joules

## To subtract two data sets from each other or to remove an offset

It may be useful to remove one data set from another to create a dataset of the difference between two data sets.

**Example:** In an investigation into the cooling of water in a beaker, someone has suggested that the temperature of the air around the beaker may affect the cooling rate. To test this you repeat the experiment and record the air temperature as well as the water temperature. You can create a difference of the two temperatures and examine if the difference in temperature has any effect

Open Post-log Function from the Tools menu.

Select the formula function **ax – by**

**x** = the 1<sup>st</sup> data set (temperature in the beaker)

**y** = the 2<sup>nd</sup> data set (temperature outside the beaker)

**a** = 1

**b** = 1

**Name** = Temp Difference

**Units** = Celsius

The graph produced will show the temperature difference between the two sensors and can be plotted against time.

## Dividing one data set by another

Many values in science are derived by the division of one data set, by another. The Post-log Function makes this an easy task.

### Example

In electricity investigations, you will record voltage and current. Resistance is calculated by dividing voltage (V) by current (I). The Post-log Function can complete this calculation to show the change of resistance over time, perhaps to show how resistance changes with the temperature of the wire or resistor for example.

Open the **Post-log function** from the **Tools menu**

Select the formula function **ax/y**

**x** = Voltage

**y** = current

**a** = the correction factor depending upon the units of the current and voltage (A, mA, V, mV). It is chosen to make the units of resistance = ohms.

**Name** = Resistance

**Units** = ohms

## Multiplying two data sets together

Many values in science are derived by the multiplication of one data set by another. The Post-log Function makes this an easy task

**Example:** An experiment to investigate electrical power and its relationship to the size of current flowing. Power is calculated using the **axy** function. Power = Current (x) x Voltage (y).

A conversion factor may be needed. It depends on the units the Current and Voltage sensors present the data in. For example the value of  $a = 0.001$  is used to convert the measurements for current in mA to Amps if the voltage is in volts.

Open the **Post-log** function from the Tools menu

Select the formula function **axy**

**x** = Voltage

**y** = current

**a** = the conversion factor. Its value depends upon the units of measurement of the current and voltage.

**Name** = Power

**Units** = watts

You can see from the examples above that the functions are very powerful, especially if you take a few minutes to work out which parts are required for your calculations. The ability to rename any channel and to extract the “unusable” parts from any function should not be underestimated. It can give very good practice for students in working with formulae in a “real world” environment.

## Two variables are interdependent – but time is not involved

There are lots of examples where one variable depends upon the other, and time is not involved. E.g. predator / prey relationships; rate of reaction/concentration, force/extension in a spring.

In these cases it is often necessary to work out the rate of change of one variable with respect to the other. E.g. the rate of change of force with respect to extension.

**Example:** A spring is stretched by a varying force until it is permanently stretched. We wish to investigate the way the spring constant varies as the extension increases. The spring is stretched using a Force sensor, and a Motion sensor to measure the extension. It will be necessary to use a function to calculate the extension from the distance readings.

Select the formula function **a dy/dx**

**Name** = Spring Constant

**a** = 1

**x** = Extension

**y** = Stretching force

The value of the spring constant can be plotted against the extension  $x$ , and displayed using X-Axis, Channel, from the Display menu.

## Creating a log linear plot e.g. for discharge of capacitor to find the time constant

Collect a charge discharge cycle from a CR circuit. Select out the discharge cycle, taking care to exclude any part of the charge cycles before and after.

Select the formula function **a log<sub>10</sub>(bx) + c**

**a** = 1 to effectively neutralise it

**b** = 1 to neutralise its effect

**x** = the change in voltage data

**c** = 0 to not add anything

The result will be the log base10 plot of the change in voltage against time. A best fit line can then be used on the voltage data to find the gradient, or you could use the gradient tool. Data may become uneven as the discharge approaches 0 V.

## Creating an absorbance data set from Transmission data

Sometimes it is easier to use transmission to collect the data from a colorimeter practical or it may be the only option you have if you are using a Light level sensor as a simple colorimeter. Most rate based colorimeter practical work requires an absorbance reading.

Select the formula function **a log<sub>10</sub>(bx) + c**

**a** = -1 to reverse the sign but leave the magnitude of the data unchanged

**b** = 1 to neutralise its effect.

**x** = the transmittance data

**c** = 2

This has created the conversion formula Absorbance =  $2 - \log_{10}(T\%)$ .