IB Physics IA Handbook

COPY MASTERS

(For use with the IB Diploma Programme)

(Fourth edition)

Authors: Cesar Reyes and Chris Talbot

Series editor: David Greig

Published by IBID Press, Victoria, Australia

Third Edition 2014

Author: Christopher Talbot

Library Catalogue

1. Physics
2. International Baccalaureate Physics Diploma Programme.
3. Internal Assessment Handbook
4. Reyes C. and Talbot C.

ISBN: 978-0-9925224-6-9

Published by IBID Press, 36 Quail Crescent, Melton 3337, Victoria, Australia.

Samples of other materials to support the teaching of IBO syllabuses can be found at: www.ibid.com.au

Foreword

This 'Student Handbook for Internal Assessment - Physics' has been written specifically to support the teaching of the current International Baccalaureate Physics course (© International Baccalaureate Organisation 2014). It has been written by an experienced and practising Senior Physics Teacher with close reference to the Group 4 Internal Assessment criteria.

The material was written with close reference to the IBO Diploma Programme Physics Guide published in March 2014. Some material is reproduced from the Guide and other material is adapted from the Guide. The assessment criteria have been divided into aspects and sub-aspects, but this division has been implemented by the author and is not mandated by the IBO.

This material has been designed to accompany and complement a Physics Textbook for use with the International Baccalaureate (4th edition) written by Gregg Kerr and published by IBID Press, and the two Volumes of Investigations (for SL and HL) for IB Physics also written by Gregg Kerr and published by IBID Press *<www.ibid.com.au>*

It will, however, be useful to IB Physics students following any practical scheme of work and using any published Textbook or other resources.

The aim of this Student Handbook is to help you, as an IB Physics student, to plan, conduct and write a report for an Individual Investigation for assessment and conduct and write a report for other practicals or investigations, including your Group 4 Project as required by your teacher. It contains a wide variety of information and advice that will help you at various stages throughout your IB Physics practical programme including the completion of your Individual Investigation. A chapter on the Extended Essay in Physics is also included.

The Guiding Questions (inspired by the IB MYP approach) have been written by the Author and the Editor and are designed to help you consider the important concepts and understandings inherent in the group 4 assessment criteria. The guiding questions are generative, meaning they generate multiple avenues of inquiry and investigation as you plan, perform and write-up your Individual Investigation. Active questioning will keep your brain engaged: an inquiring mind is absorbing information and constructing meaning. Deliberate and thoughtful questioning involves higher order thinking skills and depth of knowledge.

Both Standard and Higher Level IB Physics students should find this Student Guide useful. It includes material that will be relevant to students of all linguistic and academic abilities. Although the author is European, he has consulted a North American colleague to ensure that the conventions are also recognisable and relevant to American and Canadian students.

Christopher Talbot (Author)

Singapore 2014

Internal Assessment

The individual assessment allows students to develop and demonstrate their skills in scientific research.

The initial planning is vital to the success of the individual investigation. Students will be guided by the teacher as to the appropriateness of the research question – level of complexity and compatibility with the assessment criteria.

The individual investigation is personal research and each student will undertake a unique investigation of a question that is of interest. The formulation of the research question is the responsibility of the individual student.

Each student should decide whether the investigation is a hands on investigation or uses secondary sources such as databases. A mix of various types of investigation is allowed.

1. There is no expectation to go beyond content of the syllabus. Work can be based on concepts within the course specifications.
2. One **investigation** is required and it must be individual work - no partners or sharing of data.
3. The assessment model uses five criteria to assess the final report of the investigation with the raw marks and weightings specified (*See IBO Syllabus Guide*).
4. Levels of performance are described using multiple indicators per level. Also, not all indicators are always present. It very much depends upon the type of investigation.
5. The **investigation** should take about 10 hours of work.
6. There will be a **single investigation** by the student and the report can be **6 to 12 pages long**, have an academic and scholarly presentation, and demonstrate scientific rigor commensurate with the course.

The IA combines research and experimental Work.

Author Profile

Chris taught IB Chemistry, IB Biology and Theory of Knowledge (ToK) in the High School of the Overseas Family School, Republic of Singapore. He now teaches at a leading IB World School in Singapore. He graduated with Honours in Biochemistry from the School of Biological Sciences, University of Sussex in the United Kingdom. He also holds an Advanced Certificate in Molecular Biology from Birbeck College, University of London in the United Kingdom. He has a Masters degree in Life Sciences (Chemistry) from the National Technological University (NTU) in Singapore. He is the co-author of the MYP Student Guide and MYP Practical Portfolio and the author of the Practice Examinations for IB Chemistry and IB Biology. He is a contributing author to the fourth edition of the IB Biology text book published by IBID Press. He has had many Chemistry and Biology articles published in School Science Review and is serving a five year term as an Editorial Associate.

Acknowledgements

The author, editor and publisher acknowledge the advice, contributions and editing assistance in the production of the fourth edition, made by Ms Rae Pottenger (Narrabundah College, Canberra.)

The author, editor and publisher acknowledge and appreciate permission given by the IBO to use and adapt material from the Syllabus Guide.

Any mistakes and omissions remain the responsibility of the author. Feedback and comments relating to this publication may be sent to the Publisher. The author welcomes constructive feedback (via the publisher) from both students and teachers on the current contents and suggestions for inclusions in future editions.

The Individual Investigation

In the second year of the IB Diploma programme you will be required to research, design, perform (carry out) and write-up your own Individual Investigation. The internal assessment (IA) accounts for 20% of your final IB Diploma grade for IB Physics and requires you to spend 10 hours performing laboratory work, during which time you will be in communication with your teacher who will act as your supervisor. The time required for you to write the report for your own Individual Investigation cannot be included in the 10 hours and this should be done outside of the laboratory period.

A range of possible types of investigations can be carried out for the Individual Investigation.

You will probably be encouraged by your Physics Teacher to carry out traditional hands-on experimental work. For example, you may want to investigate the charging and discharging of a capacitor or determine the ratio e/m_e, where *e* is the charge on the electron and m_e is the mass of the electron using a Teltron tube or fine-beam tube.

You may also go on-line and retrieve data from a reliable Physics web site and process, analyse and present the data for your own analysis and investigation. Some aspect of astrophysics or climate change may be suitable for this type of Individual Investigation.

You may use of a spreadsheet to set up a model to simulate some physical phenomenon, for example, modeling gravitational orbits or radiation of heat (thermal energy). You can compare the theoretical data against experimental data and evaluate the experimental data and any assumptions in your model.

In actual practice some combinations of some or all of these approaches may be suitable, depending on the topic of the Individual Investigation.

The subject matter or content may be inside or outside the current of the IB Physics syllabus. The subject matter of your Individual Investigation is your decision, as the student, but you must ensure you are familiar with any new facts, principles and concepts. However, your knowledge of IB Physics (SL or HL) will enable you to get the maximum mark when the write-up of your Individual Report is assessed by the IBO.

The Individual Investigation (your Internal Assessment (IA)) will consist of a report 6 to 12 pages long. The report should resemble a scientific paper from the physics literature. It should be an academic piece of work and show the scientific rigour expected from the an SL or HL Physics student. You are expected to show a high degree of personal involvement and a good scientific understanding of the physics and associated mathematics that lies behind your Individual Investigation. It is important that you summarize the current thinking and knowledge of your chosen topic.

Health and Safety Symbols

Laboratories can be hazardous places. Often scientists, Science teachers and students handle equipment and materials which can be dangerous to their health and safety. Throughout these Volumes you will see a number of symbols and warnings which will represent particular hazards. For each of these we will briefly describe the hazard and indicate what precautions you should take to avoid damage and/or what responses are appropriate. In all cases, of course, you should seek advice and assistance from the teacher or laboratory technician.

A biohazard is any organism or body fluid which could possibly cause illness or disease in your body. This particularly includes micro-organisms.

A flammable substance is one which will readily burn in air. It may be a solid, liquid or gas. If you are using such a substance it is vital that there are no sparks or naked flames which could ignite it. It is vital that you know what to do in the event of fire. This may include the use of fire extinguishers and evacuation procedures.

A radioactive substance is one which emits particles or 'radiation'. This radiation is known to cause damage to cells and may also be cancer causing. If you are using radioactive substances it is vital that you wear protective clothing, use metal tongs and listen carefully to instructions given by your teacher or laboratory technician.

Sharp instruments are often used in Science and particularly in Biology, to cut sections through plant or animal tissue. These instruments, which include scalpels and razor blades are very sharp and obviously will also cut through your tissues. When using these instruments it is essential that you always cut away from your body and preferably onto a cutting board. It is also important to be very careful when carrying these instruments and also ensure they are placed on the workbench in a safe place.

When certain chemicals are mixed together they can become explosive. An explosion is caused by rapid expansion of gas in a confined space and can be very dangerous. Sometimes it is important to ensure that the space is not confined and sometimes it is important to conduct these reactions behind a protective screen.

It is often necessary to protect your hands from heat, chemicals or other hazards and gloves will be made available for these situations. The type of glove needed will depend on the particular hazard and your teacher will provide further advice. In some cases you will be advised to dispose of the gloves after use and in other cases to wash and dry them carefully.

Your eyes are the most vulnerable and easily damaged external part of your body. This is why they must be protected if you are using solids and liquids which could get into them. Whenever you are heating things or using corrosive liquids, and in other cases as instructed by a teacher, you should wear safety goggles. You should also do this if possible even if you wear spectacles to correct your vision. In the event that something gets in your eye you should immediately make use of the eyewash facility in the laboratory as instructed and then notify your teacher.

Some chemicals, which are used in a laboratory, are *corrosive*. This means that they can react with and 'eat away' materials like the bench, your books, clothing and skin. It is essential that you handle these materials, which are usually liquids, with care. Always tip from the container with the label uppermost, never add water to concentrated acid and never have your face anywhere near the container. It is usually advisable to wear both safety goggles and gloves. If protective aprons are available you should also wear one.

As a general rule, 12 or 24 volt *electrical* appliances are unlikely to cause serious injury. However, 'mains' voltage (110V or 240V or higher) can cause serious injury or death. The appliances you use should be regularly tested and certified safe. If you notice sparks or smell insulation burning, turn the power off immediately and notify staff. Be particularly careful not to allow water to get into any appliance as it may cause a short circuit.

Some chemicals are *poisonous* and should not be inhaled or ingested. It will be necessary to use a fume cupboard when using poisonous gases or volatile liquids. They could make you very ill and you may require medical assistance. It is vital that you listen to instructions, follow them carefully and notify your teacher immediately if there is accidental exposure to poisonous or toxic substances.

Lasers are very intense beams of light. They are capable of causing burns to the skin and permanent damage to the eyes. It is essential that these are only ever used under the supervision of a teacher and in a situation where people can not see the beam directly or when it is reflected from a shiny surface. Sunglasses or welding masks do not provide sufficient protection and special 'laser glasses' must be used where there is a risk.

UV light is harmful to skin and especially eyes. Do not expose these areas directly to a UV light source. If it is not avoidable, sunscreen can be applied to the skin and special goggles should be worn.

There are other *dangers* or hazards as well, for example carrying heavy or hot objects. This may also include chemicals which are not poisonous but which may smell unpleasant or irritate the skin. Whenever you see this icon more information will be provided in the adjacent text about the specific danger.

In Science and particularly in Biology, there are situations when ethics and ethical issues need to be considered in experimental work. This is particularly the case when human volunteers are being used, not just for experimental work but also when they are being surveyed to collect personal information. In these cases a consent form should be used to explain the nature of their involvement and to get their approval. Ethics will also be an issue whenever animals are used in experimentation or when they are collected in the field. They should not be exposed to conditions that are outside their natural range of tolerance and wild animals must be released back where they were sampled with the minimum of disturbance.

The environment and environmental issues become important when hazardous substances are used or produced during an experiment. Their disposal must result in minimal impact on the environment. In field work the protocol that is used must reflect practices that minimise the impact of the investigation on the site.

IMPORTANT NOTE

Although every care has been taken in preparing and trialling these investigations, absolutely no responsibility or liability whatsoever can be accepted for any damage or accident which may occur for whatever reason during the conduct of any of these activities. The Safety Warnings and Icons are advisory only and are not intended to be exhaustive or exclusive. It is a strict condition of sale that safety in the laboratory is the responsibility of the staff and students doing the laboratory work and not the author, editor or publisher of this work.

Table of Contents

This criterion assesses the extent to which the student engages with the exploration and makes it their own. Personal engagement may be recognized in different attributes and skills. These could include addressing personal interests or showing evidence of independent thinking, creativity or initiative in the designing, implementation or presentation of the investigation.

The descriptors in the following table will be used by your teacher to allocate a mark for your performance in this criterion:

MARK	DESCRIPTOR
0	The student's report does not reach a standard described by the descriptors below.
1	The evidence of personal engagement with the exploration is limited with little independent thinking, initiative or insight. The justification given for choosing the research question and/or the topic under investigation does not demonstrate personal significance, interest or curiosity. There is little evidence of personal input and initiative in the designing, implementation or presentation of the investigation.
2	The evidence of personal engagement with the exploration is clear with significant independent thinking, initiative or insight. The justification given for choosing the research question and/or the topic under investigation demonstrates personal significance, interest or curiosity. There is evidence of personal input and initiative in the designing, implementation or presentation of the investigation.

Guiding Questions

- ***To what extent does the reports show evidence of independent thinking, initiative or creativity?***
- ***To what extent has the student justified a research question that shows personal significance, interest or curiosity?***
- ***What evidence is there of personal input and initiative in designing, carrying out and presentation of the investigation?***

Your mark for personal engagement will be judged from the written evidence and is based on the your individual work on the Individual Investigation. Your teacher will take into account your self motivation and perseverance that is evidenced in the report for the Individual Investigation.

To score maximum marks under the personal engagement criterion you must provide clear written evidence and evidence to your teacher that you have contributed significant scientific thinking, initiative, or insight into your Individual Investigation. You should take 'ownership' of the Individual Investigation and show all the traits and characteristics of a Physics research student.

Your research question could be based upon some theory covered in class, for example, astrophysics, or an extension of your own personal interest, for example, engineering physics, which you may be intending to study for a degree.

It may simply be an everyday phenomenon, such as the optical properties of rainbows, treacle, bubble formation in liquids or carbonated water, or a man-made product, for example, an electromagnetic clutch, photochromic sunglass lenses or a reflecting or refracting telescope.

Your teacher may have shown an interesting demonstration that captured your interest, such as 'eddy current damping'. For example, your teacher may have levitated a piece of paper or aluminized mylar using a Van der Graaf generator. You may want to investigate its charging characteristics using a computer interfaced charge sensor.

If you have strong mathematical skills you may want to construct a spreadsheet simulation for a physical phenomenon, such as nuclear decay or some aspect of the Earth's climate, such as temperature.

For example, you could develop an interactive spreadsheet to simulate a Young's double slit experiment. It can be used to show the changes in intensity of Fraunhofer diffraction patterns produced by a single slit and a Young's double slits arrangement. Experimental data could be also be logged automatically and entered into the same spreadsheet for comparison.

If you are a school athlete you may be personally interested in the effects of forces in a particular sport or athletic event. You may want to use instrumentation available at a research laboratory or university, but you must operate the instrument and show that you understand how the instrument works.

You can demonstrate personal engagement via personal input and initiative in the design (planning), implementation (carrying out), or presentation (write-up or report) of the Individual Investigation. Perhaps you live in an active earthquake zone and you are interested in resonance in buildings – earthquake simulation. Perhaps you live in a part of the world where photovoltaic technology is being used. You may want to investigate the operation and efficiency of a solar photovoltaic cell. The relationship between voltage and angle of light source could be investigated.

Personal engagement is intended to be a way of crediting your originality in application and design. Superficial investigations or unmodified and unjustified standard methods from Physics text books would score poorly in this criterion. Your method should not simply be a 'recipe' where you follow a standard technique with no comment, no justification and no modification.

You are more likely to score highly in this criterion if you designed and built your own apparatus. For example, you might decide to build and fly a pressure powered model rocket plane. A number of manufacturers sell rockets which are propelled by water forced out by compressed air (*Figure 102*). A rocket propulsion system can also be based upon the reaction between vinegar and baking soda or tartaric acid and baking soda. The pressure generated can be calculated using a moles calculation and applying Boyle's law.

Figure 102 A water-powered rocket (courtesy Bernard Taylor)

A theory of barodynamically-powered rockets can be developed which enable the trajectory and range of a model aircraft to be determined, given the basic details of the propulsion mechanism. Fluid dynamics and kinematics will need to be used.

You are not required to remain within the confines of the IB Physics syllabus. Your Individual Investigation may involve techniques and concepts that you have not been taught. For example you could investigate how the ferromagnetic properties of iron and steel wires change with temperature and determine the Curie points.

Your self motivation towards the Individual Investigation will be formally assessed by your Teacher. This means that written work involved must always be handed in on time and complete.

You may also be assessed on the issues of plagiarism. This could involve copying someone else's investigation design or conclusion and evaluation. It could also involve using someone else's processed data from their Individual Investigation or copying their calculations.

You will also be assessed on whether you approach your Individual Investigation with integrity. This could involve making up results to fit a preconceived relationship or hypothesis, ignoring results which are unexpected (anomalous data) or not acknowledging if you obtained some of your raw data in a book or from the Internet.

Listed in *Figure 102* is a summary of what you need to do to score well in the **Personal Engagement** criterion.

Assessment criteria	Evidence required	What you must do
The evidence of personal engagement with the exploration is clear, with significant independent thinking, initiative or creativity.	A justified research question	You must justify the choice of research question and the topic under investigation and demonstrate personal significance, interest or intellectual curiosity.
	Personal engagement during the exploration	You show significant independent thinking, initiative or creativity in the report (write-up) of your Individual Investigation, especially in the introduction. Your work must be original.
	Personal engagement during, before and after the exploration	You show personal input and initiative in the design, implementation or presentation of the investigation. Any reflective modifications to the method should be outlined and justified.

Figure 102 Summary of the Personal Engagement criterion

This criterion assesses the extent to which the student establishes the scientific context for the work, states a clear and focused research question and uses concepts and techniques appropriate to the Diploma Programme level. Where appropriate, this criterion also assesses awareness of safety, environmental, and ethical considerations. The Exploration criterion encourages students to place their investigation into a genuine scientific context. This approach challenges the student to understand some physics.

The descriptors in the following table will be used to allocate a mark for your performance in this 'Exploration' criterion:

MARK	DESCRIPTOR
0	The student's report does not reach a standard described by the descriptors below.
1–2	The topic of the investigation is identified and a research question of some relevance is stated but it is not focused. The background information provided for the investigation is superficial or of limited relevance and does not aid the understanding of the context of the investigation. The methodology of the investigation is only appropriate to address the research question to a very limited extent since it takes into consideration few of the significant factors that may influence the relevance, reliability and sufficiency of the collected data. The report shows evidence of limited awareness of the significant safety, ethical or environmental issues that are relevant to the methodology of the investigation.
3–4	The topic of the investigation is identified and a relevant but not fully focused research question is described. The background information provided for the investigation is mainly appropriate and relevant and aids the understanding of the context of the investigation. The methodology of the investigation is mainly appropriate to address the research question but has limitations since it takes into consideration only some of the significant factors that may influence the relevance, reliability and sufficiency of the collected data. The report shows evidence of some awareness of the significant safety, ethical or environmental issues that are relevant to the methodology of the investigation.
5–6	The topic of the investigation is identified and a relevant and fully focused research question is clearly described. The background information provided for the investigation is entirely appropriate and relevant and enhances the understanding of the context of the investigation. The methodology of the investigation is highly appropriate to address the research question because it takes into consideration all, or nearly all, of the significant factors that may influence the relevance, reliability and sufficiency of the collected data. The report shows evidence of full awareness of the significant safety, ethical or environmental issues that are relevant to the methodology of the investigation. © IBO 2014

Guiding Questions

- *To what extent has the student stated a clear and focused research question?*
- *To what extent has the student established the scientific context for the work through a discussion of its significance?*
- *To what extent does the choice of investigation allow for concepts and techniques appropriate to Diploma level to be employed?*
- *To what extent has the student devised a methodology that shows awareness of the factors that may influence the collection of data relevant to the research question?*
- *To what extent does the methodology allow for the collection of sufficient relevant data that could enable a reasoned conclusion to be drawn?*
- *To what extent has the student shown how their method has been developed and modified?*
- *When appropriate, to what extent does the investigation indicate an awareness of safety, environmental, and ethical considerations?*

2.1 The Research Question

Guiding questions

- ***To what extent does the choice of investigation allow for concepts and techniques appropriate to Diploma level to be employed?***
- ***To what extent has the student stated a clear and focused research question?***

2.1.1 Choosing a Topic

Introduction

The Individual Investigation seeks to develop the IB candidate's investigative skills and to provide opportunities for self-motivation, independent learning and the planning and designing of appropriate experiments. It also provides the candidate with an opportunity to write in a scientific manner which reveals the significance of the findings of the Individual Investigation by analysing and interpreting the results in a critical and scientific manner and demonstrating knowledge and understanding of the physical basis of the Individual Investigation.

The Individual Investigation is assessed internally through the five Group 4 Assessment Criteria and moderated externally by the IBO (if sampled). The length of the Individual Investigation work is 10 hours and this includes the planning stage and the experimental work. After completion of the Individual Investigation, the Report for the assessment is likely to take a further 5-10 hours.

It is likely that consultation with your Physics Teacher will ensure an early focus and clear direction as to the suitability of the topic chosen for your Individual Investigation. While you will be involved in initial reading and research, it is important that this aspect of the Investigation does not take too much time of your time.

You should consult a wide variety of sources in selecting topics for investigation. The sources that might be consulted could include: Physics text books and practical books, journals and periodicals, e.g., *New Scientist*, *Physics Review* by Philip Allan (especially its project pages section), *The Australian Institute of Physics*, *Journal of Physics Teacher Education*, *Physics Education IoP*, *New Zealand Science Teacher*, and *School Science Review* published by the ASE (print and on-line) and Internet web sites, for example, *<http://seniorphysics.com/physics/eei.html>* and *<http://www.advancingphysics.org/files/PracInvest.pdf>*

Focused investigations completed in the time available are likely to be the most successful. Well-controlled investigations will score higher marks than investigations with too many independent variables from which valid conclusions cannot be drawn. A good investigation will generate a variety of raw data that can be manipulated via calculations and presented by graphs.

Time constraints, physics laboratory facilities, availability of equipment/apparatus, materials, costs and safety are all factors that need to be considered when you choose investigation topics.

While your Physics teacher should encourage the you to be creative and original, the Individual Investigation does not require to be a piece of original research but should be new to you an IB Physics candidate.

Examples of Investigation Topics

Let us consider fluid dynamics as a topic to select a reaction as an Individual Investigation. Your may have carried out a simple practical where you dropped a small steel bearing through oil in a tall tube and observed that it quickly reaches a terminal velocity.

For your Individual Investigation you may want to establish the relationship terminal velocity of a small steel ball bearing and its radius. You believe (based on suitable research that the relationship between the terminal velocity, v, of the steel ball bearing and its radius, r, $v = kr^2$, where k is a constant. You want to collect sufficient and relevant data to support or falsify that hypothesis.

A suitable Individual Investigation may take you beyond the IB Physics syllabus. For example, the piezoelectric effect describes an effect that converts a mechanical effect to an electrical signal or a mechanical effect into an electrical signal. For example, piezoelectric sensors such as quartz, silicon, or even flexible polymer sheets can produce electricity when squeezed, moved or bent. Piezoelectric transducers, such as those used in speakers, rapidly change shape when subjected to an electrical current.

Many modern devices, like the Nintendo Wii remote as well as smartphones such as the Apple iPhone have very small in-built piezoelectric accelerometers to help sense motion. Although called an accelerometer, it is actually the inertial force on a known mass that is measured by the piezoelectric material when the device is moved, which is then converted into an electrical signal and interpreted accordingly.

An Individual Investigation may involve a sample of piezoelectric material to find how the strength of the electrical signal (voltage and current) depends on how much force it is subjected to.

2.1.2 Characteristics of a good research question

A research question is a focused and challenging question addressing a physic problem or controversy with the aim of answering it by a conclusion that is based on the analysis and interpretation of numerical data.

The research question is a critical component of the investigation. When the aims of your study are clearly defined, this helps determine all other aspects of your investigation. The research question dictates the whole process; it drives your investigation design including how data are to be collected and processed and what evidence is required. It guides your analysis and interpretation of the processed data and the chemical arguments associated with them.

Hence, the research question can certainly make or ‘break’ your Individual Investigation. If your research question is weak, it would be too difficult to compensate for it in the other aspects of the study; and the whole investigative process is unlikely to be successful. Remember, a question well asked can lead to a question well answered.

Therefore, a good research question is at the heart of a great investigation. At the IB Diploma level, it is expected that the research question has a narrow focus and yet, it allows for an extensive exploration of the topic appropriate to Diploma level, given the available time, resources and ethical constraints.

A research question is deemed appropriate to IB Diploma level when it has the following characteristics:

- **The research question encourages a complex answer**. It is not answerable by a simple ‘yes or no.’ The answer to it should not be immediately obvious. It should have multiple possible answers and it is capable of generating multiple insights and possible surprises. The research question that aims to verify a known principle or physical law, such as Hooke’s law or Ohm’s law, is unacceptable in a simple context, as the answer to it is already known.
- **The research question is amenable to the formulation of a testable hypothesis**. It is grounded on a theoretical physical framework and has the potential to lead to a meaningful investigation design and methodology.
- **The answer to the research question transcends the raw data**. It is expected that the analysis and interpretation implemented to answer the research question go beyond the raw data. It involves variables that can be determined from the raw data and includes cause and effect (casual) relationships. It allows for a reasonable amount of data processing that shall include some calculations and graphing of processed physical data (not just raw data) and a meaningful interpretation of the graphs (including gradients and intercepts) and tables.
- **The research question takes ethical and safety issues into consideration.** You need to carry out a risk assessment and identify any hazards.
- **Equally important, the research question must be communicated effectively, that is, the research question is well written and well phrased.** It is both clear and concise. It identifies both the independent and dependent variables, and where appropriate, the controlled variables and possibly the method.
- It uses simple language and includes scientific terms only when they add meaning to the statement. It is such a big disservice to your study if you have an interesting investigation but your research question was stated inadequately.

For example, you may be investigating the behaviour of an LDR (light dependent resistor). Hence to write your research question, 'Investigating a LDR' is insufficient and does not reveal the complexity of the investigation.

'*Investigating how the resistance of an LDR depends on the intensity of the light incident on the LDR*', reveals the scope of the investigation.

2.1.3 Examples of unsuitable and suitable research questions

Shown below are some examples of how to formulate and write the research question.

EXAMPLE 1

To investigate light passing through two polarizing filters. (Unsuitable)

This is an unfocussed research question because the dependent and independent variables are not identified.

However, if the research question is reformulated as shown below then data can be readily collected in the laboratory using an LDR connected to an Ohmmeter. A light shield and a light source are also needed.

To investigate the relationship between the intensity of the light passing through a pair of polarizing filters and the angle between their planes of polarization. (Suitable)

EXAMPLE 2

To investigate the heating effect of a current on wire. (Unsuitable)

This research question is again unfocussed. What are you measuring; what is the dependent variable? Is current the independent variable? What type of wire is being investigated?

Here is a more focused research question:

To investigate the relationship between the diameter of a copper wire and the size of the current required to fuse (melt) the wire. (Suitable)

EXAMPLE 3

An air rifle can be used to fire small cylindrical pellets at a speed of about 150 metres per second on leaving the end of the air rifle. When an absorbent material is placed some distance from the rifle, the pellets are observed to create a hole in the material and penetrate it to a depth of several centimetres.

What is the relationship between the ratio of the depth of penetration (into clay) to the velocity of the metal pellet from an air rifle? (Suitable)

This is a very focused research question that identifies the independent and dependent variables as well as the method and controlled variables.

Note: This is given as an example of a Research Question only and is certainly not a recommended activity.

2.2 The Investigation In Context

Guiding questions:

- *To what extent has the student established the scientific context for the work through a discussion of its significance?*
- *How well has the student justified their choice of research question and approach to the investigation?*

2.2.1 Justification for the investigation

The research question can be put into context by

- stating why this is an important question to be answered and/or why you found this to be a particularly interesting question. A question is worth investigating if it is unresolved or unanswered by existing physics literature. Your methodology may also be an innovative process to find supporting data or falsify an existing hypothesis.
- discussing the background material that is particularly relevant to the research question and by summarising the current understanding of the problem you are investigating.
- addressing how your investigation will help to fill in the holes in our current physical knowledge of the topic.

Scientific hypotheses are testable hypotheses. This means that you need to be able to perform an experiment and take measurements and formulate observations to establish how two variables are related.

- A good hypothesis states an expected relationship between the dependent and independent variables and clearly explains or justifies the relationship between variables.
- A good hypothesis reflects the theory or literature on which they are based. A good hypothesis has a substantive link to existing scientific literature and theory.
- The Exploration criterion **does not explicitly require a hypothesis** but formulating one can help you give direction to your investigation and form an important part of the background of your planning and report. Formulating a hypothesis requires you to state clearly what you intend to change and measure. This is crucial as it can lead you to a reasonable experimental design.
- The ultimate value of the hypothesis is that its explanation, if linked convincingly to existing theory and literature, can give you the opportunity to demonstrate higher level order thinking skills necessary to access the assessment criteria at a higher achievement level.

2.2.2 Writing the background from the literature

A review of the physics literature related to your Individual Investigation has the following functions:

- To justify your choice of research question, theoretical or conceptual framework, and method.
- To establish the importance of the Topic.
- To provide background information needed to understand the study.
- To show your IA Assessor you are familiar with significant and/or up-to-date research relevant to the topic.
- To establish your study as one link in a chain of research that is developing knowledge in this field of Physics.

The review will provides a historical overview of the theory and the research literature, with a special emphasis on the literature specific to the Individual Investigation topic. It serves as well to support the argument/proposition behind your thesis, using evidence drawn from authorities or experts in your research field.

For example you may have chosen to use a remote controlled helicopter (*Figure 201*) as the subject of investigation for your Individual Investigation.

Figure 201 Remote controlled helicopter (courtesy of Chris Talbot)

The helicopter flies because of the thrust that is generated by the rotation of the blades of a main rotor that is mounted on a shaft above the helicopter. As the blades rotate, an airflow is created over them, resulting in lift which raises the helicopter. Newton's third law (of motion) requires that the air in turn exert an equal force upward on the rotor. For a helicopter to hover, the force exerted by the rotor blade on the air must be equal to the weight of the helicopter. A small rotor mounted on the tail of the helicopter with rotor plane perpendicular to the ground provides a torque to counter the tendency of the helicopter body to rotate.

Your Individual Investigation may involve establishing relationships between various quantities such as mass, frequency, radius, blade angle. Supporting theory where relevant would enhance the report of your Individual Investigation.

However, it is important that you do not include any advanced material that is not directly relevant to the Individual Investigation or you do not understand and explain clearly.

2.2.3 Formulating the hypothesis

Introduction

An hypothesis is a model, based on scientific knowledge and understanding, proposed to explain a particular problem or a set of observations or measurements. Having devised an hypothesis, it is possible to make predictions based on it, and these can be tested by experiment.

The 'scientific method' is based on the idea that an hypothesis can be disproved by experiment (when predictions are found to be untrue) but can never be proved (since an experimenter may, in the future, disprove it). Thus, a hypothesis which is not disproved remains in place and, when it has general acceptance, may come to be called a theory or law.

Many IB Physics investigations will start with a hypothesis or a pair of competing hypotheses. They should be supported by a detailed justification using relevant physical and mathematical concepts.

Below is an example of a hypothesis in the context of an investigation into terminal velocity of steel ball bearing falling through a liquid.

When an object falls through a liquid or gas, the fluid offers resistance to the motion. At low speeds, it can be assumed that the resistive force, F, is directly proportional to velocity, v, i.e.,

$F = -kv$

where k is a constant and depends on the viscosity of the fluid and the object and its dimensions. It is negative as the resistive force is opposing the motion of the ball bearing.

A falling object through a fluid also experiences an upthrust. An equation of motion from Newton's second law of motion is produced:

Resultant force = $Mg - U - kv$, where the resultant force = mass × acceleration or mass × dv/dt

However, in my methodology I need to use a counterweight to oppose the motion of the falling steel ball bearing, hence the above equation becomes:

$(M + m)\, dv/dt = Mg - mg - U - kv$

where U = upthrust, M = mass of the falling object and m = mass of the counterweight opposing the motion of the object.

At the terminal velocity of a falling object there is no acceleration, hence $dv/dt = 0$, which implies that

$kv_1 = Mg - mg - U$

2.3 The Investigative Process

2.3.1 Selecting, manipulating and controlling variables

Guiding questions:

- ***To what extent has the student devised a methodology that shows awareness of the factors that may influence the collection of data relevant to the research question?***

Variables

Variables are factors that can be measured and/or controlled. Independent variables are those that are manipulated, and the result of this manipulation leads to the measurement of the dependent variable. A controlled variable is one that should be held constant so as not to obscure or hide the effects of the independent variable on the dependent variable.

The variables need to be explicitly identified by you as the dependent (measured), independent (manipulated) and controlled variables (constants). Relevant variables are those that can reasonably be expected to affect the outcome.

Consider an investigation into the oscillation of a cantilever. The cantilever is a beam that is supported on only one end and it can be represented by a loaded wooden rule. As a result of support only at one end, a cantilever will oscillate when it is subjected to an external force.

An investigation may involve determining how the period of the oscillation of the loaded wooden rule depends on the overhanging length *l* of the rule.

The independent variable is the load and the dependent variable is the oscillation period. Controlled variables include the tension supplied by the G-clamp, the position of the load, the nature of the cantilever and its dimensions.

2.3.2 Establishing the rationale for the method

Guiding questions

- *To what extent does the methodology allow for the collection of sufficient relevant data that could enable a reasoned conclusion to be drawn?*
- *To what extent has the student shown how their method has been developed and modified?*
- *When appropriate, to what extent does the investigation indicate an awareness of safety, environmental, and ethical considerations?*
- *To what extent does the student engage with the investigation and make it their own?*

Introduction

Planning a scientific investigation is one of the most demanding and difficult skills to learn. In order for training in planning skills to be effective you must have confidence in your practical abilities.

It is not sufficient that you have simply learnt to follow instructions; you must be able to apply the experience you have got from earlier exercises in order to see the consequences of a given choice on the outcome of your plan.

It is therefore vital that you understand the rational for using particular approaches, pieces of equipment, recording and analysing techniques, rather than simply performing a given exercise in a particular prescribed way.

An appreciation of precision and reliability is essential when choices of measuring equipment or apparatus are made, and when experimental procedures are suggested.

An understanding of random errors and possible systematic, associated with individual pieces of apparatus is fundamental to the successful choice of apparatus for a given task. A similar argument applies to the identification of variables that need to be controlled, and the proposing of suitable measures to control them.

The advantages and limitations of one type of measuring device, control measure or practical approach compared to other possibilities must be understood if the appropriate equipment, approach and quantities are to be used.

The proposed experimental procedure should be workable. It should, given that the apparatus is assembled appropriately, allow data to be collected without great difficulty.

There should be a description, including labelled diagrams in cross section, of how the experiment should be performed and how the key variables are to be controlled. However, drawings perhaps should be perhaps be limited to complex set-ups, non-standard equipment or standard equipment being in an unusual manner.

Equipment or apparatus, of a level of precision appropriate for the measurements to be made, and quantities (and concentrations) of chemicals (IUPAC names and formulas) to be used should be specified. Note that some Physics investigations may use chemicals (e.g. optics and fluid dynamics).

Also, details of how the raw data are to be recorded, manipulated, analysed and evaluated should be given. Your method should not be a 'recipe' or simple list. It should justify the techniques and apparatus selected. It is suggested that it is in two sections: the planning and development of the method and the method actually used.

Below is a detailed method describing the methodology of the cantilever investigation outlined previously. Note the sections that describe how the controlled variables are controlled and how measures are implemented to ensure reliable sufficient and relevant raw data are collected.

Methodology

1. Measure the overhanging length l of the rule using the scale on the rule.
2. Slightly displace the end of the rule vertically downwards so that the end of the rule starts oscillating in a vertical plane.
3. Measure the time taken t for many oscillations such that the time is more than 20 seconds using an electronic stopwatch.
4. An oscillation is considered when the end of the rule moves from A to B, then back to B to A.
5. Repeat to obtain another 10 set of values of t with different overhanging length l of the rule by shifting the rule.
6. The period of oscillation, T, is calculated using $T=t/N$.
7. Plot a graph of $\log_{10} T$ against $\log_{10} l$ to determine the relationship.

Control of the variables

- Ensure that the mass of the load at the end of the strip remains unchanged by using the same slotted mass.
- Ensure that the position of the mass remains unchanged by taping or gluing it at the end of the rule.
- Ensure that the Young modulus of the rule remains unchanged by using the same wooden rule.
- Ensure that the width and/or thickness of the rule remain unchanged by using the same wooden rule.

Reliability measures

- The same mass should be used (to keep the mass of the loaded wooden rule constant)
- The load should be secured to the rule using tape and/or glue (to keep the position of the mass constant).
- The same rule should be used (to keep the Young Modulus and the dimensions of the rule constant).
- Start timing after the oscillations become stable (as the first few oscillations are usually irregular and will contribute to the random errors in measuring the time taken).
- Take repeated readings of time taken t to reduce the random errors incurred due to the
- starting and stopping of the stopwatch
- The mass of the load should be large enough to make the period, T, large.
- A fiducial marker should be used to help in the measurement of the time taken, t.
- The amplitude/angle of oscillations should be small (to ensure that the oscillations follow simple harmonic motion).

Listed in Figure 205 is a summary of what you need to do to score well in the Exploration criterion.

Assessment criteria	Evidence required	What you must do
Identifies a topic, a relevant and fully focused Research Question is clearly described. Relevant and appropriate background information is provided to increase the understanding of the context of the investigation	A topic, a relevant and fully focused Research Question are described	Identify the topic and state the Research Question, for example: The investigation will determine how the 'independent variable' affects the 'dependent variable'. The following will be kept constant: controlled variable 1, controlled variable 2,… and the method for measuring the dependent variable.
	Relevant and appropriate physical background is included	Give relevant background information including a summary of the literature and a testable hypothesis and perhaps reference to a relevant model or theory and identifies the main physical processes involved and the likely causes. Makes quantitative predictions in words and in the form of graph.
	State the relevant variables explicitly	Classifies and tabulates key variables. • Independent variable (one only) • Dependent variable (one only) • Processed variables (one or more) • Controlled variables (typically more than one) • Identify variables over which little control can be exerted
Designs a methodology that allows relevant, reliable and sufficient data to be collected. Shows full awareness of safety, ethical and environmental issues	Appropriate choice of materials and apparatus	List of all apparatus and instrumentation (state manufacturer (where appropriate) with specifications including precision/random uncertainty. A labelled and cross-sectional diagram of any set-up of apparatus with a justification and explanation for the methodology.
	Effective control and manipulation of variables	A clear description of the method which includes • how the independent variable is to be varied and measured accurately • how the dependent variable is measured • a logical sequence of steps to be taken and their rationale • details of any modification or adaptations of standard methods and justification for their use • a clear account of how and why the controlled variables are kept constant. • a statement of how the plan will produce relevant, reliable and sufficient results. • a statement of how the plan will produce accurate and precise results. • results tables and graph axes and how the raw data will be processed • where appropriate, an explanation of the physical principles behind your plan. • control experiments should be described (if relevant) • a detailed statement of how the plan ensures an ethical and safe investigation (risk assessment) that minimises the impact on the environment. • safety precautions taken to keep risks to a minimum
	Appropriate number and range of readings to be taken	State you will take measurements for at least five values of the independent variable. Also consider what the reading at zero will be. State the range of values for the independent variable i.e. the lowest and highest values and the size of the increment. State the number of repetitions for each value of the independent variable.

Figure 205 Summary of the Exploration criterion

This criterion assesses the extent to which the student's report provides evidence that the student has selected, recorded, processed and **interpreted** the data in ways that are relevant to the research question and can support a conclusion.

The descriptors in the following table will be used by your teacher to allocate a mark for your performance in this criterion:

MARK	DESCRIPTOR
0	The student's report does not reach a standard described by the descriptors below.
1–2	The report includes insufficient relevant raw data to support a valid conclusion to the research question. Some basic data processing is carried out but is either too inaccurate or too insufficient to lead to a valid conclusion. The report shows evidence of little consideration of the impact of measurement uncertainty on the analysis. The processed data is incorrectly or insufficiently interpreted so that the conclusion is invalid or very incomplete.
3–4	The report includes relevant but incomplete quantitative and qualitative raw data that could support a simple or partially valid conclusion to the research question. Appropriate and sufficient data processing is carried out that could lead to a broadly valid conclusion but there are significant inaccuracies and inconsistencies in the processing. The report shows evidence of some consideration of the impact of measurement uncertainty on the analysis. The processed data is interpreted so that a broadly valid but incomplete or limited conclusion to the research question can be deduced.
5–6	The report includes sufficient relevant quantitative and qualitative raw data that could support a detailed and valid conclusion to the research question. Appropriate and sufficient data processing is carried out with the accuracy required to enable a conclusion to the research question to be drawn that is fully consistent with the experimental data. The report shows evidence of full and appropriate consideration of the impact of measurement uncertainty on the analysis. The processed data is correctly interpreted so that a completely valid and detailed conclusion to the research question can be deduced.

Guiding Questions

- ***Has the student selected and recorded raw data, including uncertainties and qualitative observations where relevant, that allow for coherent analysis?***
- ***Has the student selected (an) appropriate method(s) for analysing the data?***
- ***How successfully has the student analysed the data?***
- ***Is the analysis of data accompanied by evidence of an appropriate consideration of uncertainties?***
- ***How successfully has the student interpreted their analysis to form a conclusion?***
- ***Has the student drawn a conclusion that is relevant to the purpose of the investigation?***
- ***Has the student compared their conclusion to accepted scientific theory?***

3.1 Recording raw data

Raw Data

Physics is the most quantitative of all sciences and in many Investigations, you will be expected to measure physical quantities. In IB Physics, measurements are considered complete only when the associated uncertainty is stated. Measurements consist of the best estimate and its associated uncertainty is the range of values within which the correct value lies. Therefore, all measurements must be expressed as $x \pm \Delta x$ where x is the best estimate of the measurement and Δx is the uncertainty. For example, the time for five complete oscillations of a simple pendulum can be expressed as (5.3 ± 0.2) seconds.

Uncertainties are associated with all raw data and an attempt should always be made by you to quantify uncertainties. For example, when there is an uncertainty in a time measurement because of reaction time, you must estimate the magnitude of the uncertainty.

Presenting raw data

Most of the observations and measurements that you will record need to be presented in a table of results. It is important that your table of results is effective and easy to read. Therefore, when designing your results table, it should be able to clearly communicate the relationship between the dependent and independent variables.

Here are a few guidelines that may help you design a clear and efficient table of results.

- The independent variable column should be on the left, the dependent variable column on the right.
- Often there is a need to do repeat readings. Sub-divide the column for the dependent variable to reflect the number of trials conducted.
- Column headings; the heading of each column must clearly describe the data the column represents, the units in which the measurement is made and an indication of the uncertainty.
- Where appropriate, record and show the value of any controlled variable.
- Where appropriate, indicate the source of uncertainty in the measurement.

Uncertainty and Precision

- Readings made directly from measuring instruments should be given to the number of decimal places that is appropriate for the measuring instrument used, that is, the number of significant digits must clearly reflect the precision of the measuring instrument.
- Be consistent with the degree of precision for each column of raw data (i.e. if data is precise up to 1 decimal place, record 2.0, not 2).

Measuring instrument	Smallest division	Probable Uncertainty	Examples of three consecutive readings
Metre rule	0.1 cm	± 0.05 cm	10.20 cm 10.25 cm 10.30 cm
Vernier caliper	0.01 cm	± 0.01cm	6.23 cm 6.24 cm 6.25 cm
Micrometer screw gauge	0.01 mm	± 0.01 mm	5.15 mm 5.16 mm 5.17 mm
Electronic balance	0.01 g	± 0.01 g	179.99 g 180.00 g 180.01 g
Analogue stopwatch	0.1 s	± 0.05 s	2.00 s 2.05 s 2.10 s
Digital stopwatch	0.01 s	± 0.01 s	15.19 s 15.20 s 15.21 s
Liquid-in-glass thermometer	1 ^{0}C	± 0.5 ^{0}C	30.0 ^{0}C 30.5 ^{0}C 31.0 ^{0}C
Digital thermometer	0.01 ^{0}C	± 0.01 ^{0}C	29.89 ^{0}C 29.90 ^{0}C 29.91 ^{0}C
Digital ammeter	0.01 A	± 0.01 A	1.49 A 1.50 A 1.51 A
Analogue ammeter (0 – 3 A)	0.1 A	± 0.05 A	2.60 A 2.65 A 2.70 A

Figure 301 Common instruments and their uncertainty

Note again that the measurement and the uncertainty must be expressed to the same degree of precision, that is, the same number of decimal places. See *Figure 301*.

Example: Data Collection

Independent variable is the first column

Precision of uncertainty and measurement is consistent e.g. two decimal places

Clear headings with units and uncertainties

Length of the pendulum / cm (± 0.05 cm)	Time to complete 5 oscillations / s (± 0.21 s)		
	Trial 1	Trial 2	Trial 2
40.00	6.54	6.67	6.76
50.00	7.47	6.91	6.84
60.00	7.87	7.75	7.95
70.00	8.93	8.47	8.53
80.00	8.97	8.87	9.00
90.00	9.63	9.60	9.46
100 .00	9.97	10.15	10.19

Precision of measurements is consistent.

Column subdivided to show repeat readings

Controlled variables → Mass of the pendulum bob = 300 g
Angle of release = 5^0

Error explained → Uncertainty in time is due to reaction time (± 0.20 s) and instrument limitation (±0.01 s)

Figure 302 Sample data for the investigation "Period of a pendulum"

Good practices in data collection

- It is important that you keep an accurate record of what you do in the laboratory. What you use is a matter of personal choice but it is suggested that you keep a laboratory notebook for this purpose.
- It is important that you have drawn the results table before the experiment is performed. It is not good practice to initially record your results on a piece of rough paper and transfer it later to an organized data table. This runs the risk of copying errors or worse, of losing the paper.
- Carry out your measurements carefully and as accurately as possible. No amount of careful calculation after the investigation is over can compensate for improperly recorded data. If the data are incorrect, the aim of the investigation is completely lost.
- When collecting data, it is good routine to do a practice run before doing the actual measurement. This will give you a feel of the measurements to be recorded and of the possible problems that may be encountered. This will also help you decide whether you need to do repeat readings.

3.2 Processing Raw Data

Data processing in the IB Physics course can take a variety of forms. Listed below are ways by which you can process data. Note that you may not need to do all of these methods with every investigation that you will be doing.

3.2.1 Calculating the average

When measurements are repeated, you need to calculate the average of the values. The calculated average value will then be used as the value of the measurement in the subsequent stages of the data processing. Also, the average value cannot be more precise than the measurements, thus it should be rounded off to the same number of decimal places as the measurements.

The method for calculating the uncertainty in repeated measurements is described later.

3.2.2 Calculating a physical quantity

In some investigations, you will need to directly calculate some physical quantity by using measured variables. At times, this physical quantity can be derived from the gradient of the graph. As an example, you might be asked to investigate a factor which affects the electrical resistance of a conducting wire. If you have a graph of electrical resistance against length, you would be able to calculate the resistivity of the wire from the gradient.

What is important is that you show the working clearly and you round off your final value to the correct number of significant figures. You would also need to show how the uncertainties are propagated in the calculation. For this, it is most helpful if you change the absolute uncertainties into percentage uncertainties.

Calculation involving measurements and uncertainties entails some rules that you need to remember.

These rules are described in Chapter 10 which cover uncertainties and the propagation of errors.

3.2.3 Plotting graphs

Graphing is an essential part of data processing in the IB Physics course. Plotting a graph is a way of:

- averaging the data so that the effects of random errors are minimized.
- identifying anomalous points.
- eliminating some systematic errors.

In many cases, you would need to plot a graph to determine or verify the relationship between the independent and dependent variable, and the graph is usually (although not always) a straight line. In most graphs, you must always plot the best-fit straight line or curve. The line of best fit and how to draw it are described in *Section 8.2.1*.

The graph that is easiest to analyse and interpret is that which has a straight line. However, when the values of the dependent and independent variables are plotted, not all trends will produce a straight line. The analysis of a graph with a curved line is not as simple as that of a straight line graph. Fortunately, it is possible, by carefully selecting the variables to be plotted, to 'linearise' a curved line graph.

If the equation relating the variables is known, you must be able to select the appropriate variables to plot to obtain a straight line. When the equation relating the two variables is not known, you may use a log-log graph to obtain a straight line graph and use its gradient to deduce the relationship. The method of linearising a graph is described fully in Chapter 10.

3.2.4 Calculating and interpreting the gradient

The determination of the gradient of the graph is an essential component of data processing. Note that if a graph is present, data processing is not considered complete unless the gradient is obtained. The method of calculating the gradient is shown in *Section 8.2.2*. In many cases, you may also need to interpret the significance of the gradient or use it to obtain another physical quantity.

3.3 Presenting Processed Data

The processing of data needs to be presented in a clear and efficient manner. All key stages must be presented sequentially so that the pathway to the conclusion is clear to the reader. Also, tabulate the processed data if possible.

A good data processing presentation will include:

- a display of key calculations in a clear and sequential manner.
- the propagation of errors in the calculated values.
- a graph with the appropriate scales, clearly labelled axes with units.
- uncertainty bars in straight line graphs.
- lines of minimum and maximum gradients.
- determining the uncertainty of the best straight line gradient.

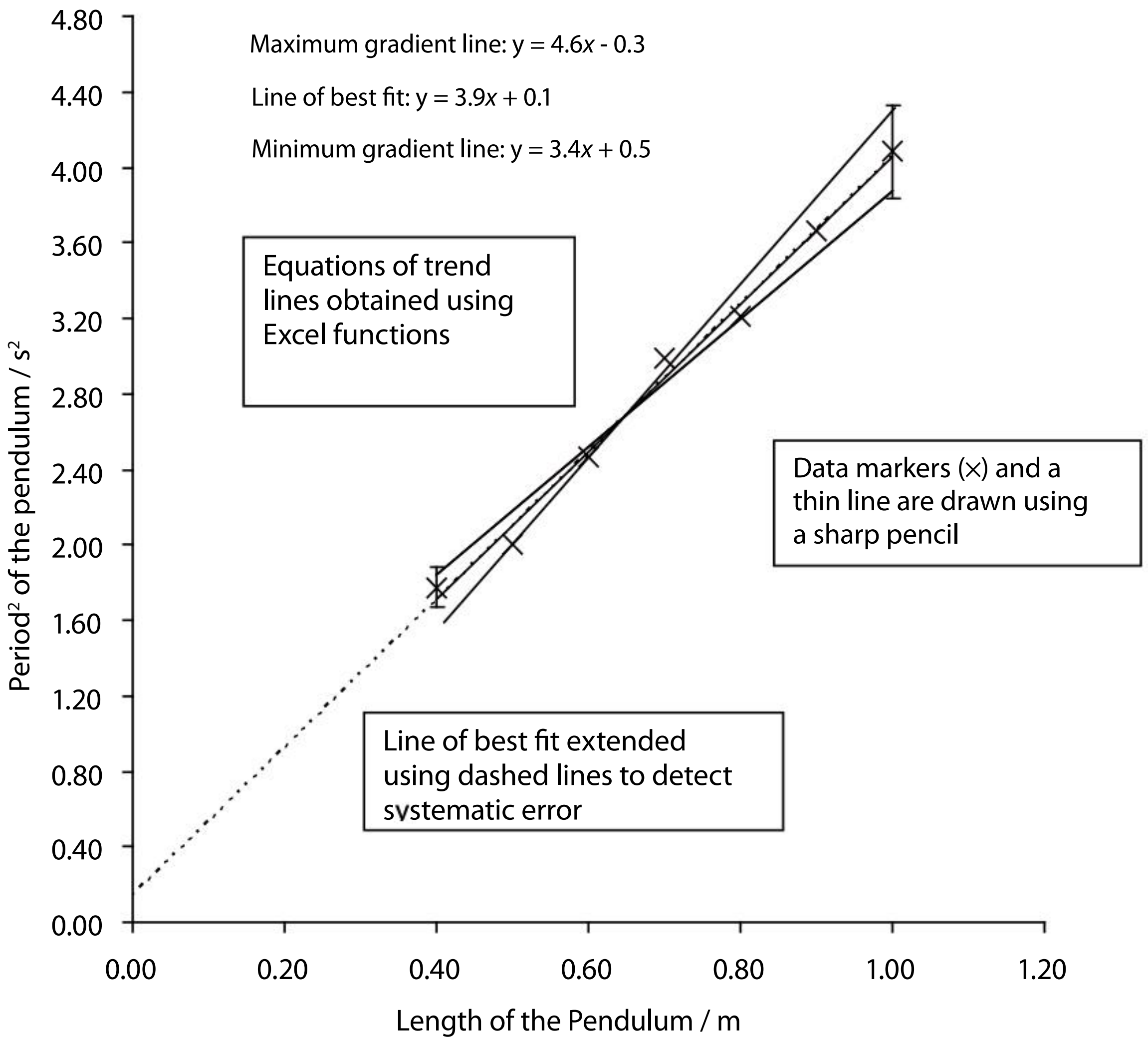
Length of the pendulum / m ± 0.0 005 m	Average time for five oscillations / s ± 0.21 s	Period / s	Period ^{2} / s^2
0.40 00	6.66	1.33 ± 0.03	1.8 ± 0.1
0.50 00	7.07	1.41 ± 0.03	2.0 ± 0.1
0.60 00	7.86	1.57 ± 0.03	2.5 ± 0.1
0.70 00	8.64	1.73 ± 0.02	3.0 ± 0.2
0.80 00	8.95	1.79 ± 0.02	3.2 ± 0.2
0.90 00	9.57	1.91 ± 0.02	3.6 ± 0.2
1.0000	10.10	2.02 ± 0.02	4.1 ± 0.2

Uncertainty rounded off to one significant figure. The data value is also rounded off so that it has the same precision as the uncertainty.

Calculated values have the same precision as the measured values

Length is converted to the necessary unit. Note that the uncertainty and the data have the same precision.

Figure 303 An example of a table of processed results



Gradient = $3.9 \pm 0.6\ s^2\,m^{-1}$

The uncertainty is obtained by calculating the average deviation between the gradient of the line of best fit and the maximum or minimum gradient.

Figure 304 Graph of Period² against length of a simple pendulum

Important note: Unfortunately the software used to generate this graph did not allow the uncertainties to be shown.

Example: Calculation for the gravitational acceleration constant g from the gradient

From the graph, the gradient is equal to $\frac{\Delta T^2}{\Delta l}$.

Since $T^2 = 4\pi^2 \frac{l}{g}$, then by comparing it to the gradient, g is equal to

$$g = \frac{4\pi^2}{\text{gradient}} = \frac{4\pi^2}{3.9} = 10.1$$

To obtain the uncertainty in *g*, use the above formula with the maximum and minimum values of *g*.

$$\text{Maximum value: } g = \frac{4\pi^2}{\text{gradient}} = \frac{4\pi^2}{3.2} = 12.3$$

$$\text{Minimum } g = \frac{4\pi^2}{\text{gradient}} = \frac{4\pi^2}{4.6} = 8.6$$

$$\text{Uncertainty in } g = \frac{12.3 - 8.6}{2} = 1.9$$

Therefore $g = (10.1 \pm 1.9)\ \text{m s}^{-2}$

or more realistically, the result should be quoted as

$g = (10 \pm 2)\ \text{m s}^{-2}$

3.4 Concluding

In the IB Physics programme, the conclusions that would be drawn from an investigation are of two types. It could be determining the relationship between two variables or it could be measuring an already known physical quantity. There would be some investigations where both have to be done.

When determining the relationship between two variables, your conclusion must include the following:

- a statement of any patterns or relationships between the independent and dependent variables.
- use of data to support your conclusion.
- comparison of the conclusion with the accepted theory.
- effect of systematic errors, if present, on the results.

When measuring an already known physical quantity, your conclusion must include the following:

- a comparison between the experimental value and the literature value. (*The literature value must be referenced appropriately.*)
- the percentage error should also be calculated.
- the effect of systematic errors, if present, on the results.

3.4.1 Determining the relationship between two variables

Graphs provide a visual representation of the results and make the mathematical relationship between the variables obvious. Most of the graphs that you will be plotting are straight line graphs and this makes interpretation of the results simpler. However, you need to be careful about the stating whether the relationship is "proportional or linear." (*See Chapter 10*)

- Two variables are proportional if the straight line passes through the origin.
- Two variables have a linear relationship if the graph is a straight line but does not pass through the origin.

Use data to support your conclusion.

Aside from stating the relationship, you need to provide support for your conclusion. It is not enough to write "*the graph shows that the relationship is proportional.*"

If the two variables are proportional, you can prove this by showing that doubling the x-value will double the y-value. When doing this, you need to use values that lie on the line and not the data points that you have plotted.

If the relationship is linear, you can show this by citing values that will show that the gradient is constant.

After stating your conclusion, you will also need to compare this with the accepted theory.

If your result is consistent with the theory, you should state "*the results support the theory*" rather than stating that "*the results are correct.*"

This part is quite tricky. In most cases, comparison with the accepted theory can help you decide whether there is systematic error or not. If the accepted theory suggests that the line should pass through the origin but your line is shifted away from the origin, then this might be due to a systematic error.

Listed in Figure 305 is a summary of what you need to do to score well in the Analysis criterion.

ASSESSMENT CRITERIA	EVIDENCE REQUIRED	WHAT YOU MUST DO
Recording raw data	Records sufficient and relevant quantitative and associated qualitative raw data	Records sufficient and relevant raw data (qualitative observations and/or quantitative data (usually tabulated). This may include data-logger print outs and digital photographs. Records data for the controlled variables. The data must allow a detailed and valid conclusion to the research question. This often implies data supporting a relationship between an independent and dependent variable.
	Records units and absolute uncertainties where relevant.	Records all measurements to the correct number of significant figures and records appropriate units, usually SI units (showing derivation where appropriate). Records the level of absolute uncertainty or precision for each quantitative reading.
Processing raw data	Processes the quantitative raw data correctly.	Raw data is subjected to relevant calculations (processing). Calculations are correct and accurate to the level necessary. Units are included in the calculations. Significant figures rules are stated and followed. Converts absolute uncertainties to percentage uncertainties and propagates percentage uncertainty calculations correctly. Converts tabulated data into graphical form as relevant. Extracts relevant quantities from the graph (ideally a linear graph) via extrapolation or interpolation or determination of the gradient. Makes appropriate choice of graph or chart. Simple statistics may be performed if relevant.
	Presents and interprets processed data appropriately and, where relevant, includes errors or uncertainties in calculations and graphs.	• Use of proper scientific conventions in tables (for example, units written once at top of columns), drawings of graphs and charts. • Sample calculations are shown and explained/justified; derived units are included in final calculations. • For graphs, labels and units are correct and scale is appropriate; error bars may be present. • For a graph a line or curve of best fit is drawn (if appropriate). • Final numerical answers are accompanied by an absolute uncertainty.

Figure 305 Details of what is required in the Analysis criterion

This criterion assesses the extent to which the student's report provides evidence of evaluation of the investigation and the results, with regard to the research question and the accepted scientific context.

The descriptors in the following table will be used by your teacher to allocate a mark for your performance in this criterion:

MARK	DESCRIPTOR
0	The student's report does not reach a standard described by the descriptors below.
1–2	A conclusion is outlined which is not relevant to the research question or is not supported by the data presented. The conclusion makes superficial comparison to the accepted scientific context. Strengths and weaknesses of the investigation, such as limitations of the data and sources of error, are outlined but are restricted to an account of the practical or procedural issues faced. The student has outlined very few realistic and relevant suggestions for the improvement and extension of the investigation.
3–4	A conclusion is described which is relevant to the research question and supported by the data presented. A conclusion is described which makes some relevant comparison to the accepted scientific context. Strengths and weaknesses of the investigation, such as limitations of the data and sources of error, are described and provide evidence of some awareness of the methodological issues* involved in establishing the conclusion. The student has described some realistic and relevant suggestions for the improvement and extension of the investigation.
5–6	A detailed conclusion is described and justified which is entirely relevant to the research question and fully supported by the data presented. A conclusion is correctly described and justified through relevant comparison to the accepted scientific context. Strengths and weaknesses of the investigation, such as limitations of the data and sources of error, are discussed and provide evidence of a clear understanding of the methodological issues* involved in establishing the conclusion. The student has discussed realistic and relevant suggestions for the improvement and extension of the investigation.

Guiding Questions

- ***To what extent has the student discussed limitations and/or likely sources of error in their methodology?***
- ***To what extent has the student discussed the reliability of their data?***
- ***To what extent has the student demonstrated an understanding of the impact of experimental uncertainty on their conclusion?***
- ***To what extent has the student suggested relevant and feasible modifications to their methodology?***
- ***To what extent has the student suggested relevant and feasible extensions to the investigation?***
- ***To what extent has the student demonstrated an understanding of the implications of the conclusion?***

4.1 Evaluating procedure(s)

When you evaluate an investigation, this means that you will judge the validity of the conclusion that you have formed by looking at the accuracy and reliability of the measurements, and at the suitability of the procedure.

To score well in this aspect, your evaluation needs to include the following:

- comment on the quality of the data collected in terms of its accuracy and precision
- comment on the suitability of the design and method of the investigation, including the choice of apparatus
- outline of weaknesses in the method and the significance of the weaknesses in the results

4.1.1 Commenting on precision and accuracy

- Accuracy of data is measured by how close they are in conforming to the accepted theory.
- On a graph, the average distance of the data points from the line of best fit is an indication of the data's accuracy. The closer the data points are to the line of best fit, the more accurate the measurements are.
- When measurements are repeated, precision can be judged by looking at how close the replicated measurements are to each other. In theory, the closer the repeated measurements are to each other, the more precise the measurements are.

4.1.2 Commenting on the method and apparatus

Possible sources of systematic errors include, but are not limited to, the following:

- reaction time
- synchronization of the start of motion and of the timer
- non-calibration of instruments
- frictional effects, air resistance
- mechanical problems (e.g. release mechanism in free falling bodies)
- heat transferred to the environment, to the thermometer, to the container
- electrical resistance
- heating up of electrical devices
- electrical resistance of ammeter and voltmeter
- current diverted into the voltmeter
- background count in radioactivity investigations

N.B. An important type of systematic error is a **zero error**. It is any indication that a measuring instrument gives a false reading when the true value of a measured quantity is zero, e.g., the needle on an ammeter failing to return to zero when no current flows.

4.1.3 Identifying weaknesses

To identify weaknesses, you need to be critical of the procedure and the equipment used during the investigation.

Weakness in the method and equipment may involve one or more of the following questions:

- Were there other factors that you failed to consider that might have affected the results? Was the management of the controlled variables effectively done?
- Was there any measurement that was difficult to record? Did the difficulty cause a large variation in the measurement? If there is, state which one it is and comment on the effect of this in the final result.
- Were there any repeated measurements with a large range, and therefore imprecise, and if so, how did this affect the other measurements?
- Was enough raw data collected? Was the range and distribution of data points appropriate?
- What was the largest source of uncertainty?

  You can look at the uncertainty of each measurement that you had recorded. Next, look at how the different measurements are combined to obtain the final result. Most of the time, you will see that one of the measured quantities is the critical quantity, that is, it has the biggest contribution to the uncertainty in the final result.
- Did the equipment provide the necessary precision in the measurements?
- What is the effect of the uncertainty to the result? Did it lead to an over-estimation or an under-estimation of the final results?

Note that your weaknesses should not include human error, incompetent use of the equipment, poor time management, or worse, a comment on the ineptness of your lab partner.

4.2 Improving the investigation

You will be expected to suggest ways that can make your measurements more accurate and reliable. The suggested modifications must be linked to the sources of errors that were identified earlier. Therefore, your suggestions must reduce random error, remove systematic error and/or obtain greater management of the controlled variables. It is also important that these suggestions are realistic and achievable.

In general, suggestions may include, but are not limited to the following:

- change in the procedure followed.
- the use of a more appropriate measuring instruments, e.g. data loggers.
- performing the measurements in a different manner.
- taking a greater number and a wider range of measurements.

4.2.1 Precision

- If there is one critical quantity that contributes the greatest error to the final result, how can the uncertainty of this quantity be reduced? Is there a more appropriate apparatus or method? How can such apparatus or modified method improve the accuracy of the results?

  Note that it is not sufficient to state that a more precise or advanced piece of equipment be used.

- If there is not enough data, do you collect more outside of the present range? Or do you collect more data within the range, that is, to reduce the intervals between measurements? Why do you need to collect more data? How will the collection of more data improve the results?
- It is common for students to suggest doing more repeat measurements or more trials as an improvement. However, if using the current method you have already done three to five trials, then the suggestion is impractical. Besides, if you keep doing the same method, your results' precision will not vary much.

4.2.2 Accuracy

- If you found a measurement difficult to make, is there a more appropriate instrument to use? Or can you suggest a different method to do the measurement?
- If there is a systematic error, how can this be reduced or eliminated?

Suggested improvements must also be realistic. In a free fall investigation, air resistance is a source of systematic error. It causes the measured time to be longer and in effect, the measured acceleration due to gravity becomes less than the correct value. Stating "perform the investigation in a vacuum" is unrealistic. High school laboratories are not equipped to have vacuum chambers that are large enough to study the motion of a falling object. Besides, how the experimenter will do the investigation without suffocating in a vacuum is hard to imagine.

A more realistic improvement would be to use an object in which the effect of air resistance is less. A heavier and smaller object would experience less air resistance than a lighter and bigger object. Thus, if a tennis ball was used in the original investigation, a steel ball could be suggested as an improvement. You must also state how using a steel ball would improve the accuracy of the results.

What improvement would I suggest if my result agrees with the correct value within the stated uncertainty?

If this is the case, then there are no significant systematic errors in your investigation. The limitation of your results is the size of the uncertainty. Your aim now is to reduce this uncertainty. Thus, you need to identify the quantity which contributes the most to the uncertainty in the result. Your suggested improvement must then focus on reducing this uncertainty.

Example 1 Period of a simple pendulum

From the graph (*Figure 204*), it can be seen that within the limits of uncertainty the square of the period of a simple pendulum is directly proportional to its length ($T^2 \propto L$). To prove this, when the length (L) is 0.40 cm, the square of the period (T^2) is 1.65 s^2. When L is doubled to 0.80 cm, T^2 is also roughly doubled to 3.25 s^2. (*Note that points along the line of best fit are used, not the data points*). This result is consistent with the formula:

$$T = 2\pi\sqrt{\frac{L}{g}} \quad \text{or} \quad T^2 = \frac{4\pi^2 L}{g}$$

Furthermore, by using the value of the gradient in the above formula, the value of g (acceleration due to gravity) is deemed to be equal to 10 ± 2 m s^{-2}. The correct value of 9.8 m s^{-2} is within the range of the calculated value. However, the percentage uncertainty is 20% and therefore the value has low precision.

The equation above predicts that the graph of T^2 against L should pass through the origin. However, the line obtained is shifted slightly above the origin. This suggests that the measured values of T^2 are overestimated. This could be due to starting the timer early and/or a delay in stopping it resulting in a longer measured time.

In this investigation, the measurement of time contributes greatest to the uncertainty. The time periods measured are short and the effect of reaction time is significant. Therefore, increasing the time period that is measured will help reduce the effects of reaction time and thereby increase the precision of the result. This can be done by:

- measuring the time for a greater number of oscillations, say from 10 to 20 oscillations.
- increasing the range of lengths of the simple pendulum (0.6 – 1.6 m). According to the equation above, a simple pendulum with a longer length has a greater period.

4.2.3 Further examples

Example 2 Use of ticker tapes (friction effects)

Weakness: Friction effects

The time and distances measured from the ticker tape can be precise. However, the drag of the ticker tape through the ticker timer reduces the speed of the object. This is a systematic error and a design flaw that limits the accuracy of the results.

Improvement: Friction compensation

The effect of the drag can be eliminated by slightly raising one end of the plank. This is to compensate for the frictional effects caused by the ticker tape sliding through the ticker timer. One end is raised such that the dots produced in the ticker tape are equal distances apart.

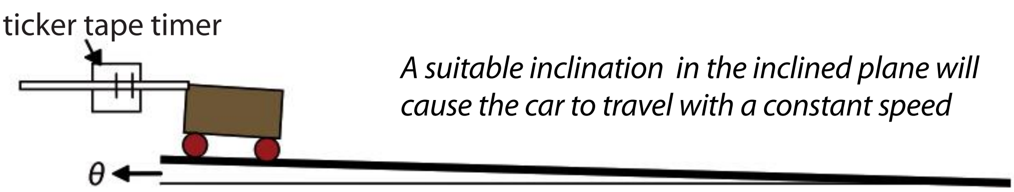


Figure 401 Friction compensation

The frictional effects in this case can be estimated as $F = mg \sin\theta$ where m is the mass of the cart.

The following is an example of Evaluation and is not intended as a good example of a Research Topic.

Example 3 Measurement of specific heat capacity of a metal block

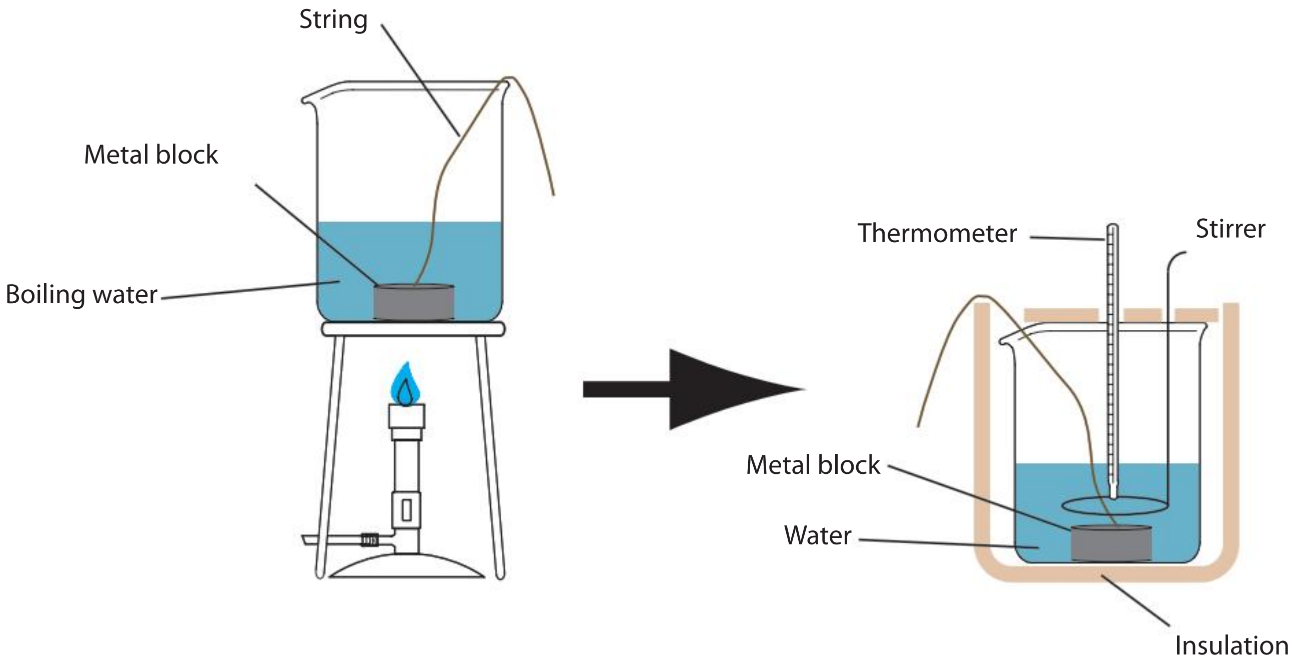


Figure 402 Measuring the specific heat capacity of a metal block

The metal of known mass is heated in boiling water for a long time. It is then transferred to a calorimeter with a known mass of water and initial temperature. The final equilibrium temperature is measured. The specific heat capacity *c* of the metal block is then calculated using the formula:

$$c = \frac{(m \times c \times \Delta T)_{water} + (m \times c\,\Delta T)_{calorimeter}}{m \times \Delta T_{block}}$$

The given formula is used under the following assumptions:

- The temperature of the metal block is uniform and when transferred, is 100 ^{0}C.
- There is no heat transferred into the surroundings during the experiment.

However, these assumptions are not true and by looking closely at them, it is easy to see that they can be sources of systematic errors.

For example, the temperature of the metal block is not uniform. The bottom part of the block, which is closer to the flame, is slightly hotter than the other parts. Furthermore, the metal block cooled down while being transferred to the calorimeter from the boiling water. Lastly, when the metal block is placed in the calorimeter, heat is transferred to the calorimeter, the thermometer and the stirrer.

The next step is to deduce how each systematic error would affect the result and whether it significantly affects the results.

4.2.4 Systematic errors – effect on the results and estimation

a) The block cools down when transferred to the cold water.

Effect on the calculated value of c.

When the block cools down before it is transferred into the calorimeter, the initial temperature is lower. Then ΔT_b is an overestimate, therefore, c_b is an underestimate.

Estimated amount of error

Since air is a poor conductor of heat, most of the heat lost by the hot metal block is due to convection, i.e. evaporation of water clinging on to it. It can be assumed that all the water evaporated from the ball during the transfer to the cold water. This is very little water and its mass is negligible. Since $Q = mL$, the amount of heat lost is therefore minor.

b) The thermometer and the stirrer absorb a significant amount of heat during the experiment.

Effect on the calculated value of c

If all heat from the hot block flowed to the water and calorimeter only, then the change in temperature $\boldsymbol{\Delta T}$ of water would have been higher than the actual measurement. Therefore $\boldsymbol{\Delta T}$ is an underestimate and **c** would also be an underestimate.

Estimated amount of error.

The glass thermometer and the stirrer would have experienced the same amount of ΔT as the water-calorimeter system. Therefore the amount of heat transferred to the thermometer and stirrer is $Q = mc\Delta T$ and would be significant.

c) Heat is transferred into the environment during the experiment.

Effect on the calculated value of c

If there was no heat lost to the surroundings, $\boldsymbol{\Delta T}$ would be higher. Therefore $\boldsymbol{\Delta T}$ of the water-calorimeter system is an underestimate and c would be an underestimate.

Estimated amount of error

The greater the temperature difference is between the surroundings and the metal-water system, the greater is the heat loss.

4.2.5 Suggested improvements

In many of the heat experiments, the main concern is how to reduce heat loss to the surroundings. This problem must be addressed and in many cases, should go beyond suggesting the use of a heat insulator. Outlined below are some suggested improvements and their effects on the final result.

a) Lower the temperature of the water-calorimeter system before transferring the hot metal block. This can be done by melting some ice in it. If possible, estimate the mass of ice so that the temperature is lowered from the room temperature by the same amount that it will be increased from room temperature. This is done so that the amount of heat it absorbs from the surroundings when it is below room temperature is approximately equal to the amount of heat it loses to the surroundings when it is above room temperature. Another reason is that with a larger temperature difference between the metal block and the water-calorimeter system, the equilibrium temperature is reached faster. This reduces the amount of heat lost to the surroundings and increases the accuracy of the result.

b) Place more water into the calorimeter. By doing this, the fraction of heat absorbed by the water and calorimeter increases and that of the thermometer and stirrer decreases. This makes the calculation of c more accurate. This also makes ΔT smaller. With a lower temperature difference between the water-calorimeter system and the surroundings, less heat is lost. This increases the accuracy of the result.

c) Finally, the use of a digital thermometer will reduce the uncertainty in the temperature measurement. Digital thermometers have a precision of ± 0.01 ^{0}C. This increases the precision of the calculated value of the specific heat capacity *c*. Furthermore, being made of a thin metallic rod, less heat will be transferred to the digital thermometer than would be transferred to the glass thermometer. Thus the use of a digital thermometer increases both the accuracy and precision of the result.

Example 4 Measurement of resistivity

In determining the resistivity of a copper wire, the following measurements were made.

Instrument used	Quantity measured	Value	Percentage uncertainty
Digital multi- meter	Resistance (**R**)	5.1± 0.1 Ω	2 %
Micrometer screw gauge	Diameter of the wire (**d**)	0.13 ± 0.01 mm	8 %
Metre rule	Length of the wire (**L**)	1.00 ± 0.01 m	1%

Figure 403 Sample resistivity measurements of a copper wire

$$\rho=\frac{\text{Area}\times\text{Resistance}}{\text{length}}=\frac{\pi\times\frac{d^2}{4}\times R}{L}=\frac{\pi\times\frac{(0.13\times10^{-3})^2}{4}\times1.23}{1}=1.63\times10^{-8}\ \Omega\ \text{m}$$

% error in ρ = (% error in R) + 2 × (% error in d) + (% error in L)

= 2% + 2 × 8% + 1%

= 19%

Therefore, the calculated resistivity ρ = (1.6 ± 0.3) × 10^{-8} Ω m. The correct value of 1.7 × 10^{-8} Ω m is within the range of the calculated value. The result is therefore accurate but is not very precise. Therefore the suggested improvement must focus on increasing the precision of the result.

Weakness: Large uncertainty in the measurement of the diameter

In the above measurements, the diameter has the largest percentage uncertainty. Not only is this large but is also doubled when calculating the total error in the resistivity ρ. Therefore, reducing the uncertainty in the measurement of the diameter is crucial in improving the precision of the result.

Is there a more precise instrument? The instrument used to measure *d* already has a precision of 0.01 mm. Besides in a typical high school laboratory, it is not easy to find an instrument more precise than the micrometer screw gauge. Therefore, using a more precise instrument is not possible.

Improvement: Increase the diameter

Instead, if one uses a thicker wire, the percentage uncertainty in *d* is reduced. In theory, a thicker wire will result in a smaller resistance *R* and thus, a higher percentage uncertainty in *R*. The total uncertainty will still be reduced because a smaller uncertainty in *d* is instead doubled.

To improve the result further, one can use a longer wire. A longer wire will increase the resistance value *R* and this reduces the percentage uncertainty in *R*. A longer wire also reduces the current through it and thus helps keep its temperature constant. This results in a higher accuracy in the result.

The 'Conclusions and Evaluation' section of your report may include:

- giving your report closure
- a summary of major results
- prospects for future extensions
- possible applications, relevance to other work

Listed in Figure 404 is a summary of what you need to do to score well in the Analysis criterion.

Assessment criteria	Evidence required	What you must do
Concluding	States a conclusion, that is described, justified and supported by the data.	Analyse and explain the data from the experiment and draws a valid conclusion which is relevant to the research question and its scientific context (background information that may include a hypothesis, competing hypotheses and a scientific model). The conclusion must be supported by the raw and processed data, (though it may be tentative and subject to some statistical uncertainty). If a graph is present, the correct graphical relationship is stated and numbers quoted to support the relationship. The graph may be used to obtain a gradient or intercept or be used for extrapolation or interpolation. If appropriate, uses the graph to identify any anomalous data points. Where appropriate, compares the experimental result with the accepted result: calculates absolute and percentage errors from the expected or literature value. Compares results obtained by repetition, or against the literature, and comments on the reliability of the values obtained. Some simple statistics may be included if large numbers of repeated random measurements are recorded.
Evaluating methodology and data	Evaluates strengths and weaknesses, such as limitations of data and sources of error	Outline any limitations to the accuracy/reliability/amount/range of data that you have obtained. States simplifying assumptions that were made which may affect the accuracy of the results. Discusses any limitations of the methodology used. Identifies and quantifies limitations due to the precision and accuracy of the equipment. Performs error propagation with random errors. Identifies possible systematic errors or other unanticipated factors. Strengths may involve control of variables, reduction of random errors and identification of systematic errors. Weaknesses may involve inability to control or monitor important controlled variables, natural variation, large random errors or large percentage errors in small measurements.
Improving and extending the investigation	Suggests realistic improvements in respect of identified weaknesses and limitations.	Suggests modifications to improve the existing investigation to reduce random errors and to identify possible sources of systematic error. Suggests alternative methodology to improve the investigation, perhaps by better control of controlled variables and more precise measurements of the dependent variable. Suggests alternative equipment or apparatus (with higher sensitivity) if applicable. Suggests how to extend the experiment, for example, collecting additional and more precise data outside the current data range

Figure 404 Summary of the Evaluation criterion

This criterion assesses the extent to which the student's report provides evidence that the student has selected, recorded, processed and **interpreted** the data in ways that are relevant to the research question and can support a conclusion.

This criterion assesses whether the investigation is presented and reported in a way that supports effective communication of the focus, process and outcomes.

The descriptors in the following table may be used by your teacher to allocate a mark for your performance in this criterion:

MARK	DESCRIPTOR
0	The student's report does not reach a standard described by the descriptors below.
1–2	The presentation of the investigation is unclear, making it difficult to understand the focus, process and outcomes. The report is not well structured and is unclear: the necessary information on focus, process and outcomes is missing or is presented in an incoherent or disorganized way. The understanding of the focus, process and outcomes of the investigation is obscured by the presence of inappropriate or irrelevant information. There are many errors in the use of subject-specific terminology and conventions*.
3–4	The presentation of the investigation is clear. Any errors do not hamper understanding of the focus, process and outcomes. The report is well structured and clear: the necessary information on focus, process and outcomes is present and presented in a coherent way. The report is relevant and concise thereby facilitating a ready understanding of the focus, process and outcomes of the investigation. The use of subject-specific terminology and conventions is appropriate and correct. Any errors do not hamper understanding.

* e.g. incorrect/missing labelling of graphs, tables, images; use of units, decimal places. For issues of referencing and citations refer to the academic honesty section.

Guiding Questions

- ***To what extent is the student work concise, clear, and structured in a logical sequence?***
- ***How well does the reporting of the methodology allow the investigation to be successfully repeated by others?***
- ***How well does the report allow the process of data analysis to be followed?***
- ***To what extent are graphs, tables, and images presented unambiguously?***
- ***To what extent is appropriate subject-specific terminology used throughout the investigation?***
- ***To what extent is appropriate subject-specific notation used throughout the investigation?***
- ***To what extent has the student used correct conventions for presentation of quantitative data, including appreciation of decimal places, significant figures, and uncertainties where appropriate?***
- ***how well does it reflect the overall use of terminology, scientific conventions, the overall structure and focus of the report, and that it is written in a concise way.***

The report should be clearly written and logically presented. The explanations should be focussed on the research question rather than general information about the topic.

There is no prescribed format for a student's exploration report.

The new IA should model a scientific journal article. Students should be familiar with a number of high-school level Physics journal articles.

Journals like the British "Physics Education" (see *<http://iopscience.iop.org>*) publication or the American "The Physics Teacher" publication (see *<http://tpt.aapt.org>*) often have articles that are appropriate for high school students.

Many of these articles can provide good ideas for a project/investigation.

See the document "Introduction to Journal-Style Scientific Writing" which is published free and available online from Bates College.

<http://abacus.bates.edu/~ganderso/biology/resources/writing/HTWgeneral.html>

Sources include textbooks, the library, and of course the Internet.

Communications assessment reflects the overall use of terminology, scientific conventions, the overall structure and focus of the report, and that it is written in a concise way.

When writing your Conclusion

You want to use your closing words to convey the main point of your report. The conclusion has to be strong and leave the reader with a solid understanding of your work. A good way to start is by summarizing your results. Make sure not to introduce anything that wasn't already mentioned in the previous parts of your report. You should state very briefly the essential conclusion or conclusions you have drawn from the experiment. It should satisfy the statement set out in the research question. Be sure to include any conditions that apply to your result (eg 'at constant temperature'). It is important not to overstate what you can rightly claim as a result of the experiment. Statements like 'the results supported…' are more justifiable than 'the results proved…'

N.B. Reports exceeding the maximum page length may be penalized.

5.1 Organization of the written report

The following is a suggested layout for the written report for the Individual Investigation. It is not mandated by the IBO and other presentations may also be acceptable.

5.1.1 Formatting a Report

Title

List the title of the experiment or meaningful name for your research report, for example:

To investigate how temperature affects the vibration of a tuning fork.

This could be in the form of a cover page that also includes your full name (as registered with the IBO), your school's name and your IB candidate number.

Contents page

The contents page will list the contents and page numbers for ease of cross-referencing. All pages must be numbered throughout the report. Hotlinks to the pages may also be useful.

Abstract

The best way to learn how to write a good abstract is to read published abstracts from Scientific journals, for example, the *'Physics Education' or do an Internet search for other titles.*

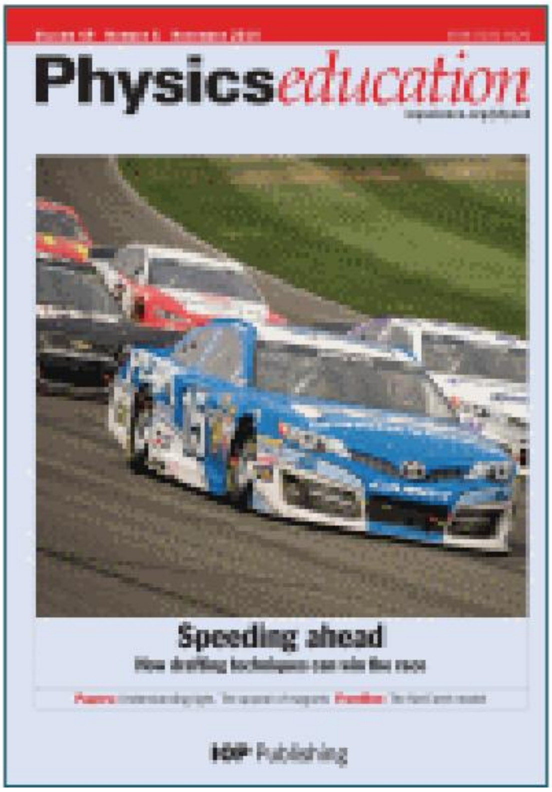


Figure 501 Example of a Physics Journal

The abstract should 'stand alone' which means that one of your peers should be able to read only your abstract and understand the basic nature of the report for your Individual Investigation. For this reason, a good abstract clearly identifies the purpose of the investigation and the important results.

Avoid comments such as, '*this experiment helped me learn about the nature of radioactive decay*' or '*the goal of this experiment was to learn about the relationship between temperature and frequency of a tuning fork.*' Although those are important aspects and goals of the lab experience, the research report should focus only on the data and results. Avoid starting your abstract with, 'The purpose of this investigation was.....'

Background information on the scientific theory or applications of your investigation belongs in the Introduction section. Avoid referencing any other sources or parts of the report, because the abstract should 'stand alone.'

Be specific about what was done: name the materials and instruments that were used, the results of the investigation, numerical values that were measured or calculated, etc. but do not be too detailed.

Introduction

The introduction section explains what focused research question is being addressed. It includes general background material and a brief historical perspective on the topic being investigated. It presents brief summaries, with references, of previous work. Any relevant laws, theories, models and hypotheses must also be included. An effective introduction directs the person reading from a larger area of research, through examples of progress in that field to a clear statement of the research question and approach being addressed in the Individual Investigation Report. Diagrams, formulae and calculations, etc. must be included as appropriate.

Downloading directly from the Internet or copying directly from books may suggest to your Teacher and the IB moderator that you have not understood the physics involved and may be considered as plagiarism. It is always best to put everything into your own words.

Method

The experimental section should provide all the necessary detail for someone to be able to reproduce your work and obtain the same results (within experimental error). There should also be a 'Planning' section you explain what various options were open and why one technique was chosen rather than an alternative.

This approach may or not be appropriate for your Individual Investigation report, but the guiding principle here is reproducibility.

Results (Data)

This section should include a summary of your raw data (preferably in tabular form) and important observations (qualitative data). Major calculations may be included in this section, or in as a separate Interpretation section or in an Appendix. A description of the mathematical equations used in your calculations must be presented.

All quantities should have units and be expressed using the correct number of significant figures and decimal places and random uncertainty. Scientific notation should be used when appropriate. For values less than unity, use a leading zero. Avoid writing values having too many zero; use scientific notation. Error propagation must be performed.

Examples:

'2.5×10^{-5} T' not '0.000025 T'

Important experimental conditions should be listed as footnotes, especially when the table includes data obtained under different experimental conditions. All tables, figures and graphs should be numbered sequentially and must be mentioned in the text.

Discussion (Analysis)

A discussion section should take the form of an analysis of your results and whether you have answered your research question.

Comment on the purpose of the experiment. What do the results indicate? What are sources of random and systematic error (experimental uncertainty/precision)? What additional experiments could help address any unresolved issues? Do the results agree with what other researchers have found? Do the results support a chemical model or hypothesis?

Conclusion and Evaluation

Summarise your results and discussion with a short conclusion that is more than simply a repetition of your results. Phrase it in terms of the research question addressed in the Introduction.

References

Citations of the literature used in the previous sections.

Appendices

Photographs of the apparatus and results may appear here, along with lengthy mathematic or statistical calculations or additional material not needed when reading through the report, e.g. preparation of solutions or buffers. The risk assessment and safety information, e.g., CLEAPSS hazcards or MSDS data sheets may also appear in the Appendix.

5.1.3 A Sample Report

Introduction

The following write-up of an investigation involving a spring is a suggested layout for the written report for the Individual Investigation. Relevant critical comments have been inserted after each section. This approach is *not* mandated by the IBO and other presentations may also be acceptable.

Title/Aim and Research Question

List the title or aim of the experiment or meaningful name for your research report followed by your research question, for example,

An investigation into the mechanical properties of a spring.

To investigate the relationship between force and extension of a screen-door steel spring and to determine its spring constant.

This could be in the form of a cover page that also includes your full name (as registered with the IBO), your school's name and your IB candidate number.

Contents page

The contents page will list the contents and page numbers for ease of location or cross-referencing. All pages must be numbered throughout the report. Hotlinks to the pages may also be useful.

Abstract

The abstract is a brief summary or description of the investigation and should 'stand alone' which means that one of your fellow physics students should be able to read only your abstract and understand the basic nature of your Individual Investigation. For this reason, a good abstract clearly identifies the purpose of the investigation and the important results.

Avoid comments such as, '*this experiment helped me learn about Hooke's law*' or '*the goal of this experiment was to learn about the mechanical properties of steel.*' Although those are important aspects and goals of the laboratory experience, the abstract of the research report should focus only on the data and results.

Background information on the relevant physics theory or applications of your investigation belongs in the Introduction section. Avoid referencing any other sources or parts of the report, because the abstract should 'stand alone.'

The abstract must be able to stand by itself, it must be brief, and it must include the significant numerical results. Generally its structure consists of three parts: what did you do; what were your results; what the results indicate and how they relate to the Research Question. One approach to learn how to write a good abstract is to read published abstracts from physics or educational journals. Here is an abstract for a very simple investigation.

The spring constant of a screen-door steel spring was determined both statically, by measuring its extension when subjected to loading, and dynamically, by measuring the period of a mass hung from one fixed end and set into vertical oscillation. The resulting values of 219.6 ±0.4 N m^{-1} and 218.8 ±1.0 N m^{-1}, respectively, represent the fact that the spring's behaviour follows Hooke's law (force is directly proportional to extension) to within the limits of experimental accuracy of the experiment.

Introduction

The introduction section explains what focused physics-based research question is being addressed. It includes general background material and a brief historical perspective on the topic being investigated. It presents brief summaries, with references, of previous work. Any relevant scientific laws, theories, models and hypotheses must also be included.

An effective introduction directs the person reading from a larger area of physics research, through examples of progress in that field to a clear statement of the Research Question and approach being addressed in the Individual Investigation Report. Annotated diagrams must be included as appropriate.

Downloading directly from the Internet or copying directly from books may suggest to your IB physics Teacher and the IB moderator that you have not understood the physics involved and may be considered as plagiarism. It is always best to put everything into your own words.

Here is a part of a sample introduction for a simple investigation involving a steel spring.

If it is not stretched to the point where it becomes permanently deformed (that is, beyond the elastic limit), the behaviour of a wound coiled steel spring, when subjected to a stretching force, can be expected to obey Hooke's Law. [Kerr, page 110] (Note that Hooke's Law applies more generally to many more systems than springs, for example, filling a party ballon but not elastic bands.) To establish whether an ordinary screen door steel spring behaves similarly, one such spring was suspended by one end from a horizontal support and masses were hung from its other end to stretch it as shown in Figure 1. The resulting data were used to construct a graph of extension as a function of load, from which it was possible to obtain the spring constant of the spring from the gradient of the graph. In addition, for one value of load the spring was given a small additional stretch and released, thereby setting the system into vertical oscillation. Assuming this motion to be simple harmonic, its period also yields a force (spring) constant, thereby providing additional supporting data.

Note the difference between the Abstract and the Introduction. The Introduction indicates the focus of the experiment or investigation but does not indicate results. It does not have to stand by itself and can refer to later parts of the Investigation report such as a diagram or a graph. Such reference should be to a numbered figure or graph. (*Figure 1* in this example).

Theory

If a weight, $W = mg$, is hung from one end of a metal spring, causing it to stretch a distance x, then an equal and opposite force, F, is created in the spring which acts to oppose the pull of the weight. If the weight is not so large as to permanently distort the spring, then this force, F, will restore the spring to its original length after the load is removed. F is thus called a restoring (elastic) force and it known that the magnitude of a restoring (elastic) force is directly proportional to the stretch,

$F = kx.$

This relationship is Hooke's Law named after the 17th century English scientist Robert Hooke who studied it. The constant k is called the force constant (spring constant) and is a measure of stiffness. To emphasize that x refers to the change in length (L) of the spring:

$F = mg = k\Delta L$

A plot of F as a function of Δl has a linear portion, this provides confirmation that the spring follows Hooke's Law [*Kerr*, p. 229] and enables the determination of the force (spring) constant, k.

An additional approach is possible. Simple harmonic motion commonly occurs under the action of a restoring force described by Hooke's law. From Newton's second law of motion:

$F = -kx = ma$

The negative sign is included since the acceleration of the object in simple harmonic motion is in the direction opposite to the force causing it. From this definition:

$a = d^2x/dt^2 = -k/mx$

The solution to this differential equation and the resulting expression for the period, T, of the simple harmonic motion is given by the following expression:

$T = 2\pi\sqrt{m/k}$

where k is the spring constant and m is the mass under motion. This provides an additional approach for establishing whether the steel spring obeys Hooke's law.

The theory should be relevant and comprehensive. Italics should be used for all letters in mathematical equations. The equation editor in Microsoft Word can be used to generate equations. The last expression in this theory section should be derived and justified.

Method

The experimental section should provide all the necessary detail for someone to be able to reproduce your work and obtain the same results (within experimental error). There should also be a 'Planning' section in which you explain what various options were open and why one technique was chosen rather than an alternative. The method should not simply be a recipe-like list of detailed instructions. It should highlight any unusual procedures and justify and explain the approach.

Here is a sample method for a simple spring investigation:

I hung a common screen door steel spring directly from a horizontal metal rod secured to the laboratory bench by a C-clamp, another pole and a right-angle clamp. I attached a mass hanger directly to the bottom of the hanging spring to allow varying the load hanging from the spring. Vernier calipers (±0.1 mm) were used to measure the vertical distances, l_0 *and* l_1*, (see* Figure 1*) from the horizontal support rod to the top coil and the bottom coil, respectively, of the hanging spring, for a variety of load masses ranging up to 9.00 kg. (See Table 1).*

For ease in reading, the data are reproduced in Table 1 in order of increasing load. Mass, in kg, is plotted against extension, in cm, in the graph in Figure 2*. For the simple harmonic motion part of the experiment, a single mass of 4.000 kg was hung from the spring and the time required for the system of mass plus spring to perform an integer N number of oscillations was measured with a digital stopwatch. This was repeated for three values of N, and the data appear in Table 2.*

Results

This section should include a summary of your raw and processed data (preferably in tabular form) and displayed data (graphs). Major calculations may be included in this section, or in as separate Interpretation section or in an Appendix. A description of the mathematical equations used in your calculations must be presented.

All quantities should have units and be expressed using the correct number of significant figures and decimal places and random uncertainty. Scientific notation should be used when appropriate. For values less than unity, use a leading zero. Avoid writing values having too many zero; use scientific notation. Error propagation must be performed.

Examples:

'0.15 cm^3' not '.15 cm^3' and '2.5×10^{-5} N' not '0.000025 N'

Important experimental conditions should be listed as footnotes, especially when the table includes data obtained under different experimental conditions. All tables, figures and graphs should be numbered sequentially and must be mentioned in the text.

Here are some sample results for a simple spring investigation.

The measured positions of the top (l_0) and the bottom (l_1) coils of the steel spring are given below in Table 1. From these distances I calculated the length of the spring ($L= l_1-l_0$), and the extension, ΔL, which is the difference between this extension, ΔL, and the unloaded extension of 38.8 cm ±0.01 cm.

In Figure 2 I calculated the spring constant from measuring 25 to 50 continuous oscillations and calculating the period of oscillation, T. From the average value of the period, I calculated the spring constant, k.

The mass used in calculating k was not just the load attached to the bottom of the spring. The reason for this is that the system that is vibrating includes the spring itself. However, the entire spring does not vibrate with the same amplitude as the load and therefore it is reasonable to assume that the effective load is the mass hung from the end of the spring plus some fraction of the mass of the spring. The fraction used was 1/3 since similar experiments with other types of springs have led to this empirical result. [Kerr, page 45] It was assumed that a third of the mass was a reasonable approximation to the correct value for this particular spring.

Load/kg ±0.003 kg	L_0/cm ±0.05 cm	l_1/cm ±0.05 cm	$L=(l_1-l_0)$/cm ±0.10 cm	<L> /cm	ΔL /m
0.000	31.90	70.70	38.80	-	
0.000	32.10	70.90	38.80	38.80	0.000
1.000	32.00	71.10	39.10	39.10	0.003
2.000	32.10	74.30	42.20	-	
2.000	32.30	74.60	42.30	42.25	0.034
3.000	32.10	79.10	47.00	47.00	0.082
4.000	32.30	83.60	51.30	51.30	0.125
5.000	32.30	88.10	55.80	-	
5.000	34.40	88.30	55.90	55.85	0.171
6.000	32.40	92.60	60.20	-	
6.000	32.60	92.80	60.20	60.20	0.214
7.000	32.50	97.20	64.70	64.70	0.259
8.000	32.40	101.90	69.50	69.50	0.307
9.000	32.50	106.50	74.00	-	
9.000	32.60	106.50	73.90	73.95	0.351

Figure 501 Calculation of the spring constant from the loaded extension of a steel spring (mass 70 grams)

It is preferable to include a written description for every physical quantity in a table. It is strange that no results in the first two columns are recorded as xx.05 cm.

Oscillations	Time /s	T /s
50	42.80	0.856
25	21.34	0.854
40	34.11	0.853

Figure 502 Calculation of the spring constant of a steel spring from its oscillations (timing oscillator – load – 4.000 kg)

Only three results are recorded and not repeated. This is a significant deficiency in the investigation.

<T> = 0.854 s ± 0.002 s

This is very accurate and cannot be justified for hand timing (manually operated) electronic stopwatch.

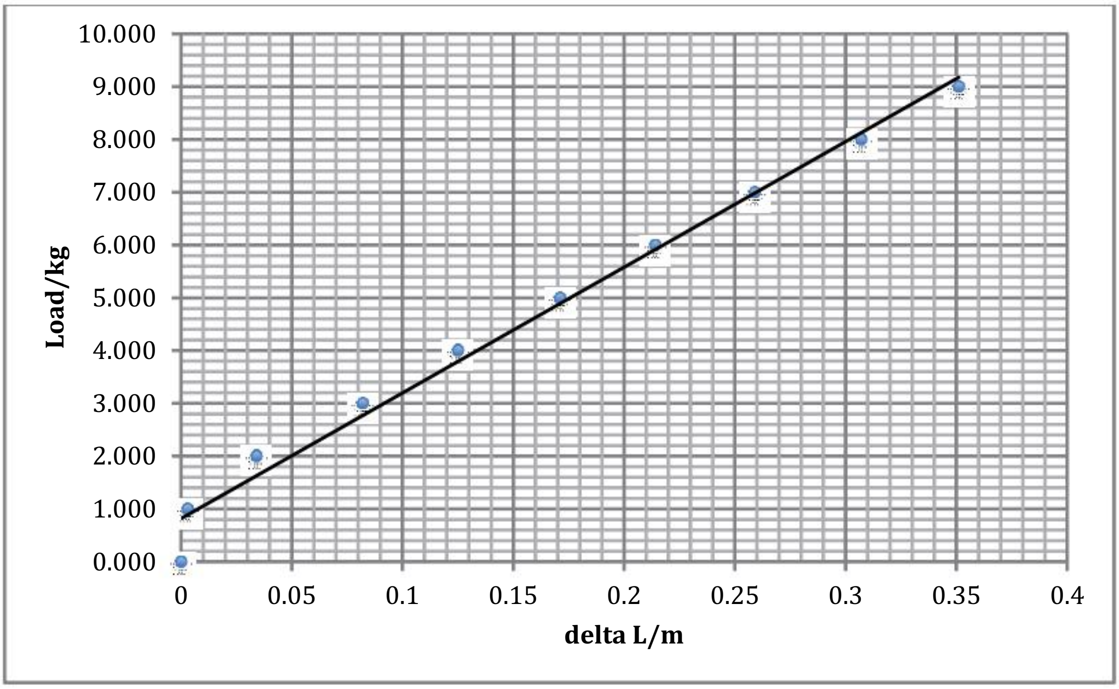


Figure 503 A graph of the data

(Unfortunately this graph is lacking error bars. They should be included to show the random uncertainties.)

Conclusion

A discussion section should take the form of an analysis of your results and whether you have answered your research question.

Comment on the purpose of the experiment. What do the results indicate? What are sources of random and systematic error (experimental uncertainty/precision)? What additional experiments could help address any unresolved issues? Do the results agree with what other researchers have found? Do the results support a physical model or hypothesis?

Here is a sample discussion for a simple spring investigation.

Figure 2 indicates that for loads greater than about 1.10 kg there is a linear relation between load and extension but that for small loads such a relationship fails, since the line of best fit does not intercept the y axis at zero. It is assumed that this is caused by an initial 'set' in the spring which requires some initial load to overcome. This is observed if one stretches the spring manually and then releases it. It seems to snap shut at the last moment.

For this reason, 0.000 and 1.000 kg were ignored and the rest of the data were treated by a least squares analysis to determine the coefficients of first degree polynomial best fit. These were used to plot the line on the graph. The slope of the line, ignoring loads of less than 2.000 kg, was found to be 22.2 ± 0.2 kg m^{-1}. From Equation 1, we see that we need to multiply this quantity by g to calculate a value for the spring constant, k = 217.4 ± 1.8 N m^{-1}.

In determining k dynamically, only one value of load (4.000 kg) was used. Since the mass of the spring was 7.0 g the value of m used to determine was 4.023 kg. This together with <T> = 0.854 ± 0.002 s gives:

$k = 4\pi^2 m/T^2 = 217.7 \pm 1.0\ N\ m^{-1}$

These two values of k show agreement within the limits of accuracy of the experiment and as such are evidence that the spring used, at least over a range of loads from 2.000 to 9.000 kg, obeys Hooke's Law.

If the dynamic experiment were extended by using a range of masses and a graph of T^2 *as a function of m were constructed, a linear plot should result. For this graph:*

$T^2 = (2\pi^2)/k\ (m + m_0)$

where m_0 *would be the effective mass of the spring. This would give a more reliable result than the estimate of 1/3 of the spring mass used here.*

References

Citations of the literature used in the previous sections.

Appendices

Photographs of the apparatus and results may appear here, along with lengthy mathematic or statistical calculations or additional material not needed when reading through the report. The risk assessment and safety information, e.g., CLEAPSS hazcards or MSDS data sheets may also appear in the Appendix.

5.1.4 Sentence style and writing style

The following guidelines are designed to improve the quality of your reports for experimental work and bring it close to the standard of a published chemical paper. The key guiding principle is clear communication. You will *not* lose any marks for poor English phrasing unless the meaning is unclear or incorrect. The IBO is aware that many IB Diploma students have English as a Second Language (ESL).

Beginning a sentence

Avoid beginning a sentence with a symbol, numeric value or equation.

Incorrect:

0.2 kg masses were added to the spring and the length measured.

Correct:

The length of the spring was measured after the addition of each 0.2 kg mass.

'Dangling modifiers' and illogical construction

Check that a modifier phrase or the pronoun 'it' actually refers to the intended subject.

Incorrect:

After transferring to a larger container, the masses were carefully weighed.

Correct:

The masses were placed in a larger container and weighed.

Equations

Mathematical equations typically appear in italics as a separate line from the text and are numbered sequentially throughout the manuscript. Equations can then be referred to by number as shown below.

e.g. $\frac{Q}{zF} = n$ .... *Equation 1*

(where F is the Faraday constant, z is the ion charge, Q is the electric charge (C) and n is the amount (mol) of substance discharged.) (*Note: this equation not required in this course*)

Spaces

There should be one space between a quantity and its units and between a quantity or word and subsequent parenthetical phrase.

6.626 kJ

25.15 K = 298.15 °C

45 cm^3

456 nm

938 MeV c^{-2}

Personal pronouns

By tradition, scientists avoid using the personal pronouns 'I', 'we' and 'you' in most scientific communications. The use of third person instead of first person is preferred when reporting results.

First person: *"We adjusted the inclined plane to..."* or *"We took the data..."*

Third person: *"This inclined plane was adjusted to ..."* or *"The data was/were taken..."*

Subject-verb agreement

Based on whether the subject is singular or plural, use the correct verb tense. A quantity used is a singular subject, even when that quantity is in a plural form of units.

Ensure you are not stating that an inanimate object is drawing a conclusion, or suggesting a strange cause and effect.

Tested

A hypothesis can be 'tested' but for most laboratory work, the terms 'measured,' 'investigated,' 'determined,' 'calculated' or 'obtained' often work better.

Incorrect: *The peak wavelength of the hot object was tested using the spectrophotometer.*

Correct: *The peak wavelength of the hot object was measured using a spectrophotometer.*

Abbreviations, Formulas and Numerals

Use standard abbreviations, for example, h = hour, min = minute, s = second and °C = degrees Celsius.

Defining abbreviations

Abbreviations for materials or methods should be defined in the text before using throughout the report for your Individual Investigation. However, this is a minor issue and is the practice of published scientific papers.

5.2 Referencing

Referencing is a standardised method of acknowledging the sources of information you have consulted for writing your Individual Investigation report. Words, paragraphs, quotes, figures, tables, theories, ideas, facts–originating from another source and used in your Individual Investigation report must be referenced (i.e. acknowledged).

Referencing is done for the following reasons:

- to avoid plagiarism.
- so that your Assessor can verify quotations.
- so that your Assessor can follow up on the original author's thinking by consulting the source you used.

There are many ways to acknowledge sources of information, for example, MLA (Modern Language Association), and none is mandated by the IBO. This publication recommends a Bibliography at the end of the Individual Report, together with in-text referencing. The style adopted is the MLA (Modern Language Association) format. However, what is important is that the method used is consistent. Do not switch from one method to another. Familiarise yourself with the format and terms (*Figure 502*) that your school or IB Physics teacher expects you to use.

Paraphrasing	This is explaining in your own words what the original source wrote.
Quoting	"To repeat (words) exactly from (an earlier work, speech or conversation), usually with an acknowledgement from the source" (Collins Paperback English Dictionary, 1998, p. 665) Put in quotations everything that comes directly from the text especially when taking notes. (Collins Paperback English Dictionary, 1998, p. 136).
Citing or In-Text Referencing	"1. To quote or refer (a passage, book or author). 2. To bring forward as evidence" When citing your sources, you are telling your IB Teacher who/what the original source. You are giving credit where credit is due.
Bibliography	This is a list of cited works.
Common Knowledge	These are facts that are located in several sources and probably known by many scientists.

Figure 502 Important referencing terms

Terms to know

In-text referencing

In-text referencing is when you provide information about the source in the text of your Individual Investigation report. The bibliography at the end of your report shows the reader which sources were researched but sometimes that is not enough. That is when you use in-text referencing **inside** your essay. Usually the author's last name and a page reference are enough to identify the source. With this information, the reader can find the complete publication information in your citation list at the end of your Individual Investigation Report.

Tips for in-text referencing

When you find a useful resource for your Individual Investigation Report, note down all the details required in your bibliography (e.g. author, title, publication details, date of access, URL etc) before you start taking notes.

When reading a resource, highlight key words, main ideas or make bullet point notes that you might want to include in your report.

If you use the exact words from the writer put them inside quotation marks so you do not accidentally plagiarise, and if possible note down the page number.

Examples of in-text referencing

Signal Phrase: introduces where the idea or quote comes from and usually has the author's name in the text.

According to Anthony *Methylacidiphilum fumariolicum* SolV bacterium, a methanotroph (methane consumer) found in Italian volcanic mudpots, relies on lanthanides to survive (Anthony 68-69).

Signal phrase = According to Anthony

Paraphrase or Summary: the idea in your own words or the main ideas only.

Current research has shown that certain species of bacteria that metabolise methane found in Italian volcanic mud need rare earth metals (lanthanides) to survive.

Direct Quote: show these are the exact same words used by the author in the source with quotation marks.

'This fascinating work has important implications for studies of most other methanotrophs growing on methane or methanol' (Anthony 47).

Citation in Bibliography: this is the source with the full publications details.

Homewood, Jon "The effect of global warming on amphibians". New Scientist. 1 October 2009: 38-41.

Because Internet sources typically have no page or paragraph numbers, and Web sites often list no author, students are often confused about how to refer to these sources within their papers. The answer is to cite the author's name whenever possible, and use the source's title otherwise (or a shortened version of the title). If no page or paragraph number is provided, leave that portion of the citation blank. Keep in mind that the primary purpose of an in-text citation is simply to point readers to the correct entry on the "Works Cited" page. Also, as web sites change, give the date it was referenced so, if necessary, cached versions may be retrieved.

Bibliography

How to cite sources

Books

Author's name (put family name first). Title. Place of publication: Publisher, Year of Publication.

Note: titles can be underlined or put into italics

e.g.: Andrew, John. Chemistry in Focus. United Kingdom: Hodder and Stoughton, 1999.

Two authors (note the order of names for the second author)

McKissack, Patricia, and Frederick McKissack. Modern Biology. United Kingdom: Oxford University Press, 1995.

Three or more authors

Adams, Roger *et al.* Encyclopedia of Science. New York: Consolidated Press, 1994.

Encyclopedia article

Article title". Title of Encyclopedia. Year of Publication.

Note: put title of article in speech marks.

e.g.: "Ozone layer". World Book Encyclopedia. 2009.

Interview

Name of the person interviewed. The kind of interview (personal, telephone, email). Date or dates of interview.

e.g.: Martin, J. K. Email interview. 8-12 May 2008.

Magazine article

Author. "Article title". Magazine title. Date of Magazine: Pages.

Note: the use of speech marks and underlining

e.g.: Churchman, Deborah. "Global warming: the sceptic's view". New Scientist.March1999: 28-31.

Remember also that:

- citations should not be numbered.
- citations should not be separated into different formats (e.g. books, websites, interviews, etc.).
- citations should be in alphabetical order by the main entry (e.g. author's surname, title, article title, etc.). Ignore a, an, the.

Website

Author (if available). "Title of the article." (in speech marks) Title of whole site. Date of visit to site. *<URL of Page>*.

e.g.: "Using MLA Format." Purdue University Online Writing Lab. January 23, 2006. *<http://owl.english.purdue.edu/handouts/research/r_mla.html>*

Online Encyclopedia Article

Author. (family name first) "Title of article". Magazine title . Date of Magazine: Page numbers. Product Name. Date researcher visited site. *<Electronic Address, or URL, of the source>*.

e.g.: Churchman, Deborah. *"Be a Nature Detective"*. Ranger Rick March 1999: 28-31. MasterFILE Premier on-line. EBSCO Publishing. 30 Feb. 2004.

<http://www/epnet.com/ehost/login.html>.

There are several on-line bibliography makers. Try them out but you are advised to use the MLA version and take care with the data you enter otherwise you will get a bad outcome. Try Landmarks Citation Machine and Bibme.org for example:

<http://citationmachine.net/>

<http://www.killerstartups.com/Web20/bibme-org-the-quickest-way-to-build-a-bibliography>

Additional materials for writing lab/research reports

Davis, Martha *Scientific papers and presentations* San Diego: Academic Press, **1997**

Dodd, Janet S. (ed.) *The ACS style guide: a manual for authors and editors* ACS, **1997**.

Eisenberg, Anne "Strategies five productive chemists use to handle the writing process." *J. Chem. Educ.* **1982,** *59,* 566.

Potera, Carol "The Basic Elements of Writing a Scientific Paper: The Art of Scientific Style" *J. Chem. Educ.* **1984,** *61,* 247.

Spector, Thomas "Writing a Scientific Manuscript: Highlights for Success" *J. Chem. Educ.* **1994,** *71,* 47.

5.3 Use of units

SI base units

The six quantities or base units of the SI system commonly used in Physics are: the metre for measuring length, the kilogram for measuring mass, the second for measuring time, the kelvin for measuring temperature, the candela for measuring luminous intensity and the ampere for measuring electric current (*Figure 503*).

Dimension	Symbol	SI unit name and symbol
Length	L	metre, m
Mass	m	kilogram, kg
Time	t	second, s
Temperature	T	kelvin, K
Luminous intensity	l_v	Candela, cd
Electric current	I	ampere, A

Figure 503 Some commonly encountered physical quantities in Physics

Strictly speaking, measurements of length should be expressed in metres and masses should be expressed in kilograms. However, often such measurements are expressed in centimetres (cm) and grams (g), where 100 cm = 1 m and 1000 g = 1 kg.

The size of the units given above is not always the most suitable for certain measurements and decimal multiples and fractions are frequently used, as shown below. A set of common SI prefixes and associated symbols is given in *Figure 504*.

Fraction	Prefix	Symbol	Multiple	Prefix	Symbol
10^{-1}	deci	d	10^{3}	kilo	k
10^{-3}	milli	m	10^{6}	mega	M
10^{-6}	micro	μ	10^{9}	giga	G
10^{-9}	nano	n	10^{12}	tera	T

Figure 504 SI Factors

SI derived units

A large number of additional SI units exist and are widely used the IB Program, for example, the joule for energy. The joule and other so-called derived units can be expressed in terms of base units.

Commonly used SI derived units and their symbols for a number of physical quantities relevant to the IB Program are given in *Figure 505*, together with a 'useful' relationship between these and the definition in terms of SI base units. (The term specific in front of a physical quantity has the meaning 'per unit mass').

Quantity	Definition	Unit	Relationship to other quantities	Basic definition
Frequency	reciprocal second	Hz		s^{-1}
Wave number	reciprocal metre	m^{-1}		m^{-1}
Volume	metre cubed	m^3		m^3
Force	newton	N	J m^{-1}	kg m s^{-2}
Pressure	pascal	Pa	N m^{-2}, J m^{-3}	kg m^{-1} s^{-2}
Charge	coulomb	C		A s
Potential difference (voltage)	volt	V	J s^{-1} A^{-1}	kg m^2 s^{-3} A^{-1}
Density	kilogram per metre cubed	kg m^{-3}		kg m^{-3}
Heat capacity	joule per kelvin	J K^{-1}		kg m^2 s^{-2} K^{-1}
Specific heat capacity	joule per kilogram per kelvin	J kg^{-1} K^{-1}		kg m^2 s^{-2} kg^{-1} K^{-1}

Figure 505 SI derived units and their symbols

The base and derived SI units are a **coherent** system of units. This means that all the units for the derived physical quantities are obtained from the base units by multiplication or division, without the need for the introduction of numerical factors. This simplifies many calculations.

For example, if we consider the ideal gas equation, $PV = nRT$, we can rearrange it to make P the subject, namely,

$$P = \frac{nRT}{V}$$

We can then substitute numerical values for the volume of gas (V), the amount of gas (n), the molar gas constant (R) and the absolute temperature (T), in coherent SI units, namely; m^3, mol and J K^{-1} mol^{-1}, respectively and calculate the numerical value of P which will also be in coherent SI units, namely pascals.

Example

If $R = 8.31$ J K^{-1} mol^{-1}, $T = 300$ K, $V = 6.34 \times 10^{-3}$ m^3 and $n = 0.250$ mol.

Then,

$$P = \frac{nRT}{V} = \frac{0.250\ \text{mol} \times 8.31\ \text{J K}^{-1}\ \text{mol}^{-1} \times 300\ \text{K}}{6.34 \times 10^{-3}\ \text{m}^3} = 9.83 \times 10^4\ \text{Pa}$$

Note that the more familiar unit of volume, the decimetre cubed, is not a base or fundamental SI unit and would not yield a pressure in pascals.

Rules for the use of SI units

1. Units may be written out in full, e.g. 5 coulomb, or by using the agreed symbol, e.g., 5 C, and printed in upright Roman type.
2. A full stop is not written after symbols, except at the end of a sentence.
3. Values of quantities are expressed in SI units using Arabic numerals (i.e. 1, 2, 3,… etc) and the symbols for the units. e.g., m = 5.0 g but not m = five gram or m = five g
4. A space should be inserted between the numerical value and the unit's symbol. e.g., a 5.00 g copper cube but not a 5.00g copper cube.
5. The digits of numerical values having more than four digits on either side of the decimal marker can be separated into groups of three using a space. e.g., 15 739.012 53 is better than 15739.01253
6. Avoid abbreviations, such as 'sec' (for either s or second) or 'cc' (for either cm^3 or centimetre cubed).
7. Avoid mixing unit symbols and unit names, for example, kg/m^3 or, better still, $kg\ m^{-3}$ is acceptable, but not $kilogram/m^3$.
8. Those symbols named after a person have a capital for the first letter. When the name of the unit is written in full it has a small letter, even when commemorating a person, for example, pascal, symbol Pa.

Common mistakes with SI Units

- The rules listed previously may seem minor at best, and at worse pedantic, but it is good practice to follow them. Below are outlined some major and common mistakes frequently made by IB students.
- It is not acceptable to record measurements with a mixture of units, for example, 5 min 10 s and 1 kg 10 g. These should be expressed as 310 s and 1.01 kg, respectively.
- Another common mistake is to confuse weight and mass. When using a balance, masses should be recorded in kilograms (kg) or grams (g). Weight is a force (due to gravity) and should therefore be expressed in newtons (N). On Earth a l.0 kg mass has a weight of approximately 9.8 N. (Weight on Earth varies slightly according to latitude and height above sea level).
- In addition, no plurals, are added to SI names or units, for example: 5 gram **not** 5 grams. This is, in part, to avoid confusion with the symbol s for seconds, but units do not have a plural form. Strictly speaking, all temperatures should be expressed as thermodynamic temperatures in kelvin. (Often expressed in the common, but less correct, absolute temperatures).
- However, unless gas law calculations are being performed, then temperatures are often expressed in degrees Celsius.
- The numerical value of a Celsius temperature expressed in degrees Celsius is given by: $t/°C = T/K – 273.15$ where t is the numerical value of a Celsius temperature and T is the absolute or thermodynamic temperature in kelvin.
- It follows that the degree Celsius is equal in magnitude to the kelvin, thus, temperature differences or intervals may be expressed in either the degree Celsius or the kelvin using the same numerical value.
- The specific heat capacity of water is approximately $4.18\ J\ g^{-1}\ °C^{-1}$ or $4.18\ J\ g^{-1}\ K^{-1}$.
- Be careful not to use the word 'amount' in the everyday sense of the word where it is used in a much more wide ranging and 'loose' way and can refer to a number, a volume or even a weight. In the SI system the term 'amount' refers only to the mol.
- When labelling graphs or tables with SI units, then the symbol of the unit is followed by a solidus(/), for example, $V/\ dm^3$ and $T/$ K. This approach converts quantities to numbers by dividing the quantity by its unit.
- Note that the solidus notation is avoided within SI units, and scientific notation is preferred for example, $kgms^{-2}$ rather than kgm/s^2 or kgm/s/s.
- A double solidus is forbidden, for example, is a/b/c meant to be (a/b)/c or a/(b/c)?

For example, the units of specific heat capacity should be written as J kg^{-1} K^{-1}. The equivalent expression using the solidus notation is J/(kg K), but its use is not encouraged.

- Spaces, not commas, are used in numbers greater than 1000, for example, 101 325 Pa and not 101,325 Pa. In some countries a stop is used instead of a comma.
- All units in calculations should be expressed in SI base units (or units derived from them), for example, an energy calculation should give an initial answer in joules, which can then be expressed in kilo joules (kJ) (a multiple SI unit).

Always make sure that terms on either side of an equal sign are capable of being equal, for example, strictly speaking, you cannot write 100 °C = 373.15 K, just as 27 apples cannot equal 1.5 dollars. However, you may write 100 °C ≡ 373.13 K.

The correct approach to writing the above temperature conversion is: T/K = t/°C + 273.15. Therefore, T/K = 100 °C/°C + 273.15. Therefore, T = 373.15 K. However, many students (and IB teachers) ignore this pedantry and simply write 100.00 °C = 373.15 K.

Non-SI units

Several non-SI units may be encountered during your IB Physics programme. They may arise from the measuring device you are using or from data that you have obtained from the literature. Ideally any raw data expressed in non-SI units (see *Figure 506*) should be converted to SI units before data processing.

Many non-SI units are now defined exactly in terms of SI units; some can only be related to SI units via fundamental constants and the relationship is therefore restricted by the precision to which the constants are known. Exact values are printed in bold type.

Non-SI unit	Unit type	SI conversion	Notes
Angstrom (Å)	Length	1Å = 10^{-10} m	Typical radius of an atom
Atomic mass unit (u)			Approximately equal to the mass of a proton or neutron; also known as a Dalton or amu
Minute (min)	Time	1 min = 60 s	
Hour (h)	Time	1 = 60 min = 3600 s	
Electronvolt (eV)	Energy	1 eV = 1.602 × 10^{-19} J	
Millimetre of mercury (mmHg or Torr)	Pressure	1 mmHg ≈ 133.322 Pa	
Atmosphere (atm)	Pressure	1 atm = 101.325 kPa	
Calorie (Cal)	Heat energy	4.184 Cal = 1 J	
Degree Celsius (°C)	Temperature	1 °C = 1 K	
Debye (D)	Dipole moment	3.336 × 10^{-30} C m	
Degree Fahrenheit (°F)	Temperature	5/9 K	
Curie	Radioactivity	3.7 × 10^{10} s^{-1}	

Figure 506 Non-SI units

Listed in Figure 507 is a summary of what you need to do to score well in the Communication criterion.

Assessment criteria	Evidence required	What you must do
Writes a well structured and clear report (write-up)	Structured report	The report must be well structured into different clearly designated sections and the English must be clear, correct and accessible. It should resemble the form of a scientific paper but must present relevant information on focus (the Research Question and introduction), process (the methodology) and outcomes (results and evaluation) in a coherent manner.
	Relevant and concise report with correct conventions and referencing	The report must be relevant and concise (10 pages). It should not contain irrelevant or tangential issues (those not directly relevant to your Research Question). The data collected should be relevant to the Research Question and support a justified conclusion. Subject specific terminology, terms and conventions, for example, referencing and labelling of all data tables, graphs and digital images, or the use of the passive voice, should be appropriate and correct. Data should be processed and displayed with the correct type of graph. All literature consulted should be referenced and cited according to well known conventions. Any errors in the report should be minor and not hamper understanding of the investigation.
	Units and calculations	Calculations should be accompanied by appropriate units, usually SI. Calculations should be carried out according to the rules of significant figures and final values reported to the correct number of significant figures. Error propagation should be performed and the working shown in the report. It may also be appropriate to show how the final units of a calculation are derived. Some simple statistics may be relevant.

Figure 507 Summary of the Communication criterion

Note: Your teacher will read your entire report in order to get an idea of what the you did and how the report is structured. Your teacher will be looking for evidence and continuity of the evidence for each of the criteria indicators.

6.1 Following instructions

A school's practical scheme of work should allow students to experience the full breadth and depth of the course including the option. This practical scheme of work must also prepare students to undertake the independent investigation that is required for the internal assessment. The development of students' manipulative skills should involve them being able to follow instructions accurately and demonstrate the safe, competent and methodical use of a range of techniques and equipment.

© IBO 2014

6.1.1 Listening to verbal instructions effectively

When only verbal instructions are given by your IB Physics teacher, you must listen carefully to the instructions given.

- **Record**. Do not sit passively. Instead, use your laboratory notebook and write down the main instructions and the precautions given. Note any values you have to use.
- **Reduce**. Write to a minimum. Draw symbols and use key words to record the steps and the instruments to be used.
- **Revise**. After the verbal instructions are given, read your notes. Ensure that they make sense to you. If there is anything unclear to you, clarify it with your teacher.

6.1.2 Watching demonstrations efficiently

When introducing a new technique, your IB Physics teacher might demonstrate the method that you will be expected to repeat afterwards.

- Before your teacher starts with the demonstration, ensure that you have a good view of both your teacher and the equipment that will be used for the demonstration.
- While the demonstration is being carried out, record each stage of the procedure in your laboratory notebook. Also, take note of any precautions or safety issues.
- After the demonstration, read your notes and see whether they make sense to you. If there is anything unclear to you, clarify it with your teacher.

6.1.3 Exploiting instruction sheets

When you are given an instruction sheet to guide you through the investigation:

- **Read**. If an instruction sheet is provided, read it thoroughly. Read the entire procedure before starting with the investigation so you have a complete picture of the investigation.
- **Reason out**. Wherever possible, suggest reasons for some of the procedures or method involved. This will help you to understand the investigation better and may assist you with the evaluation later on.
- **Reconstruct**. Try to divide the set of instructions into parts, for example: setting-up part, measurement 1, measurement 2, verification part, and so on. This helps to achieve more effective management of time.
- **Reflect**. You should understand the objective of the investigation and how the procedure fulfills the objective. Further to this, obtain a better picture of the investigation by connecting the investigation to the concepts that you have learnt. This will help you to decide later on whether your results are accurate and reliable.

6.2 Assembling equipment

When doing an investigation, you will be expected to assemble equipment. In IB Physics investigations, you will assemble a wide variety of equipment and apparatus which includes weights, pulleys, sensors and electrical equipment.

An example of an investigation set-up that you might need to assemble is shown in *Figure 601*. This apparatus is used to investigate the momentum and kinetic energy of the colliding objects. This apparatus consists of mechanical equipment like the linear air track, the gliders and the retort stands to hold the light gates, and of special electronic devices like the light gates and the motion reader. It is expected that you will be able to assemble many of the equipment and apparatus without assistance or with minimum assistance.

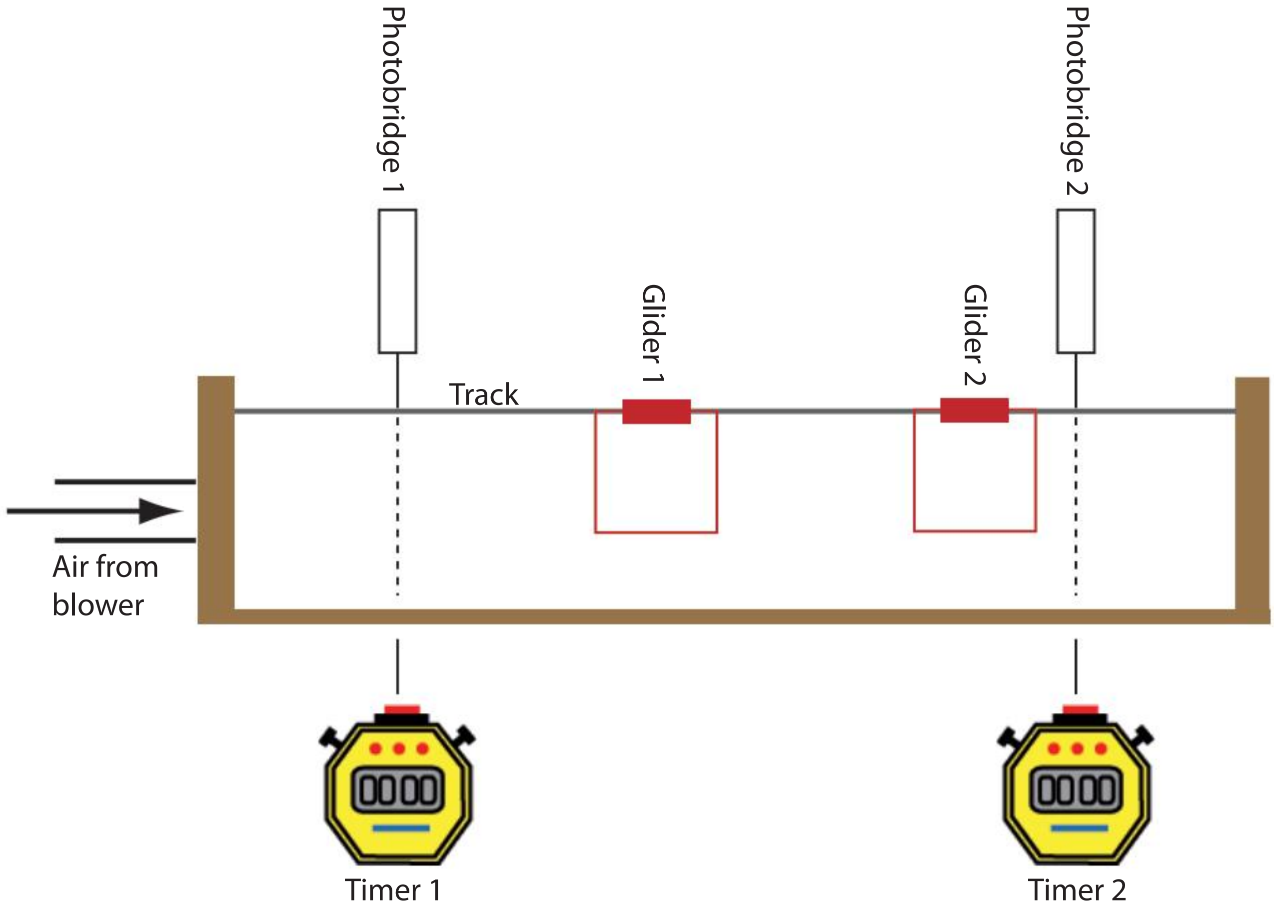


Figure 601 Apparatus to study conservation of kinetic energy

In setting up this apparatus, the following are essential:

- the linear air track is leveled.
- the two light gates are aligned.
- both interrupt masks pass clearly through each light gate.
- the leads connecting the light gates to the data logger are not tangled.

Setting up apparatus and equipment effectively requires thought and care.

Below are some guidelines when setting up apparatus for an investigation.

- Lay out the different equipment and apparatus on the work bench before putting them together. Arrange them such that electrical devices are near a power point and are far from hazards (e.g. water taps). Scales to be read should be readily visible.
- Put all mechanical devices together first, e.g. retort stands, pulleys, inclined planes, etc. Once the mechanical part of the investigation is set up and stable, connect the electrical and electronic devices.
- Before turning on any electrical or electronic devices, be clear what is expected from you. Ensure that the dial settings of the electronic and electrical devices are correct. If you are to make adjustments during the investigation, you must know which dials or knobs to turn.
- If you are not sure on how to operate any of the mechanical, electrical and electronic devices, ask for guidance from your teacher.

6.3 Adapting to circumstances

This aspect will also examine your ability to adapt to new circumstances. This means that you are expected to respond appropriately to serious sources of systematic and random errors by modifying a technique or a stage in the procedure in order to obtain results which are as accurate and reliable as allowed by the apparatus. For example, during a Hooke's Law investigation, it may happen that the suggested masses that hang do not produce measurable extensions of the spring. You would then be expected to increase the masses that you hung to obtain more reliable results.

Readings are usually taken at regular intervals. However, you need to be mindful of your data. If, after repeated measurements, you notice that the data has changed rapidly or slowly over a certain range, then readings must be taken at closer intervals over this range. This will help you plot a better graph later on. You might have obtained a critical value where the linear relationship between the variables you are investigating no longer applies. For example, the voltage - current graph for a filament lamp is linear for low voltages but curved for higher voltages. Or the spring might have exceeded its elastic limit, which is why the extension of the spring becomes irregular as more loads are added.

In some IB Physics Investigations, you will be instructed to measure a certain quantity (dependent variable) but you may not be told exactly how to measure it. Before starting with the investigation, devise a plan so that you can effectively measure this quantity. As an example, in the Hooke's Law investigation, you may be instructed to measure the extension of the spring. But you may not be told exactly how to measure it. Efficient measurement of the extension would include the use of a pointer to avoid parallax error, placing the load on the spring carefully and taking the reading only when the spring has stopped moving.

6.4 Carrying out techniques

Aside from accurately following instructions, you should also be able to carry out techniques effectively. This would involve the correct use of a range of basic Physics apparatus and the sound development and efficient implementation of good practical techniques with due regard for safety.

The succeeding pages will outline techniques that you can use when performing investigations.

6.4.1 Mechanics Experiments

1. Measuring lengths

a) Using a Metre Rule

A metre rule is a very simple instrument but care must be taken when using it to take measurements. To avoid 'parallax error', there must be no gap between the object being measured and the rule, and the line of sight must be at right angles to the scale. For metre rules, the zero position is always doubtful either because the end is worn out or the zero marking is incorrect in some way. To avoid the 'zero error' when measuring length, use the 1 cm mark as your reference point, as shown in *Figure 602*. Align the object against the 1 cm mark and subtract 1 cm from the reading.

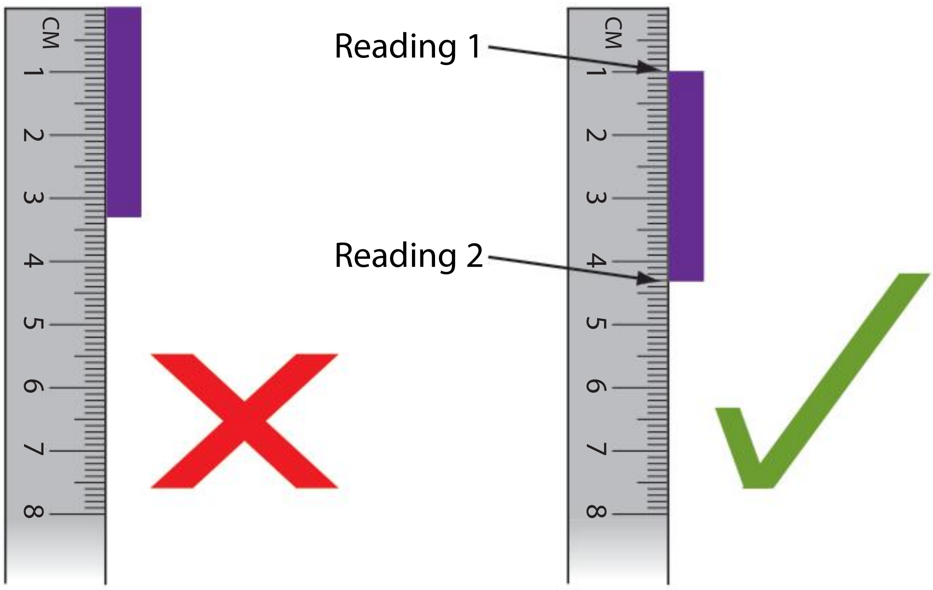


Figure 602 Measuring the length of an object

b) Diameter of round objects

If the diameter of the object you are going to measure is less than 5 mm (e.g. a bare wire or a small ball bearing), use a micrometer screw gauge. If the diameter of the object you are measuring is between 5 mm and 5 cm (e.g. a coin or a test tube), use a vernier caliper (see *Figure 604*).

If the diameter is greater than 5 cm, the method is shown in *Figure 603* below. You will need a metre rule and two set squares.

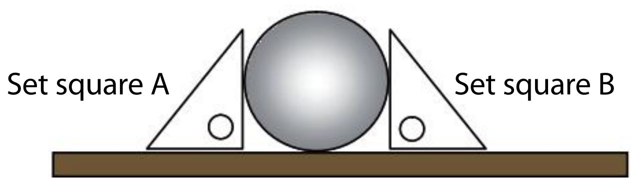


Figure 603 Measuring the diameter of large objects

c) The Vernier Caliper

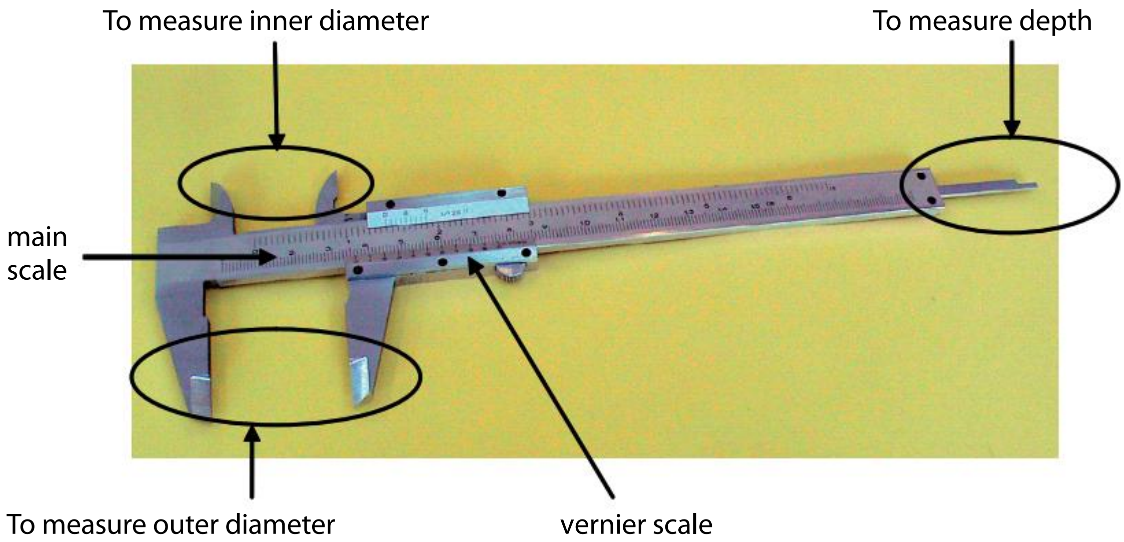


Figure 604 The vernier caliper

A vernier caliper (see *Figures 604, 605*) can measure up to a length of 15 cm with a higher degree of precision. It has two scales, the main scale which is fixed and the vernier scale which is movable. The outside jaw is used to measure the external diameter of an object and the inside jaw is used to measure the internal diameter of the object. The depth gauge is used to measure the depth of a container.

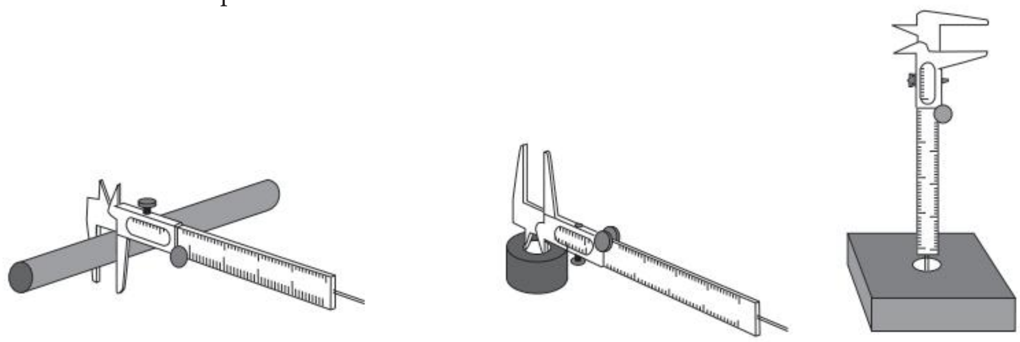


Figure 605 Uses of the vernier caliper

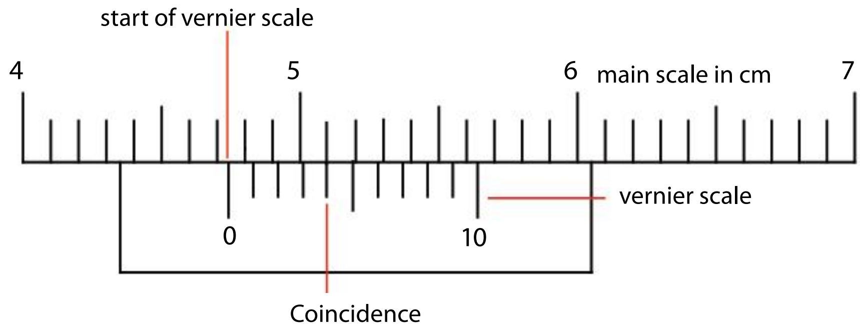


Figure 606 Reading the vernier caliper

What is the reading in the vernier scale shown in *Figure 606*?

i) The "0" mark of the vernier scale lies between the 4.7 cm and 4.8 cm marks of the main scale. Thus, the reading is between these two marks.

ii) Look at the vernier scale. Find which mark in the vernier scale coincides with the main scale mark. That vernier line gives the fraction of the main scale division you are looking for. Here it is the "4" mark, i.e. 0.04 cm.

iii) The reading is 4.7 + 0.04 = 4.74 cm

iv) Uncertainty in the reading. In the above model of the vernier caliper, the smallest division in the main scale is 1 mm or 0.1 cm. The 10 divisions in the vernier scale imply that 1 mm in the main scale is further divided into 10 divisions. This means that the smallest division in the vernier caliper is 1 mm / 10 divisions = 0.1 mm. Therefore, the scale uncertainty is 0.1 mm or 0.01 cm.

v) Finally, the complete reading is 4.74 cm ± 0.01 cm.

Note that there are various models of the vernier caliper. This implies that the scale uncertainty will be different.

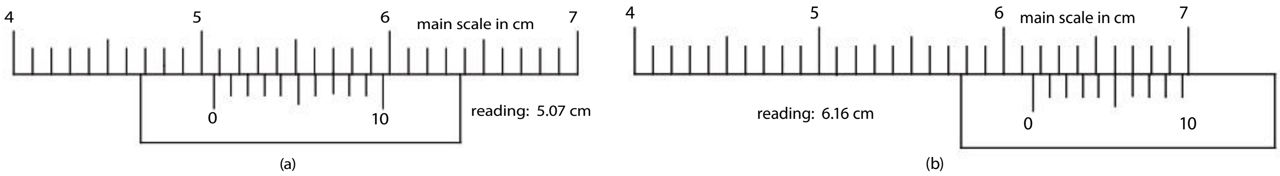


Figure 607 (a) and (b) Test yourself – can you read the vernier?

d) Micrometer screw gauge

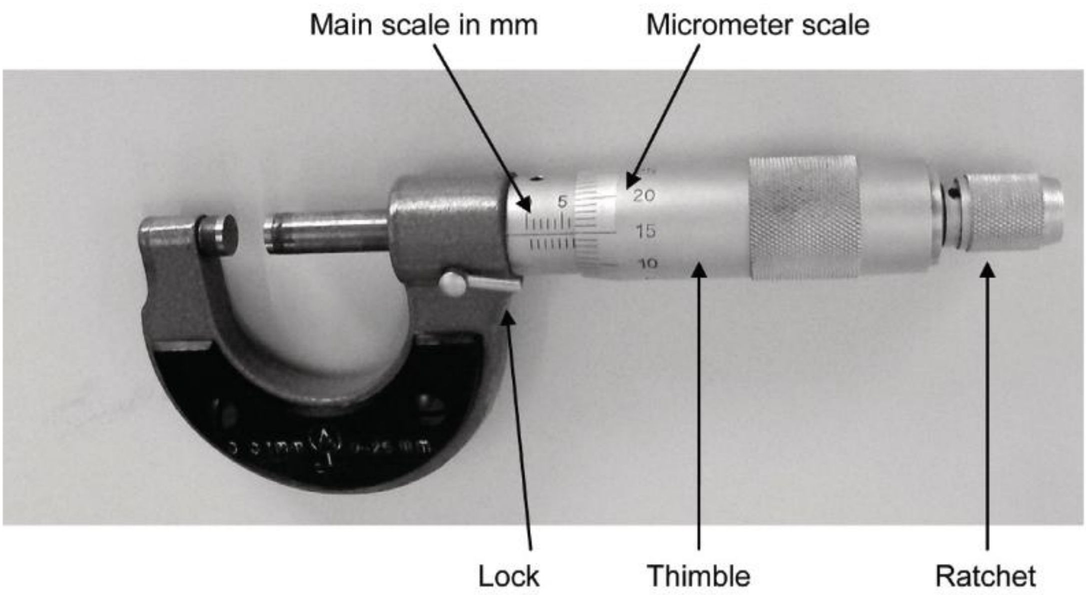


Figure 608 The micrometer screw gauge

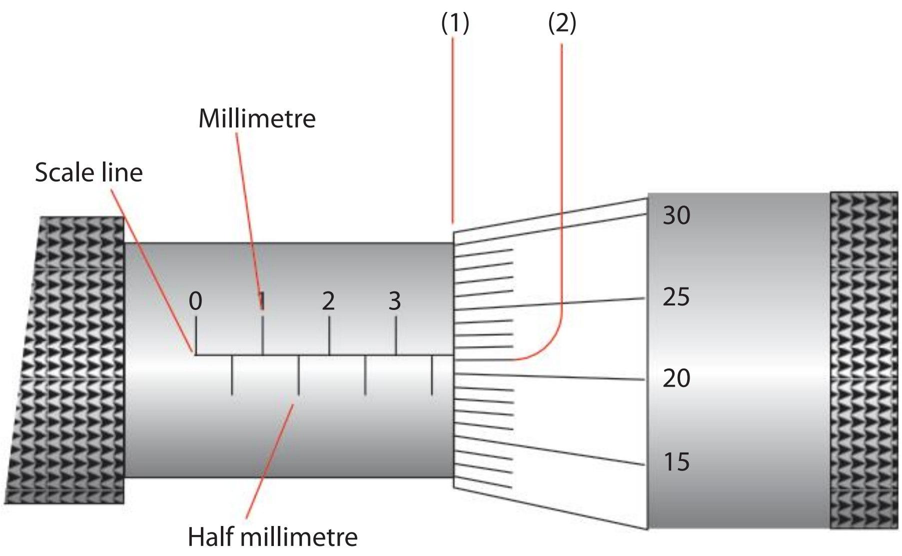


Figure 609 Reading the micrometer screw gauge

Reading the micrometer screw gauge:

1. From the main scale, the reading is between 3.5 mm and 4.0 mm. Thus, the reading is 3.5 mm plus a value less than 0.5 mm.

2. The micrometer scale reads 21.5, i.e. 0.215 mm.

3. The reading is 3.5 mm + 0.215 mm = 3.715 mm.

4. The measurement is 3.710 ± 0.005 mm.

6.4.2 Basic alignment skills

1. Setting a metre rule vertically

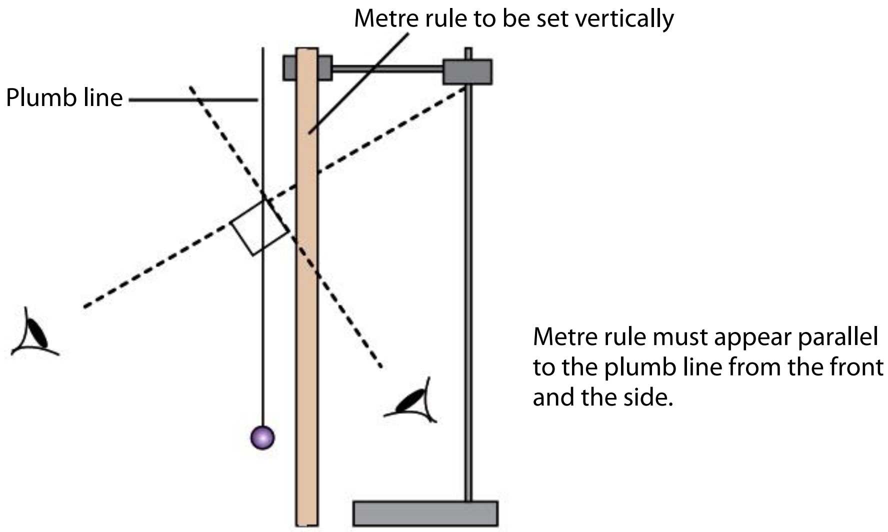


Figure 610 Use a plumb line to set a metre rule vertically

2. Setting a metre rule horizontally

Clamp the metre rule on each end. Align one side of the set square with the plumb line. Adjust the position of the metre rule to align it with the other side of the set square, as shown in *Figure 611*.

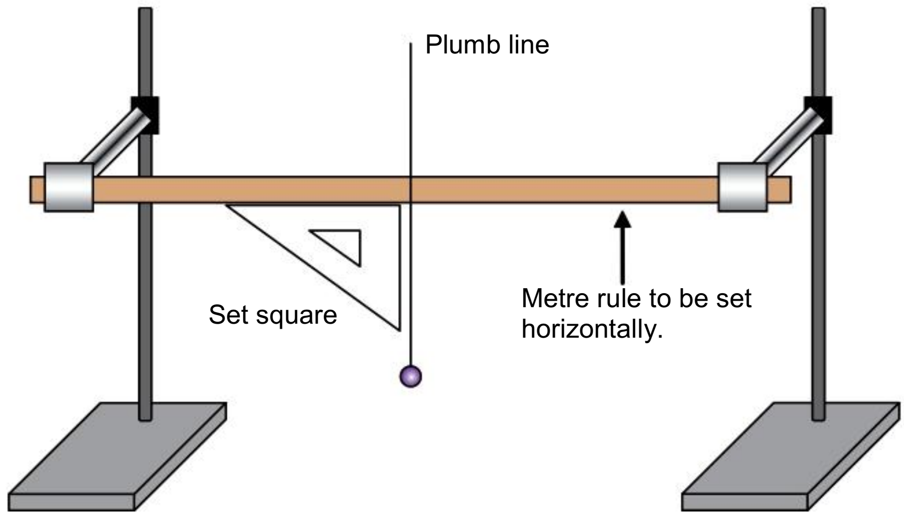


Figure 611 Using a plumb line and a set square to set a ruler horizontally

6.4.3 Setting up an oscillation apparatus

The string or the spring's end needs to be clamped tightly between two small wooden blocks. Do not simply tie the string to the clamp as this will affect the stability of the oscillation.

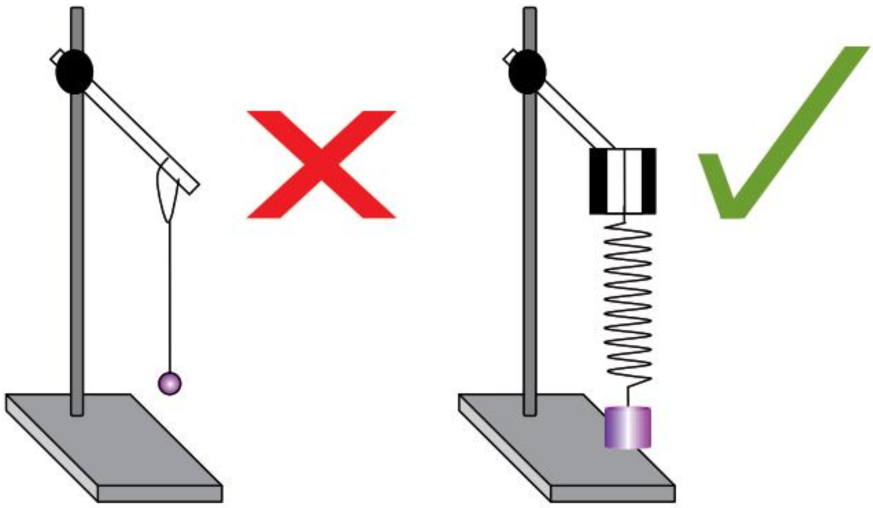


Figure 612 Setting up oscillating apparatus

6.4.4 Ticker timer to study motion

The speed of moving objects can be measured by using a ticker timer. A ticker timer is connected to an alternating current supply and makes 50 ticks or dots every second. The time interval Δt between consecutive dots is $\frac{1}{50}$ s or 0.02 s. *(In some countries, the a.c. frequency is 60 Hz, hence $\Delta t = \frac{1}{60}$ s or 0.17 s.)*

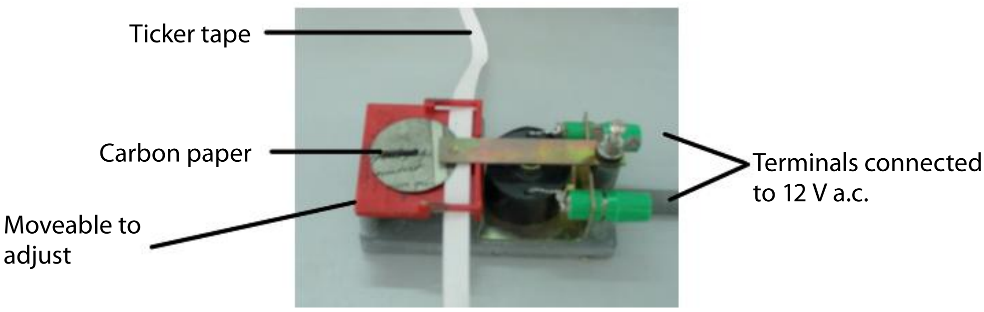


Figure 613 A ticker timer

An example of a ticker timer tape record is shown in *Figure 614*.

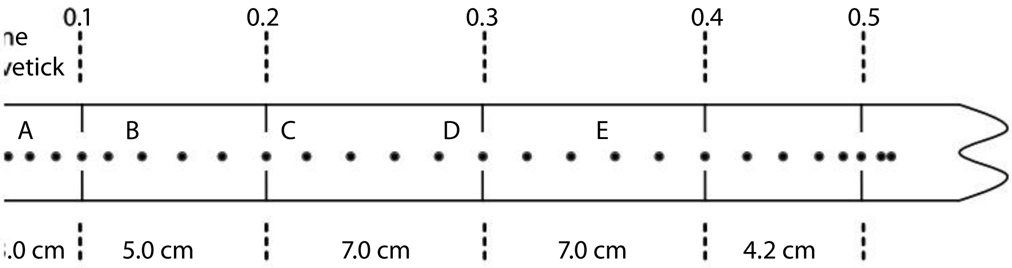


Figure 614 An example of a ticker tape

The speed of the object at different times is determined as follows:

i) Note the first distinct dot on the tape.

ii) Mark out all the "fiveticks" along the tape as shown above. A fivetick consists of 5 tick-spaces. Note that one 5 tick-space contains 6 dots. (You may use a ten-tick if the ticker tape record is quite long).

iii) Measure the length of each fivetick.

iv) The time interval for each fivetick is 0.1 s. ($\Delta t = 5 \times 0.02 \text{ s} = 0.1 \text{ s}$).

v) The average speed for an interval is given by the ratio of its length and the time interval 0.1 s.

For example, the average speed for:

Interval A: average speed $= \dfrac{3.0\,\text{cm}}{0.1\text{ s}} = 30\dfrac{\text{cm}}{\text{s}}$

Interval D: average speed $= \dfrac{7.0\,\text{cm}}{0.1\,\text{s}} = 70\dfrac{\text{cm}}{\text{s}}$

Note: If the a.c. frequency is 60 Hz, then it is most sensible to mark out your ticker tape into 'sixticks' or 'twelveticks'

6.4.5 Hooke's Law investigation

- Use a pointer to enable you to accurately mark the position of the bottom of an unstretched spring and the new position of the bottom of a stretched spring.
- Ensure that the spring is hung vertically.
- Wait for mechanical equilibrium to be established before recording the extension of the spring.
- Place the slotted masses on the mass holder carefully and slowly. The smaller the disturbance in the spring, the faster it reaches mechanical equilibrium.

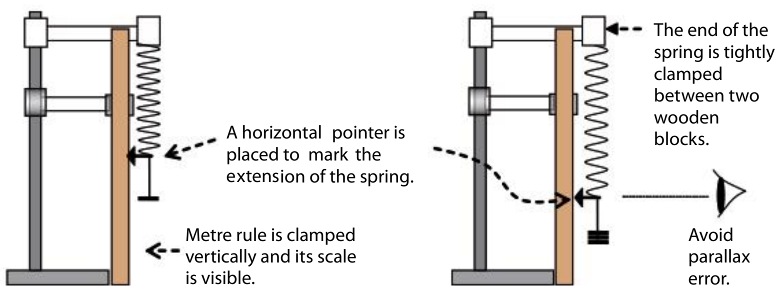


Figure 615 Measuring the extension of a spring

6.4.6 Timing oscillations (e.g. simple pendulum, loaded spring)

- Have a marker behind the oscillating object that can be used to judge when the object passes the reference point. Count each time it passes the marker in the same direction.
- It is good practice to time the oscillation when the object is at its fastest. For a simple pendulum or a loaded spring, it is at its fastest when it travels past its equilibrium position.
- Do not start the timer at the same time you start the oscillation because chances are, you cannot. Instead let the simple pendulum or the loaded spring oscillate a few times before you start the timer. Count '0' as the object passes the marker and start the timer. When it passes the marker in the same direction, count '1' and so on.
- Before oscillating a loaded spring, ensure that the slotted masses are securely attached to the mass holder and the mass holder is attached to the spring. Furthermore, do not excessively extend the spring when starting to oscillate it.

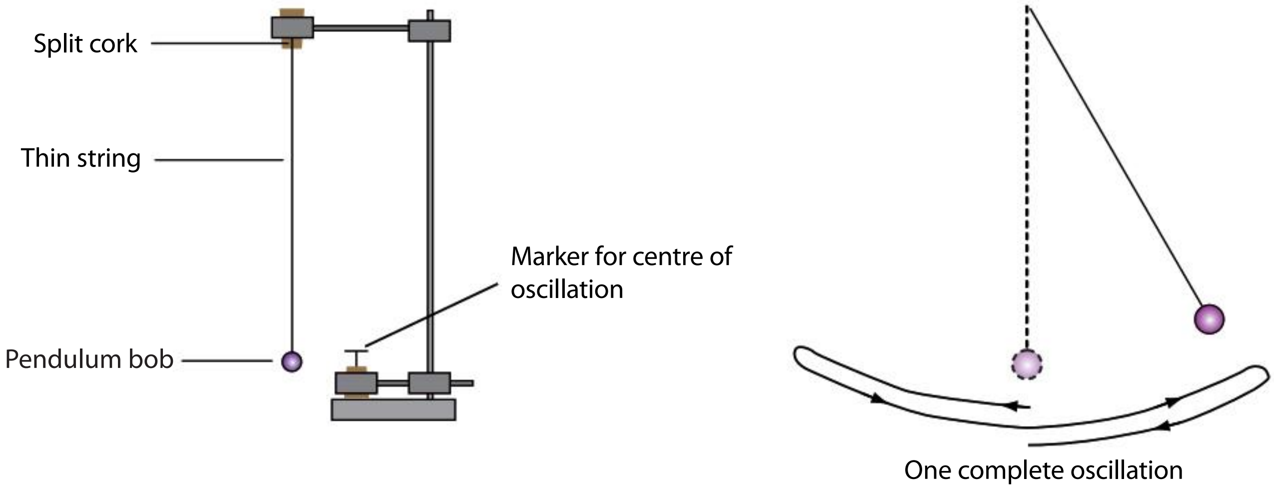


Figure 616 Setting up oscillations for a pendulum

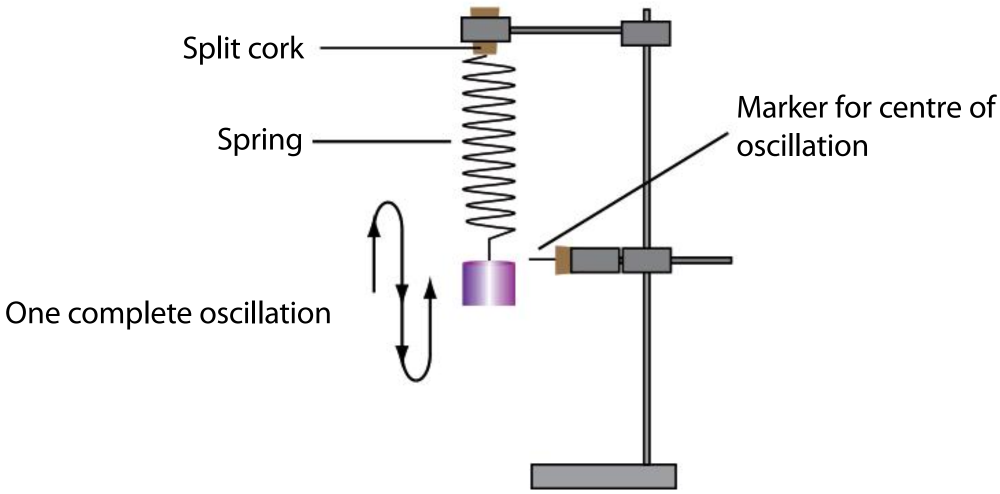


Figure 617 Setting up oscillations for a spring

6.4.7 Using electronic balances

- Always tare to zero the electronic balance before using it. This eliminates the zero error.
- Warm up the electronic balance before using it. The required warming-up time is usually indicated on the balance. This is needed to enable all parts of the balance to equilibrate to the same temperature and therefore give stable readings.
- Place the object to be weighed on the centre of the pan. This ensures that a uniform pressure is applied on the mechanisms inside the balance and that more reliable results are obtained.
- Place objects carefully on the pan. Dropping objects on the pan can damage the electronic balance and affect the accuracy of the readings.
- Do not place a hot object directly on the pan. Use an insulating pad between the hot object and the pan if you need to measure the mass of a hot object.

6.4.8 Heat experiments

1. General skills

- Use tongs to handle and safely transfer hot objects.
- Stir the hot liquid before measuring its temperature. This ensures that the liquid is at a uniform temperature. However, do not use the thermometer as a stirrer unless instructed to do so. (*Some thermometers have reinforced bulbs and can be used as a stirrer.*)
- Wait for the thermometer to reach thermal equilibrium before taking a reading.
- Ensure that the thermometer does not touch the bottom of the container when measuring the temperature of a liquid that is being heated. This is because the bottom of the container is hotter than the liquid. Ideally, the thermometer should be clamped as shown below.

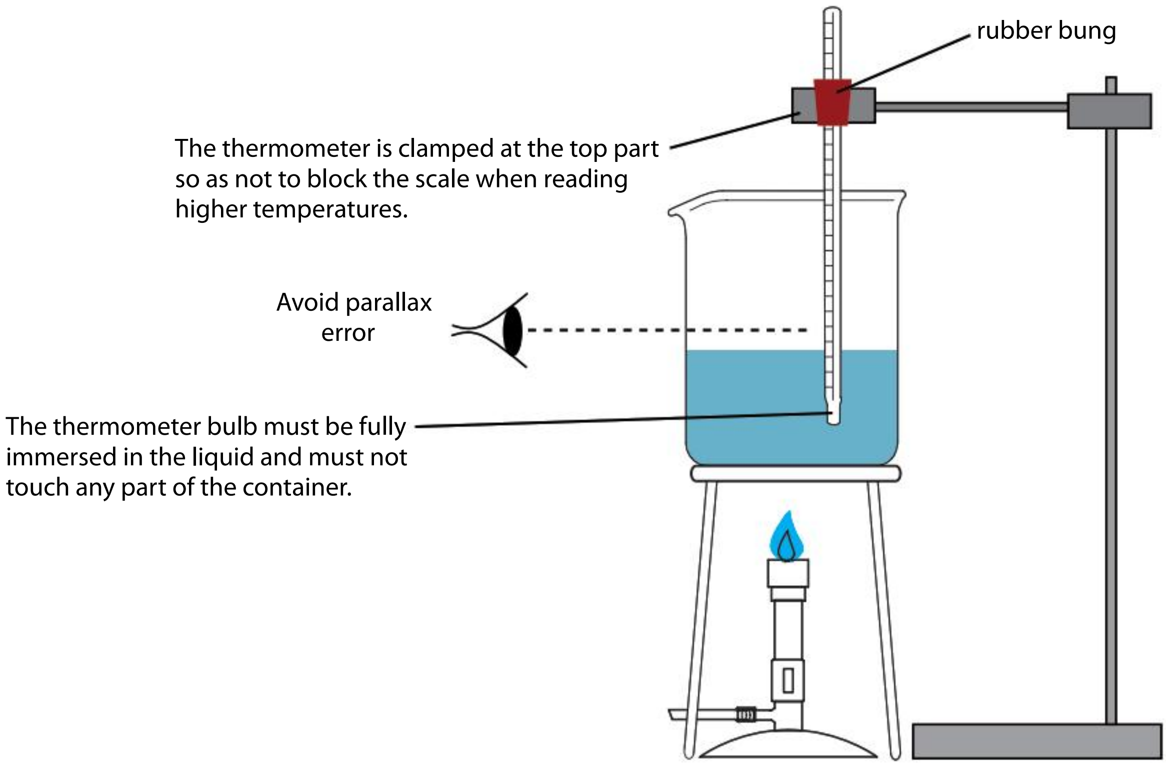


Figure 618 Setting up a liquid-in-glass thermometer

2. Calorimetry

Calorimetry is the name given to the experimental technique used to determine the heat energy absorbed or released during a chemical reaction. Calorimetry experiments in Physics use special containers called calorimeters (see *Figure 619*).

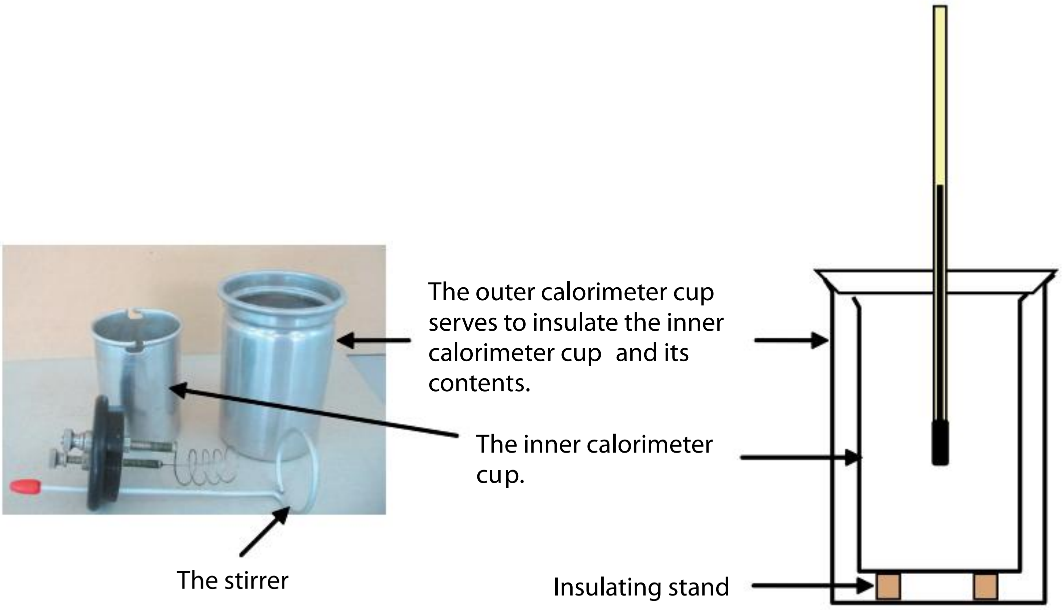


Figure 619 A calorimeter

a) Precautions to minimise heat losses

- Polish the inner part of the calorimeter to reduce heat loss due to radiation.
- Support the calorimeter on an insulating stand to reduce conduction losses.
- Place the inner calorimeter inside a larger calorimeter to reduce convection and conduction losses.

b) Initial cooling method

In this method, the calorimeter and its contents are cooled down to 10 ^{0}C below room temperature. It is then heated steadily by electrical means to 10 ^{0}C above room temperature.

When the substance is below room temperature, it will absorb heat from the surroundings. When the substance is above room temperature, it will lose heat to the surroundings. It is assumed that the heat absorbed by the substance when it is below room temperature is equal to the heat lost by the substance to the environment when it is above room temperature.

Note that you may cool down the calorimeter and its contents to a different temperature below room temperature. It is important that the calorimeter is cooled below room temperature by the same amount that it will be increased above room temperature.

It is possible that the calorimeter and its contents are heated up first and then cooled down. As an example, the specific latent heat of fusion of ice can be obtained by the method of mixtures. In this method, a known mass of ice is mixed with a known mass of water. Temperature changes are measured and the specific latent heat of fusion of ice is calculated. More accurate results would be obtained if the water-calorimeter system is heated up first, i.e. to around 10 ^{0}C above room temperature. You then need to estimate the mass of ice you need to mix with the water so that the final temperature of the water-ice-calorimeter system is approximately 10 ^{0}C below room temperature.

c) Determination of the specific latent heat of fusion of water by an electrical method

This is one investigation where your manipulative skills will be very important.

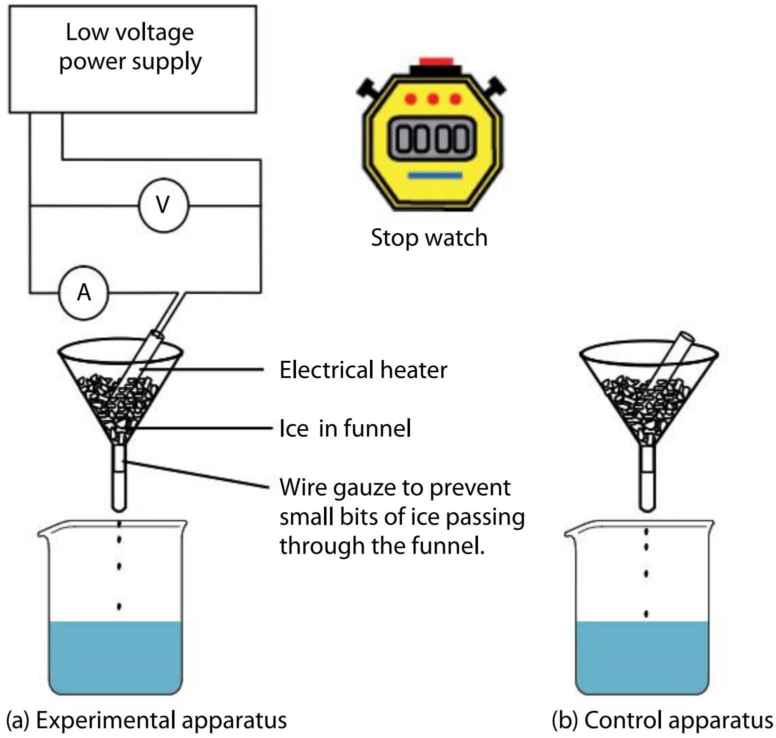


Figure 620 Experimental set-up to measure the specific latent heat of fusion of ice

A concern with this method is that the ammeter and voltmeter readings change over time. This is because the resistance of the electric heater increases as its temperature increases. Prepare a table similar to *Figure 621* so you will have a more accurate value of the electrical energy supplied over the 10 minute period.

Time elapsed / min	Voltage / V	Current / A	Power / W	Electrical energy / J
0.0			Current × Voltage	Power × 30 s
0.5				
1.0				
↓ 10.0				
			Total electrical energy	

Figure 621 A sample table

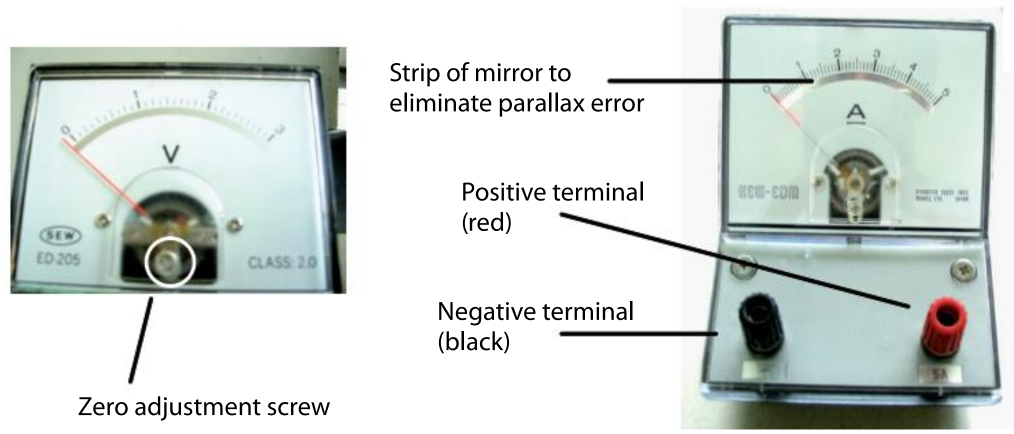
6.4.9 Electricity experiments

1. Building electric circuits

- Ensure that the power is switched off when connecting the components together or when taking them apart.
- If you have to build a circuit from a schematic diagram, follow the polarities of the components. For ammeters and voltmeters, it is positive terminal to positive terminal.
- When building electric circuits, there must be a minimum of tangles, or if possible none at all, so that the circuit can be easily followed. Tangles can be reduced or avoided by completing the series part of the circuit first and connecting the electrical component that has to be connected in parallel last (e.g. voltmeter).
- It is important to keep the temperature of the electrical components constant. Turn on the electrical circuit when you are ready to take a reading and turn it off to allow the component to cool.

2. Use of analogue ammeters and voltmeters

- Before using, give the moving-coil part of the ammeter or voltmeter a gentle tap. This is to loosen the coil parts just in case there is some residual friction in it.
- Check that the ammeter or voltmeter reads zero before connecting it to the circuit. If it does not, with your teacher's permission, you can set the needle pointer to zero by adjusting the screw at the base of the pointer (see *Figure 622*).
- To avoid parallax error, analogue ammeters and voltmeters are equipped with a strip of mirror on the scale. Position your eyes vertically above the needle, such that the needle and its image on the mirror coincide.



(a) Voltmeter scale with zero error

(b) An ammeter

Figure 622 An analogue voltmeter and ammeter

3. Connecting an ammeter and voltmeter

The ammeter must be connected in series to the circuit in order to measure the current passing through the circuit. On the other hand the voltmeter is connected in parallel to the device to measure the potential difference across the device. See *Figure 623*.

The terminals of the ammeter and the voltmeter have a polarity. They need to be connected to the correct poles of the power source. The red terminal is positive (remember 'red cross') while the black terminal is negative. To work properly, the positive terminal of the ammeter or of the voltmeter must be connected to the positive side of the power source.

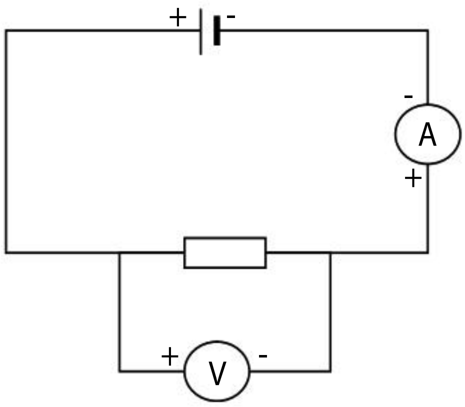


Figure 623 Connecting the ammeter and voltmeter

4. Dual range ammeter and voltmeter

A dual range ammeter or voltmeter has three terminals (one negative terminal and two positive terminals) and two scales. When using this type of ammeter or voltmeter, it is critically important that you read the correct scale.

Take the voltmeter below (*Figure 624*) as an example. It has three terminals: 0 V (terminal A), 3 V (terminal B), and 15 V (terminal C). It has two scales: the upper scale reads 0 – 15 V while the lower scale reads 0 – 3 V. Since the maximum reading for the upper scale is 15 V, it has a full scale deflection (fsd) of 15 V. The lower scale has a fsd of 3 V.

When terminals A and B are connected to the circuit, the voltmeter can measure up to a maximum of 3 V. You must therefore read the lower scale. On the other hand, when terminals A and C are connected to the circuit, the voltmeter can measure up to a maximum of 15 V and you must read the upper scale. Note that it is not possible to connect the three terminals concurrently to the circuit.

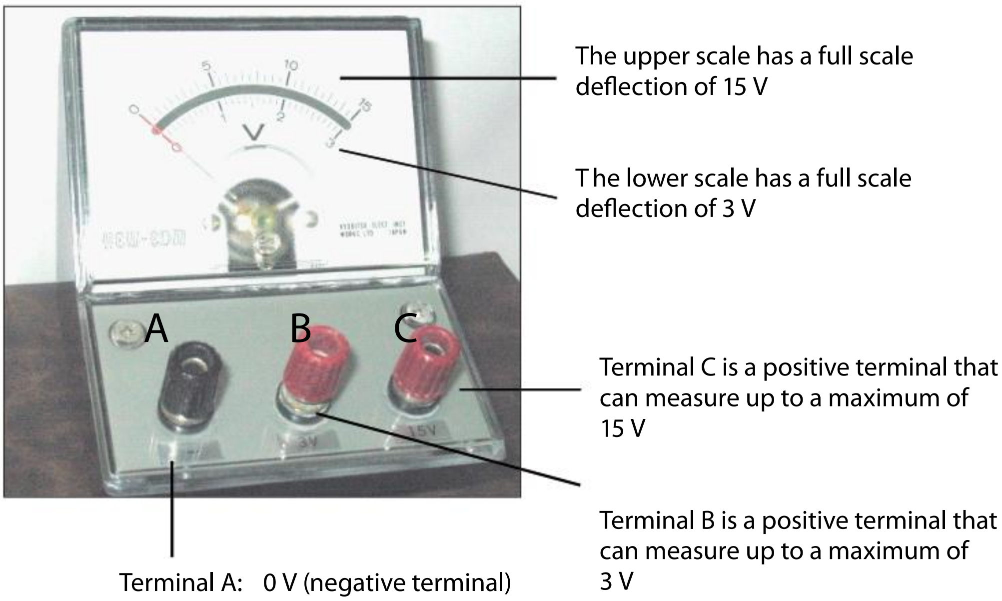


Figure 624 A dual range voltmeter

5. Multi-range meters

A multi-range meter has two components: a milliammeter or microammeter and a series of specially-mounted resistors. A milliammeter is a galvanometer that can measure currents within the range of 10^{-3} A (mA) while a microammeter can measure very small currents within the range of 10^{-6} A (μA). The unit stamped on the meter will tell you whether it is microammeter or a milliammeter (*see Figure 425*). The specially-mounted resistors are designed to be connected in parallel (i.e. as shunts) to produce a range of ammeters or in series (ie, as multipliers) to produce a range of voltmeters.

Consider the multi-range meter below (*Figure 625*) as an example. The multiplier resistor will convert the microammeter into a dual range voltmeter with fsd 1 V and 5 V. The shunt resistor will convert the microammeter into a dual range ammeter with fsd 1 A and 5 A.

As various shunt and multiplier resistors can be mounted onto the microammeter, care must be exercised when reading the scale. If the fsd of the mounted multiplier or shunt resistor is 5 V or 5 A, common sense tells you to read from the upper scale. However, if the fsd is some other value (e.g. 2.5 A), then the correct reading can be obtained by using the formula:

$$\text{correct reading} = \text{fsd value} \times \frac{\text{raw reading on scale}}{\text{maximum reading on scale}} .$$

For example, the maximum reading on the upper scale is 10.00 A and the raw reading is 7.60 A. The shunt resistor has a fsd of 2.5 A. Then the correct reading is:

$$\text{Correct reading} = 2.5 \times \frac{7.60}{10.00} = 1.90 \text{ A}$$

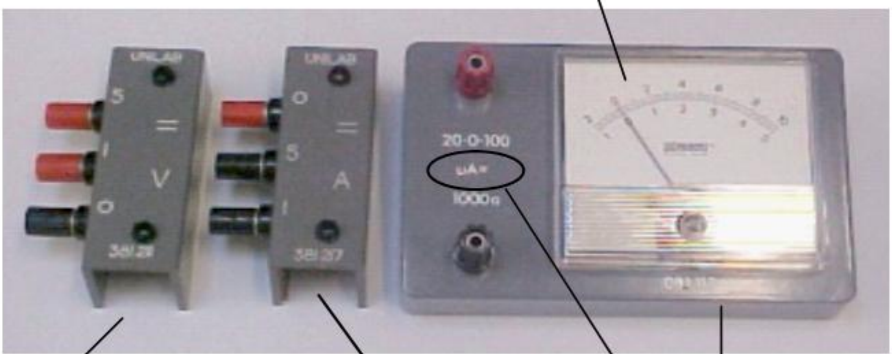


Figure 625 A multi-range meter

6. Using an ammeter and a voltmeter to measure resistance

Moving coil galvanometers used as ammeters or voltmeters need a small amount of current to operate. As such, the use of these devices changes the current flowing in the circuit. See *Figure 626*.

An ammeter is connected in series to the circuit. For it to have minimal effect on the current, it should have a very small resistance. Since it is connected in series, its presence increases the total resistance. This additional resistance, though small, causes the current in the circuit to decrease.

A voltmeter, on the other hand, is connected parallel to the circuit. For it to have minimal effect on the current, it should have a very high resistance. The voltmeter creates an extra parallel branch and as such, it draws additional current. However, due to its very high resistance, the current drawn by the voltmeter is very small. Even so, the voltmeter causes an increase, however minimal, to the total current in the circuit.

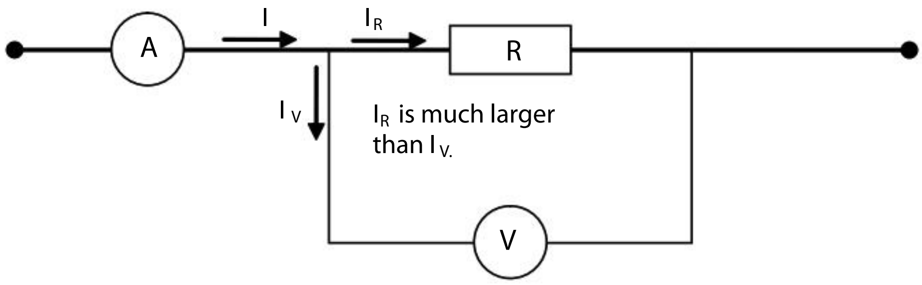


Figure 626 *Systematic error due to the voltmeter*

A voltmeter and an ammeter are used in tandem to determine the resistance of a conductor or of a resistor. How the two devices are to be connected depends on the resistance of the conductor relative to the resistance of the voltmeter.

Measuring small resistances

When the resistance R of the resistor is much smaller compared to the resistance of the voltmeter, the circuit in *Figure 627* is used to determine the resistance R.

In the circuit the resistance of the voltmeter is much higher. As a consequence, it draws a small current and this increases the total current in the circuit. Therefore, the current measured by the ammeter is higher than the actual current flowing through the resistor.

Since $R = \frac{V}{I}$, then the calculated resistance R is underestimated. This is an example of a systematic error.

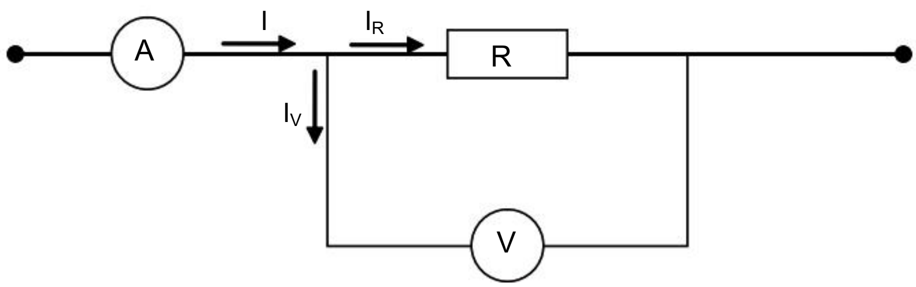


Figure 627 *Ammeter-voltmeter connection to determine low resistances*

Measuring large resistances

When the resistance of the resistor is comparable to that of the voltmeter, the circuit shown in *Figure 427* is not suitable. This is because the voltmeter will draw a significant amount of current. If voltage-current measurements are performed using the circuit shown in *Figure 627*, the current measured by the ammeter is considerably higher than the actual current flowing through the resistor. Consequently, a large systematic error would be introduced into the results.

If the resistance R of the resistor is equal to the resistance of the voltmeter, then the current I splits equally at the junction, that is, $I_R = I_V$ and $I = 2 \times I_R$.

Consequently, when R is calculated using $R = \frac{V}{I}$, the R value obtained will be half of its actual value.

Therefore, when the resistance R is large, the circuit shown in *Figure 628* is most suitable to use to determine the resistance of the resistor. In the given circuit, the ammeter measures the actual current that flows through the resistor.

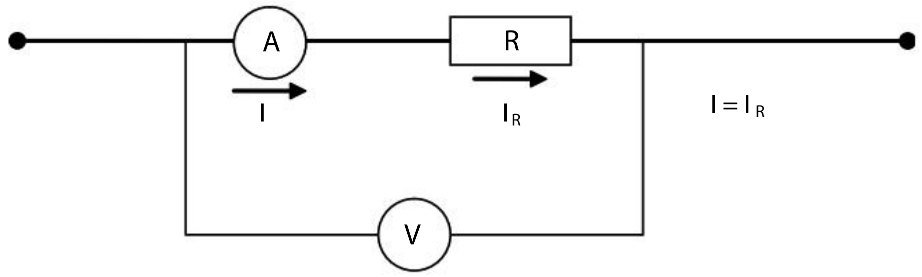


Figure 628 Ammeter-voltmeter connection to determine high resistances

Then again, the use of the circuit in *Figure 628* to determine large resistances introduces a small systematic error. The voltmeter measures the potential difference (p.d.) across the ammeter and the resistor. Thus it measures a p.d. that is higher than the actual p.d. across the resistor. However, due to the low resistance of the ammeter, the p.d across it is very small. Since the resistance *R* is high, the p.d. across it is much higher than the p.d. across the ammeter. As a result, using $R = \frac{V}{I}$ causes a slight overestimation on the calculated value of *R*.

Note that when resistance is large, both circuits introduce a systematic error. However, the second circuit (*Figure 428*) results in a smaller error, hence it is better to use.

7. Rheostat

A rheostat is a resistor that has a variable resistance and it is an important instrument for controlling current. It has three terminals. You have to connect the wires to the correct terminals of the rheostat to achieve a varying resistance when the slider is moved. The diagrams in *Figure 629* describe how the resistance between points x and y changes when different terminals of the rheostat are used.

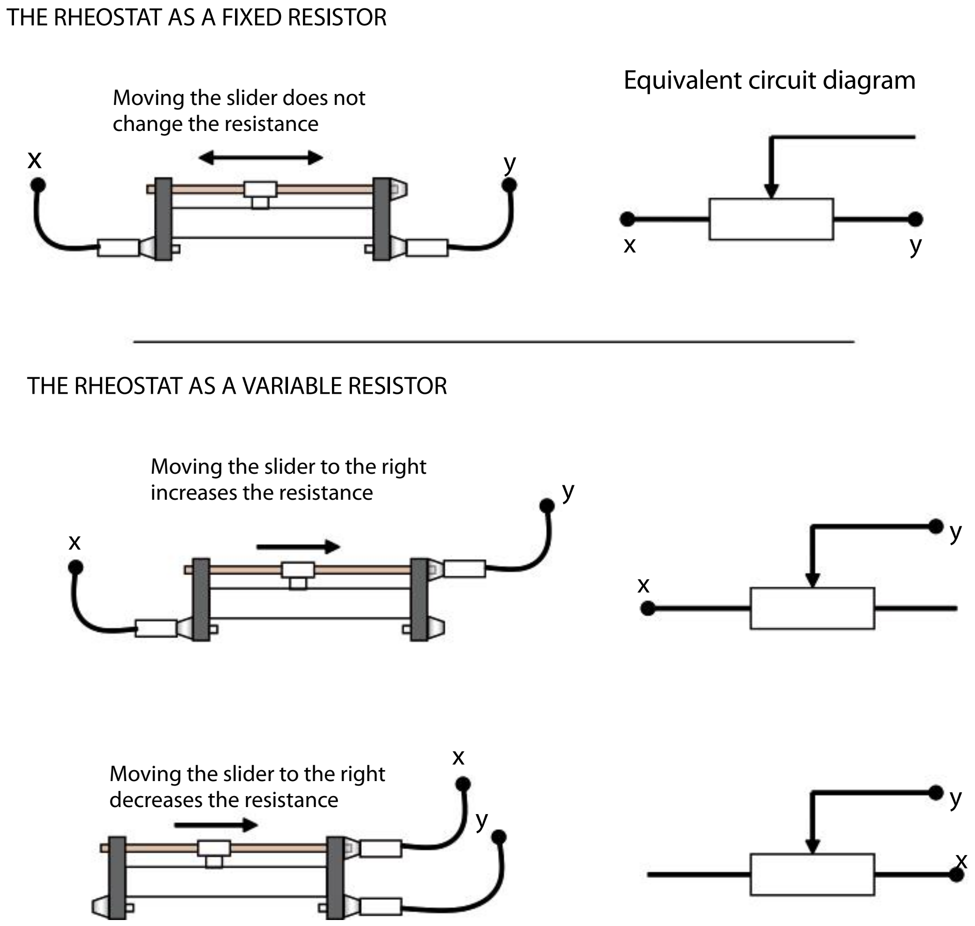


Figure 629 The terminals connected to the circuit affects how its resistance changes

8. Measurement of magnetic force

An electronic balance can be used to measure the magnetic force on a current-carrying conducting wire. *Figure 630* shows how this can be done.

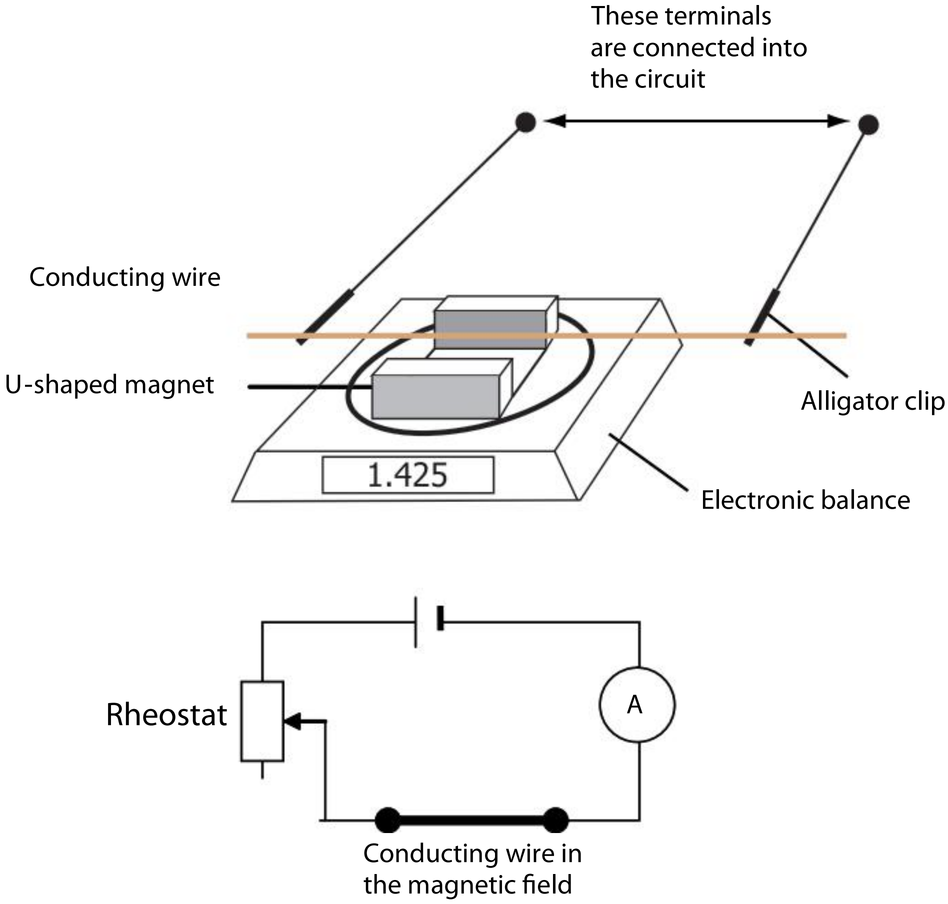


Figure 630 Experimental set-up to measure the magnetic force on a current-carrying conducting wire

A U-shaped magnet is placed on the top of the electronic balance. The conducting wire is fixed horizontally between the poles of the magnet such that the length lies in the field of the magnet. The conducting wire is connected into the circuit shown above. The current flowing in the conducting wire can be varied through the rheostat.

When a current is flowing through the conducting wire, the magnet will experience an upward or a downward force, depending on the direction of the magnetic field of the U-shaped magnet and of the current. Either way, this will result in a change in the electronic balance reading, that is, the reading in the electronic balance may increase or decrease. The change in the electronic balance reading is proportional to the force between the conducting wire and the U-shaped magnet. The force is obtained by multiplying the change in the electronic balance reading (in kg) by 9.8 N/kg.

Note that the strength of an electromagnet can be investigated in the same manner by replacing the conducting wire by the electromagnet.

6.5 Working safely

Your approach to safety during investigations in the laboratory or in the field is very important. Nevertheless, the IB Physics teacher will not put you, the students, in situations of unacceptable risk.

In Physics laboratories there are many *potential* hazards and your safety depends on your awareness and understanding of these. In most cases, these hazards will be dealt with by your teacher as they arise, often in connection with the investigation. Any practical work should be approached sensibly and carefully. If there is anything you do not understand, ask your teacher first.

Listed and discussed below are the types of dangers that can cause problems or injuries when performing IB Physics investigations.

6.5.1 What you need to do

- Carry out laboratory work only when supervised by a teacher.
- Use common sense. Accidents during an investigation can be avoided if you, the student, have really thought about what you need to do.
- Listen to instructions carefully. Ask your teacher if there is anything unclear to you.
- Before doing anything, remove all clutter from your work bench.
- Before starting, ensure that you have all the necessary apparatus, equipment and material. This prevents you from stopping your investigation halfway through to locate missing equipment.
- Stay in your work area and monitor your investigation closely.
- Consult your teacher before making any modification in the suggested method.
- If you need to handle any potentially dangerous substances, wear gloves and wash your hands thoroughly after the investigation.
- Before you leave your work area, ensure that the water, electricity and gas are all turned off. Equipment should be returned to its proper storage place.

6.5.2 Mechanics investigations

Investigations in mechanics usually involve rapidly moving objects, falling objects and stretched springs. Being hit by rapidly moving objects can produce bruises, scratches and cuts. Safety precautions are mostly common sense.

Projectiles

- Pre-test the projectile to determine the path it will take. Ensure that no one is along the path or the impact area.
- Do not use sharp-pointed objects as projectiles.
- Wear safety goggles.

- Use a simple mechanical launcher (e.g., compressed spring, compressed air, stretched elastic). Load the launcher only when it is to be fired.

Falling objects and moving equipment

Heavy masses may be used in experiments involving Atwood's machine, free fall, Newton's laws, and momentum. Care should be taken to prevent hands and feet from being caught between a moving heavy mass and the floor or table surfaces. For falling objects, always place a 'crash box' (a box which contains a soft material that will cushion the fall of the object and prevent it from bouncing).

Powerful permanent magnets

Large permanent magnets and electromagnets may attract opposite poles or steel objects with an unanticipated strong force. There is the potential risk that fingers get pinched when caught between the magnet and the metallic object.

Stretched or compressed springs

Care should be taken to avoid unexpected release of the spring's potential energy when working with dynamics carts, spring-type simple harmonic oscillators, and springs used in wave investigations. A stretched spring, unexpectedly released, can tweak fingers. A compressed spring, when suddenly released, can hit someone or send a projectile at high velocity toward an observer.

6.5.3 Heating

- Loose fitting clothes or long hair not tied back can pose a hazard when working with a naked flame.
- Beakers of liquid on a tripod are tall structures that are top heavy and can easily fall over. Place them on the centre of the work bench to reduce the chances of them being accidentally knocked down.
- Know where the fire blanket, fire extinguisher and sand bucket are before starting an investigation which will utilise a naked flame,
- Many materials like glass remain hot for a long time after they are removed from the heat source. Always check an objects' temperature by bringing the back of the hand near it before attempting to pick it up without tongs, hot pads, or gloves.
- Never set hot glassware on cold surfaces or change its temperature suddenly (e.g. pouring cold water), because uneven contraction may cause breakage.
- Never heat a closed or sealed container that has no means to release pressure.
- Make sure that steam outlets are not directed towards yourself or to anyone else.

6.5.4 Laser

The laser produces an intense, highly directional beam of light that can cause burns and retinal damage. Some lasers concentrate visible light to an extent that retinal damage can occur in a very short time. Fortunately, lasers found in secondary school science laboratories are the low power (0.5 – 3.0 mW) helium-neon lasers. Nonetheless, they should be handled with great care and certain precautionary measures need to be taken when working with lasers.

- Never put your eye directly in path of the laser beam.
- Ordinary safety goggles or sun glasses will not protect your eyes against lasers.
- When using lasers, do not darken the room more than is necessary as this dilates or enlarges the pupil. A dilated pupil is more prone to damage when accidentally hit by laser light.
- Before switching on the laser, remove any reflective material or object that lies in the path of the laser beam. Ensure that there is no possibility of multiple reflections. In this regard, do not use the laser in rain, snow, fog or heavy dust.
- Investigations using a laser should not be set up at eye level.
- Do not move the laser when it is on.
- Do not leave the laser unattended.
- When the laser is not in use, block off the beam or better still, turn it off.

6.5.5 Ultraviolet (UV) rays

- UV rays pose a danger to the eyes. When a UV lamp is used, it should be shielded. You need to wear eye protection.
- UV rays used for investigating the photoelectric effect have short wavelengths and they do not transmit through ordinary glass. Therefore, ordinary glass may be used as a shield.
- Turn off the UV lamp when not in use.

6.5.6 Electricity

Safety measures in investigations using electricity are as follows:

- Use only low voltage (LT) power packs which have a maximum of 12 V.
- During initial experiments, ask your teacher to check your circuit before switching it on.
- Monitor the temperature of your wires. When the circuit is on, feel the wires by putting the back of your hand close to it but not touching it. If they are warming up, there is a current overload. Reduce the current by lowering the emf or by increasing the resistance.
- When part of the circuit has been assembled, check that the ammeter and voltmeter are deflected in the right direction. This can be safely done by quickly touching the final connection to one terminal of the power pack.
- Damaged three-pin plugs, exposed wires and worn and frayed leads must be reported to the teacher immediately.
- Always switch off your circuit when making any changes to it.
- The use of high voltage (HT) and extra high voltages (EHT) are usually reserved for teacher demonstrations. Experiments with EHT, for example in electrostatics or cathode rays, can involve a few thousand volts. If you are instructed to use EHT, the current must be limited to a few milliamperes.
- For completed circuits to watch out for:
  - hand-to-hand connections that allow current to flow through the heart
  - hand-to-ground connections that allow for maximal current flow through the body.

6.5.7 Radioactive sources

Radioactive sources used in the laboratory are relatively weak emitters. The α, β and γ sources that are used for the Geiger-Muller tubes are mounted in metal holders and one face is open. The source is held in place inside by gauze or a wire mesh. These sources always come in lead-lined containers.

Listed below are some precautions to be followed when handling radioactive sources.

- Use the radioactive source only if you have permission from your teacher and when your teacher is present in the laboratory.
- The radioactive sources must always be transported in their containers.
- Keep your exposure to the radioactive source to a minimum. Prepare everything and ensure that apparatus and equipment are all set-up before taking out the radioactive source from its container.
- Use one radioactive source at a time. Return one radioactive source to its container before using another.
- Always use a pair of tongs or forceps when handling radioactive sources. Hold the forceps with stretched arms and keep the radioactive source as far as possible from your body. Wear protective gloves if available.
- Always make sure that the open face of the radioactive source is pointing away from you and from anybody else.
- Do not tamper with any radioactive source. Report to your teacher if you observe any damage in the radioactive source.
- Wash your hands thoroughly after handling radioactive sources.

6.6 Risk Assessment

Basic safety instructions are described in the IBID Press Physics Practical Investigations and potential hazards are identified in the investigations described. However, sometimes the investigation will be more open-ended, for example, your Group 4 Project or your Individual Investigation.

If you are planning your own practical work, then your IB Physics teacher will need to approve your plans from the point of view of safety. You are also required to take into account any environmental impact your investigation may have.

A Risk Assessment is a way of identifying and assessing risks and hazards associated with the materials and equipment that you plan to utilize in an investigation. This includes predicting what might go wrong, how likely it is to go wrong and how severe the consequences would be.

Figure 632 A laboratory laser

The stages in carrying out a Risk Assessment are given below:

1) Identify the nature of the risk. For IB Physics investigations, the hazard may be one of the following:

a) Ultraviolet rays/ Lasers

b) Nuclear Radiation

c) Naked Flame/Hot equipment/Hot Liquid

d) Moving Objects/Heavy Objects/Sharp objects

e) Compressed/Stretched Springs or wires

f) Electricity

2) Assess the hazards.

a) What is the worst case scenario that could happen?

- i) First aid is enough
- ii) Medical attention
- iii) Serious medical attention
- iv) Permanent disability
- v) Fatal

b) What is the possibility that this will happen?

- i) High
- ii) Medium
- iii) Low

3) Control the hazards. This means thinking about and implementing measures that can reduce or eliminate the risks and hazards related to the investigation.

a) Can you eliminate it?

b) Can you substitute a less hazardous alternative?

c) Can you change the way the task is done?

d) Will you have to use personal protective equipment?

4) **Overall assessment**

RISK ASSESSMENT FORM

Title of investigation

……………………………………………………

……………………………………………………

Completed by ____________

Date ____________

Approved by ____________

Nature of risk

☐ Electricity ☐ Naked flame/Hot equipment/Hot Liquid ☐ Ultraviolet rays/ Lasers

☐ Moving/Heavy/ Pointed Objects ☐ Nuclear Radiation ☐ Compressed/Stretched Spring or wire

What harm can these risks bring?	Worst case scenario	Possibility of occuring	What can be done to avoid or reduce risks?
		☐ High ☐ Medium ☐ Low	
		☐ High ☐ Medium ☐ Low	
		☐ High ☐ Medium ☐ Low	
		☐ High ☐ Medium ☐ Low	

Overall risk assessment

☐ Insignificant

☐ Significant but effectively controlled

☐ Significant and not readily controlled

Comment :

……………………………………………………

……………………………………………………

……………………………………………………

Figure 633 A sample of a Risk Assessment form

The information in the following table provides some indication of how the Extended Essay will be assessed. Individual teachers and schools may provide additional information as they wish.

Assessment criterion	Highest mark for criterion	Description of highest achievement level for each criterion.
A: Research question	2	The research question is clearly stated in the introduction and sharply focused, making effective treatment possible within the word limit
B: introduction	2	The context of the research question is clearly demonstrated. The introduction clearly explains the significance of the topic and why it is worthy of investigation.
C: Investigation	4	An imaginative range of appropriate sources has been consulted, or data has been gathered, and relevant material has been carefully selected. The investigation has been well planned.
D: Knowledge and understanding of the topic studied	4	The essay demonstrates a very good knowledge and understanding of the topic studied. Where appropriate, the essay clearly and precisely locates the investigation in an academic context.
E: Reasoned argument	4	Ideas are presented clearly and in a logical and coherent manner. The essay succeeds in developing a reasoned and convincing argument in relation to the research question
F: Application of analytical and evaluate skills appropriate to the project.	4	The essay shows effective and sophisticated application of appropriate analytical and evaluative skills.
G: Use of language appropriate to the subject	4	The language used communicates clearly and precisely. Terminology appropriate to the subject is used accurately, with skill and understanding.
H: Conclusion	2	An effective conclusion is clearly stated; it is relevant to the research question and consistent with the evidence presented in the essay. It should include unresolved questions where appropriate to the subject concerned.
I: Formal presentation	4	The formal presentation is excellent
J: Abstract	2	The abstract clearly states all the elements listed above. The requirements for the abstract are for it to state clearly the research question that was investigated, how the investigation was undertaken and the conclusion(s) of the essay.
K: Holistic judgement	4	The essay shows considerable evidence of such qualities (qualities that distinguish an essay from the average, such as intellectual initiative, depth of understanding and insight).

The Extended Essay in Physics

General advice

The Extended Essay is one of the core requirements of the IB Diploma Programme. The Extended Essay is an academic study of a focused physics-based research question. It is intended to give you the experience of working on a research project under the guidance of a physics teacher who acts as your supervisor. He or she will meet with you a number of times and comment on the final draft of your Extended Essay. He or she will also conduct a short interview, known as a *viva voce*, after your Extended Essay (maximum of 4000 words) is complete. The Extended Essay is graded on a scale from A (highest) to E (lowest).

Extended Essays in physics may involve hands-on practical work in the following broad research areas: kinematics (including circular motion and aerodynamics), fluid dynamics, aerodynamics, hydrodynamics, material sciences (for example, stress, strain and Young's modulus), mechanics (for example, friction, cantilevers, gears and other simple machines), thermal properties, thermodynamics, capacitance, optics, electromagnetism, electric and magnetic fields, bio-mechanics, photovoltaics and waves (for example, acoustics harmonic decay on a guitar string and polarization) and, possibly, radioactivity. A number of Extended Essays in Physics are set in the context of sports, Tennis Racquet 'Sweet spots', sailing, energy generation or musical instruments.

You may collect and analyse raw primary data from secondary sources for your Extended Essay. This data may be related to astrophysics (for example black holes this topic is not recommended as it is too difficult how about Gravitation and the motion of the Planets), nuclear, atomic or particle physics or relativity (for example, lensing of gravitational waves is also very difficult and not recommended). However, experimental investigation may allow you to respond adequately to all of the criteria.

The scope of the Extended Essay is open-ended and the topic or phenomenon and associated theory under study may not appear in the IB physics syllabus, for example, inductance, the Hall effect, LED (light emitting diodes), semiconductors and superconductivity (in ceramic superconductors), may be suitable topic for an Extended Essay.

The Extended Essay may involve the collection and analysis of primary data from the published physics literature. However, the majority of Extended Essays also involve the collection and analysis of primary data often using relatively simple apparatus or experimental techniques. In other words, you carry out investigations in the physics laboratory and collect raw numerical data, which is compared to published data.

The most successful Extended Essays in physics are those based on a small number of clearly defined and easily manipulated independent variables and a quantifiable and easily measured dependent variable. Good physics Extended Essays often combine theory, experiment and iteration.

It should be noted, however, that it is the approach to the Extended Essay rather than the topic itself which will determine whether it is suitable for an Extended Essay.

Consider optics, a superficial Extended Essay in this topic may involve measuring the refractive indexes of several transparent liquids, by real and apparent depth using a travelling microscope. A more suitable topic may be a more open-ended investigation, such as an investigation of the optics of a zoom lens in a single lens reflex camera.

In summary:

- It is important to have a clearly and sharply focused Research Question to guide your Extended Essay. This should be generated by you and then discussed with your supervisor.
- You will then need to formulate an aim perhaps with a testable and justified hypothesis. It should be testable and falsifiable which means that your results should either support the hypothesis or show it to be false.
- You will need to be identify what data you plan to obtain and outline a procedure to obtain the raw data and process it.
- Once your supervisor has discussed safety issues then you may be allowed to start preliminary data collection. You may then need to modify your method and/or the apparatus. You may also be required to carry out a risk assessment before any practical work is allowed to commence.

Criterion A: The Research Question

A focused Research Question is the first step in a successful Extended Essay in physics and should be stated in the introduction (in bold), perhaps at the end of the introduction.

It must be clearly focused on the principles of physics, and capable of being answered within the word limit and time limitation (40 hours) of an Extended Essay. You may need some assistance from your supervisor to help formulate a research question from a topic you are interested in. You should not have several research questions since they may indicate a lack of clear focus.

The Research Question does not have to be a question; it could be a statement which outlines what you are trying to discover. A Research Question clearly states the variables that are to be manipulated, measured and analysed.

The Research Question should be naturally developed and then integrated in the introduction and not presented as an independent heading or added to the title page.

Research Questions

An example of a Research Question related to fluid dynamics:

To investigate the variation of the surface tension of water with temperature, via Jaeger's method.

Another example from sport

'Investigate a Tennis Racquet - Sweet and other spots' or 'The effect of light on degradable materials'.

An example of a Research Question from semiconductors:

To investigate the electrical properties of a n-p-n transistor amplifier.

An example of a Research Question from mechanics:

To investigate the relationship between the rate of penetration of steel wire with applied pressure on a block of frozen carbon dioxide (dry ice).

An example of a Research Question from engineering physics:

An investigation into the relationship between spin angular velocity and the period of precession in a small metal gyroscope.

Research Questions can come from a number of different sources. They may be formulated after carrying out an investigation (as part of your Internal Assessment) or watching a demonstration by your physics teacher. They may be stimulated by observation of the everyday world around you, such as the Leidenfrost effect, the Mpemba effect, soap bubbles and Faraday heaping, or seeing an exhibit in a science museum, for example, a ferro-fluid or a sand clock, or from viewing or using a piece of specialized scientific apparatus, for example, a Wilson cloud chamber or Kelvin's water dropper.

The Research Question must appear on the title page, abstract and in the introduction. The Research Question must be identical in all the places where it occurs in your Extended Essay. The Research Question may or not be the title of the Extended Essay, but the Research Question should not just be a reiteration of the Extended essay title, but carefully 'unpacked' and qualified. Generally, the Research Question should be different from the title of the Extended Essay.

The Research Question should allow you to apply your knowledge of IB physics and analysis of data in a personal way. You should not choose a Research Question that is a simple extension of your Internal Assessment (IA) or can be easily answered by looking at an IB physics text book.

There are a number of publications that can be sources of ideas or topics for investigation by a physics Extended Essay: School Science Review (*Figure 701*) *<http://www.ase.org.uk/journals/school-science-review/>* published by the Association for Science Education (ASE), Physics Review published by Philip Allan *<http://magazines.philipallan.co.uk/Holding-Page1.html>*.

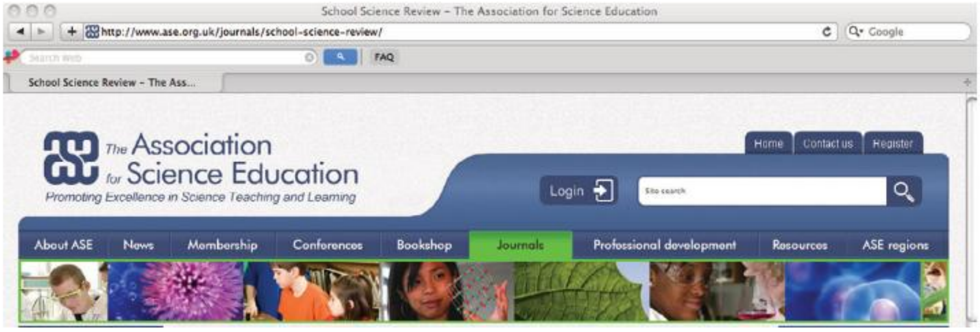


Figure 701 Screenshot of the ASE web site

EBSCO *<http://www.ebscohost.com/>* and Science Direct *<http://www.sciencedirect.com/>* (produced by Elsevier) are on-line databases subscribed to by many International schools. Find out from your Library Supervisor whether your school has access to EBSCO and Science Direct. There are also two CDs available from the on-line IB shop *<https://store.ibo.org/diploma-programme>*, called 50 Excellent Extended Essays, which contain useful exemplars, for supervisors and students.

Criterion B: Introduction

The introduction should include relevant background to the study, which means a summary of any theoretical or previous experimental work or observations that led to the Research Question. Background information will include references to published work in books, papers from the physics or educational literature and on-line web sites. It may also include a brief review of competing hypotheses or interpretations of data. You should also briefly discuss any personal motivation and personal involvement you have in selecting your topic of investigation worthy of at least 40 hours of work. However, not at the expense of presenting the physics principles relevant to the Research Question.

There are several aspects to this criterion: the physics context and the importance and significance of the investigation. In order to score the highest mark all aspects must be addressed. In order to demonstrate the physics context and significance and worthiness of the research question you need to present a summary of the physics literature (typically published papers and journal reviews) and other external sources, such as book chapters, that you have consulted. You should avoid making any sweeping statements with no attributable sources. Only immediately relevant and well-focused physics, relevant and pertinent to the Research Question, should be in the Extended Essay.

The detailed development of the relevant theory belongs to a separate chapter of the Extended Essay. The content required for the introduction and the abstract are different.

The introduction is the first opportunity for the student to show knowledge and understanding of relevant physics, to demonstrate academic strength. Any statement of a hypothesis does not belong to the introduction. A hypothesis does not replace the required physics content.

Criterion C: Investigation

This criterion covers both data collected from printed sources as well as data collected by the candidate (through doing experiments in the physics laboratory). You will be judged about the range, accuracy and appropriateness of the data you have collected as well as the method used to obtain the raw data. You must show strong evidence of planning and exploratory investigative work and an awareness of uncertainties and limitations inherent in techniques and apparatus. You should explain how information from your sources (on-line and print) helped you decide on your approach. The relative merits and disadvantages of other methods should be discussed.

Your method must be reproducible and full details of all apparatus and instrumentation should be given including the random uncertainty (tolerance) and range, where appropriate. Any modifications and refinements to a well-known protocol or method, or constructed apparatus, should be outlined and justified. Results should be compared to the literature values and known relationships. Basic/well-known equations should not be derived nor the definitions of basic terms given. You should not used specialised equipment in university or industrial laboratory as 'black boxes' without really understanding and explaining their working. You should not tolerate clear and serious flaws in your procedure relying on the evaluation as an (invalid) excuse.

Criterion D: Knowledge and understanding of the topic studied

You can display knowledge and understanding of the topic by presenting relevant background academic information and explaining how this relates to the Research Question. You can demonstrate understanding by referring to the variables that may affect the investigation and by referring to the significance of the outcomes. You should provide explanations and justifications for your apparatus and methodology and choice of techniques to process, present and analyse your data. You should also explain why alternative approaches were considered but not adopted.

Equations and symbols should be clearly explained and appropriate units stated for physical quantities. Where possible and appropriate the equation should be derived or justified mathematically and from the principles of physics. Any weaknesses or limitations in the law or relationship described by the equation should be outlined. You should not simply present mathematical formulas and 'plug' in numbers without a clear understanding of the relationships of the variables involved. Relevant and appropriate diagrams to illustrate physics principles are a requirement of this criterion.

You should demonstrate appropriate knowledge of mathematics and physics. You should have a firm grasp of any physics concepts relevant to your Extended Essay. You do not need to explain and justify simple physical facts, principles or concepts from the core of the IB physics programme. For example, an Extended Essay involving sound waves does not require a derivation of the wave equation and definitions for terms such as wavelength and frequency. A hypothesis may be present in your Extended Essay, but the focus of the Extended Essay must be centred on the Research Question.

Criterion E: Reasoned argument

A convincing and coherent argument in relation to resolving your Research Question is the key to the success of the development of a well-written Extended Essay. You should set your ideas clearly and logically and analyse the strengths and weaknesses of your claims and refer explicitly to the processed and displayed data. You should not arrive at a conclusion to your experimental work without questioning any assumptions or considering possible competing explanations (counter claims). You should attempt to analyse the validity and reliability of any secondary sources of data you have accessed. This is the criterion that often distinguishes the excellent extended essays from the mediocre. High marks for this criterion requires close reasoning and good communication.

Criterion F: Application of analytical and evaluative skills

Criterion F requires you to apply appropriate mathematical, graphical and evaluative skills. This includes deductive reasoning (generalizing from examples), graphical analysis and mathematical analysis (where appropriate). Critical thinking and reflection are important skills that need to be demonstrated under this criterion. There should be reference to alternative perspectives, competing physical models, analogies and comparable situations.

Terms to describe graphical relationships like 'directly proportional', 'inverse square', 'exponential', and 'inversely proportional' should be used correctly. Log-log plots may be necessary if simple power relationships are involved. Results should not be 'forced' to fit an expected linear relationship if one was not observed. Errors bars should be displayed on graphs. Check to see if the fit of a line graph is constrained by making the line of best fit pass through the origin (0,0). Graphs, where appropriate, should have equations, lines or curves of best fit,

You should show a through understanding of the raw data collected, the magnitudes of uncertainties, systematic errors and limitations of the experimental design. The rules for significant figures should be followed and truncation of final figures clearly shown. Error propagation should be performed for calculations, including averages, and the relative importance of errors and limitations should be discussed. A common mistake in data tables is to present the uncertainty (absolute error) of measured value that did not match the digits of the value, for example, (2.5 ± 0.05) cm is inconsistent. It is important to inform the IB Examiner how uncertainties are determined but this should **not** become too laborious or the main focus of the analysis.

A typical question to answer is "is the theoretical value within the uncertainty range of the experimental value? If not, why?". A reliance only on mathematical software does not satisfy the need to relate the analysis and evaluation to physics.

You should also analyze the validity of your secondary resources, by careful reading and cross referencing to test their reliability.

Criterion G: Use of language

There are two aspects to this criterion: the use of clear and precise language and the use of terminology appropriate to the physics area. You need to have a clear and precise style and show an understanding of and fluency in the main physics terms associated with the topic. Any new and unusual terms, units and mathematical formulas need to be introduced and defined. The use of non-SI units is not encouraged and any non-SI units should be justified and a conversion to SI units given.

Diagrams are a powerful tool in describing and explaining physics facts, principles and concepts. Diagrams, selected photographs (which must add value to the Extended Essay), data tables and graphs must always be clearly and completely annotated with titles, units and symbol identification thus strengthening communication.

Equations, tables and graphs must be numbered and referred to by number in the text. Such careful presentation is in line with scientific language and enhances its clarity and precision.

There is no requirement to write in the passive voice, for example, '*the end of the cantilever was depressed by the addition of a mass*'. You can use the first person singular, active voice, for example, '*I depressed the end of the cantilever by adding a mass*'. However, you must be formal, consistent and use key physics terms accurately.

Criterion H: Conclusion

In an effective conclusion, which must be consistent with the body of the essay, you should restate the research question and outline the extent to which it has been answered, dealing also with issues that have not been resolved and suggesting future research directions. You should refer to your quantitative outcomes (processed data) but must not overstate your findings and always be tentative in your conclusions. Use statements along the lines of the following: '*the graph suggests a possible relationship between variables X and Y*'. You should not present new material in the conclusion and you should not repeat preceding argument and explanations.

Criterion I: Formal presentation

The layout of the Extended Essay should be correspond to the layout and style of scientific papers. It should not follow the same layout for an Individual Investigation, the assessment criteria for each component are different, and in following the structure of an Individual Investigation for the Extended Essay, there is the risk that you confuse the requirements of both components and subsequently lose some focus of the task in question.

An Extended Essay should flow and also not be broken up by changing the font or leaving unnecessary spaces. It should not have the appearance of a lab report consisting of almost unrelated parts.

You should follow a well-known format for correct referencing, for example, MLA (Modern Language Association). A table of contents must be included and the main body of the essay page numbered. All references cited in the core of the Extended Essay should appear in the Bibliography. Citations in the core should carry details, possibly as footnotes. When using a numbered footnote identifying a source, you should make sure that the number (superscript) is not confused as an exponent in an equation.

You should not use the Appendix as a way of keeping the word count below 4000 words. New information should not be introduced into the Appendix since the Examiner is not required to read these pages. The Extended Essay should be entirely complete and totally understandable without the help of an appendix.

Examples of correct referencing:

Auty, G. (1999) Investigation of the zoom lens. *School Science Review*, June 1999, 81 (294), 118-122.

Snoeijer, J.H., and K. van der Weele (2014) Physics of the granite sphere foundation. Date accessed: 12.9.14

<http://dx.doi.org/10.1119/1.4886365>

Kerr, G., (2014) Physics for the IB Diploma. *IBID Press*.

Criterion J: abstract

Writing an abstract is a difficult requirement for many students and this is task is left to the end after you have written the body of the Extended Essay. It is suggested you consult any reputable journal and examine abstracts from published physics papers.

An abstract should include the following: the Research Question, an outline of the method, a summary of the data collected and its analysis, a discussion of important assumptions and errors, and the conclusion.

The abstract must match the research question and give sufficient details of how the investigation was undertaken. It should not be page numbered since it is not part of the Extended Essay. Abstracts that contain more than 300 words will score zero.

8.1 Introduction to Data-logging

'The use of information communication technology (ICT) is encouraged throughout all aspects of the course in relation to both the practical programme and day-to-day classroom activities.'

© IBO 2014

The use of information communication technology (ICT) should be encouraged throughout all aspects of the course in relation to both the practical programme and day-to-day classroom activities.

Data-logging is an electronic method of gathering and recording physical measurements; electrical sensors provide signals which are calibrated and recorded by a computer system. Data-logging software not only automates the process of data collection but also provides tools that help in the process of analysing and interpreting the data.

Advantages of data-logging include:

- The experimental results can be seen on the computer screen as the experiment is being monitored.
- Accurate readings can be taken frequently in a short space of time.
- Time is not wasted collecting raw data.
- The computer can automatically plot an appropriate graph.

Experiments and processes that are amenable to data logging, given the appropriate software and sensors are available include the following:

8.1.1 Motion sensor

- General motion
- Motion along an inclined plane
- Freely falling objects
- Motion of oscillating masses attached to a spring
- Newton's Second Law of Motion

8.1.2 Acceleration sensor

- Collisions and momentum
- Acceleration in an elevator, cars and roller coasters

8.1.3 Force sensors

- Forces during collisions
- Force exerted by an oscillating mass and of a swinging pendulum
- Mechanical equilibrium investigations

8.1.4 Temperature sensor

- Charles' law
- Determination of Specific heat capacity
- Heating and cooling curves

8.1.5 Light intensity sensor

- Transmission of light through a transparent material
- Interference and diffraction of light

8.2 Data logging within a narrowly focused task

You may use data-logging software to perform a traditional experiment in a new way. Use of data-logging software is appropriate with respect to assessment if you decide and input most of the relevant software settings, for example, sampling rate.

Data-logging software that automatically determines the various settings and generates the graphs is inappropriate with regard to assessment. This would be appropriate if you are responsible for choosing the number of data points to be collected.

To decide whether an experiment is suitable for assessment, the following guidelines must be followed.

8.2.1 Data collection and processing

Use of software for graph drawing is appropriate as long as you are responsible for most of the decisions, such as:

- what to graph
- selection of quantities for axes
- appropriate units
- graph title
- appropriate scale
- how to graph, for example, linear graph line and not scatter.

Note that a computer-generated graph is acceptable.

Example 1 Use of motion sensor to study acceleration along an inclined plane

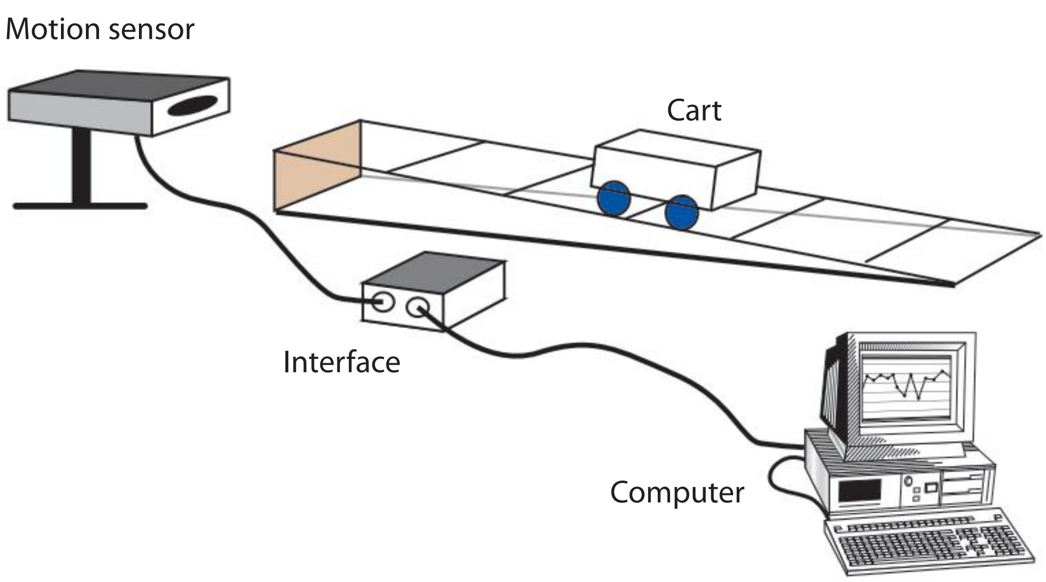


Figure 802

In this investigation, (see *Figure 802*) the student wants to find out whether the acceleration of the cart along the inclined plane is uniform or not.

The investigation was carried out and the computer generated a displacement-time graph.

The student then measured the gradient of various tangent lines to obtain a results table showing the velocity at different times. He used this results table to plot a velocity - time graph. He used the noise the data logger makes when there is no motion as a basis for the uncertainties of the velocity values. The process is shown in *Figure 803*.

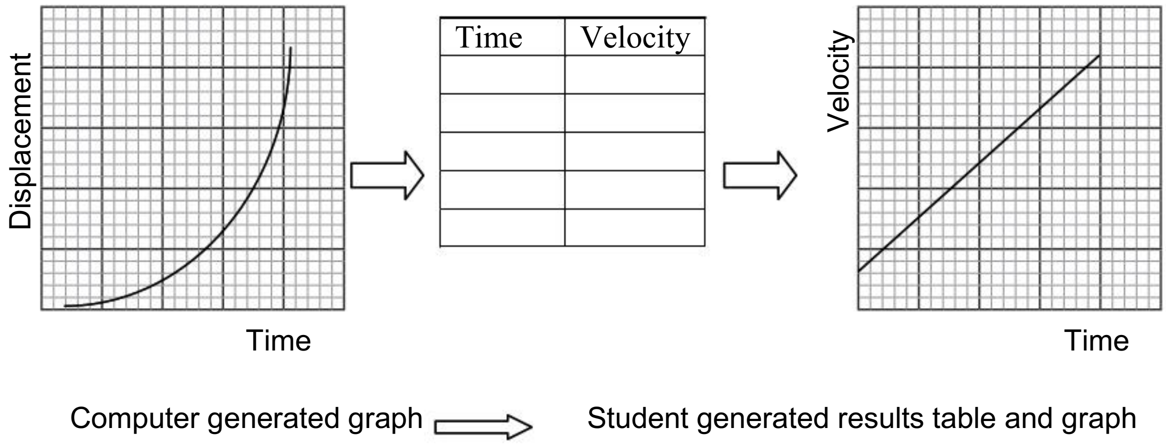


Figure 803 An example of data collection and data processing

8.3 Data logging in an open-ended investigation

Example

Exploration

Students must come up with their own investigation, teacher suggestions are not acceptable.

As an example, suppose a student decided to use a motion sensor to track the motion of the muffin cup. The motion sensor is connected to a computer which generates displacement-time and velocity-time graphs. The software is fully automated and all the settings were pre-set. From the graphs, the terminal velocities will be obtained.

By putting one muffin cup inside another, the mass is changed but the surface area and the shape of the object is controlled.

The student carried out preliminary tests where he dropped the muffin cup from various heights. A drop height that produces a reasonable set of data is identified.

The student repeated the experiment twice to produce three sets of data for each mass. The differences can be used to estimate the uncertainty and assess reliability.

Analysis

The student used the velocity time graphs to obtain the terminal velocities for the different masses. A results table which shows the variation of the terminal velocity with mass is constructed. For each mass, there are three measurements of the terminal velocity. The average value is calculated and the uncertainty of the averaged value of the terminal velocity is obtained.

Using a suitable spreadsheet with the processed data, the student was able to plot a graph of the logarithm of the terminal velocity against the logarithm of the mass.

Check to ensure:

1. all uncertainties have been correctly propagated.
2. the presentation of the processed data is accurate, with appropriate scales, labelled axes and correct units.
3. data points are plotted accurately and a line is suitably best fit.

8.4 Using Microsoft Word functions

8.4.1 Formatting tables

To insert a table using this method, simply click the Insert Table toolbar button when your cursor is positioned at the place in your document where you would like the table to begin. A grid will pop up allowing you to select how many rows and columns you would like your table to contain. Simply use your mouse to select the number of rows and columns by highlighting the boxes (text at the bottom of the grid will indicate what your selection is). When you have specified the correct number of rows and columns, simply click once, and your table will be inserted.

You can still customize your table after it is inserted by right-clicking on the table handle (the double-headed arrow at the top left corner of the table) and using the options on the shortcut menu to make changes.

Group	Ultra violet intensity/lux	5 days	10 days
Control	10	70.3 ± 2	90 ± 10.5
Test	10	60.4 ± 1.5	78 ± 7.9
Control	17	75.7 ± 8	100 ± 23
Test	17	52.2 ± 2	81 ± 26.7

Figure 808 Concentration of chemical X in sample after treatment

Look at the results in *Figure 808*. Two columns of data have been placed in the same cell, with the data arranged using the space bar.

Tables should be created with the correct number of rows and columns. You can also add new rows and columns to an existing table by right clicking on the table, selecting 'Insert' and choosing to insert new rows and columns above or below the existing rows or columns.

It is also possible to insert multiple rows/columns to a table by highlighting the number of rows/columns you require on existing rows/columns. For example, if you would like to add three columns to the left of your table, highlight the first three columns, right click and choose "Insert Columns to the Left".

8.4.2 Inserting symbols

When writing the report for your Individual Investigation you may need to use a number of special symbols from Microsoft Word. They can be accessed by selecting the Insert pull down menu and then choosing Symbol. Click on the symbol you want, then on 'Insert' and 'Close.' A small selection of mathematical and scientific symbols and their use is shown below in *Figure 809*.

Special symbol	Use or meaning
α	Proportionality
→	Reacts to form
Σ	Sum of
π	Pi (mathematical constant)
Ω	Omega (symbol of electrical resistance)
√	Square root
±	Plus or minus (indicates an absolute error or uncertainty)
°	Degree (used to indicate a temperature in Celsius)
÷	Division
⇌	Reversible reaction
≈	Approximately equal
λ	Wavelength
θ	Angle

Figure 809 A selection of special symbols

8.4.3 Inserting charts and graphs

It is very easy to insert charts and graphs from Excel into Word. Select the Excel Spreadsheet so that it is highlighted and copy it by clicking "Ctrl+C." Mac users click "Cmd+C." In the Word document, click where you want the chart to appear. Paste the spreadsheet into the document by holding down the Ctrl key and hitting "V." On a Mac OS, click "Cmd+V."

With your cursor next to the data, click "Paste Options." To input the spreadsheet as a Word table, click "Keep Source Formatting." The chart will look like it did in Excel. Click "Match Destination Table Style" if you want the new graph to look like others you are using in the document.

8.4.4 Creating short cuts

You will probably have to write cm^3 a number or times for your reports. You type in cm^3 and then highlight the three and change into a superscript by selecting Format, Font and then Superscript. This is quite a long process and can be avoided by using a short cut:

Type cm^3 and format it to cm^3. Highlight it and choose Tools and AutoCorrect options. cm^3 will be present in the 'with box'. Type cm^3 in the 'Replace box' and select the 'Formatted text' circle. The cm^3 in the 'with' box will change to cm^3. Click 'Add' and 'OK'. Now when you type cm3 it will be automatically changed to cm^3. The short cut can be easily deleted.

8.4.5 The Equation Editor

If you want to include an equation in your report that includes division then you need to use the Equation Editor (*Figure 810*). Select the Insert pull down menu and then choose Object followed by Microsoft equation.

A special toolbar will also appear on your screen. Use the toolbar to select symbols, brackets, etc. to place in the box. You may also type numbers and letters into this box. At the top of the screen, a simplified toolbar lets you select font size (including subscript and sub-subscript), style, and alignment.

Figure 810 A screenshot of the Microsoft Equation Editor

Here is an example of a physical chemistry equation (Graham's law) written and then inserted using the Microsoft Equation Editor: $\frac{rate\,1}{rate\,2}=\sqrt{\frac{molar\,mass\,1}{molar\,mass\,2}}$.

8.5 Using Excel functions

8.5.1 Plotting graphs

Graphing data on Excel

Type in your data, with your X axis data (independent variable) in the left-hand column, and your Y axis data (dependent variable) in the right column. Highlight your data (*Figure 811*). To the data is displayed to two decimal places Place your cursor over one of the data cells. Control click. In the drop-down menu that appears, choose "Format Cells." "Number" tab, and choose "Number" in the scroll-down menu. Type in "2".

With data still highlighted, choose the Chart Wizard icon in the menu bar (looks like a bar graph). Choose "Scatterplot" as your type of graph, and choose the version that has no line on it. Click At Step 2 (Source Data), click "Next." On Step 3 (Chart Options), give your graph a suitable title (your dependent variable versus your independent variable), and label your X and Y axes, making sure you include suitable units of measurement. Click "next," and on Step 4 (Chart Location), save graph as a "New Sheet." Change the name from "Chart 1" to a title that describes your graph (*Figure 812*). Click on "Finish."

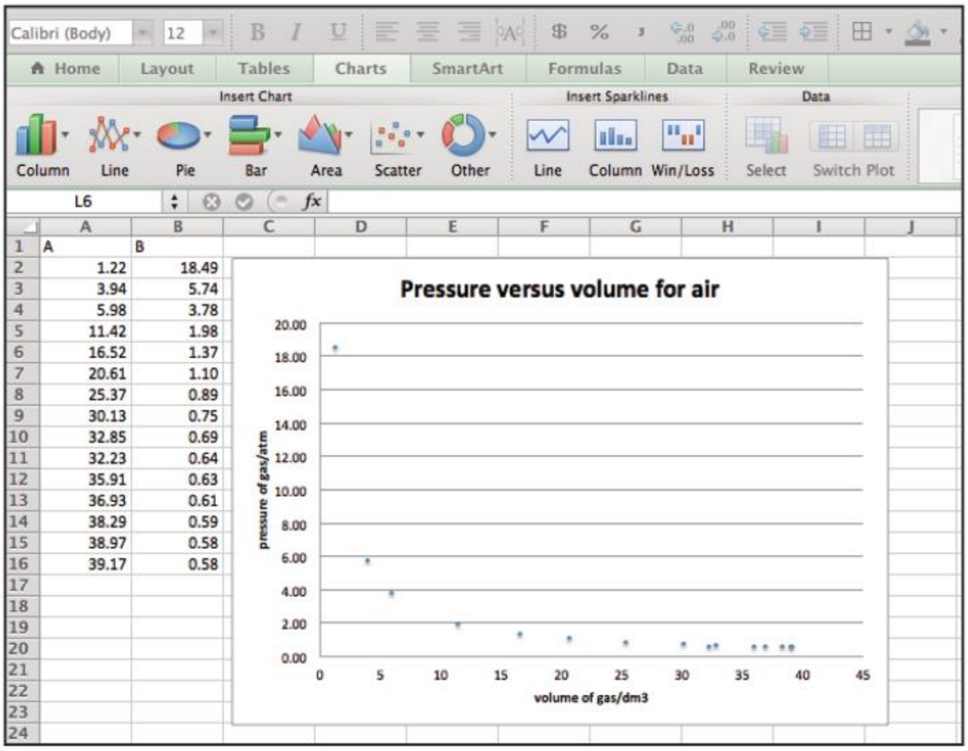


Figure 812 Gas law data plotted

8.5.2 Formatting graphs

To add a trend line and equation put your cursor directly over a data point, so that the point coordinates pop up. Control-click on this point and choose “Add Trendline” from the drop-down. For Trendline Type, choose the type of line that appears to best match the pattern your points make. This may be trial-and-error – you may have to do this more than once to find the best-fitting, but in this example a power trend line is appropriate. Click on the “Options” tab, and click on the “Display equation on chart” and “Display R-squared value on chart” at the bottom of the spreadsheet (*Figure 813*).

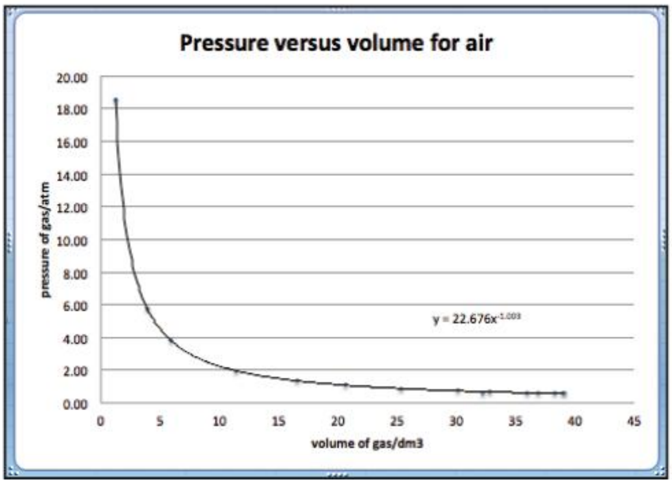


Figure 813 Gas law data plotted with power trendline

If you need to read X or Y values that are off the axes of your graph, you can forecast the trendline on your graph forwards or backwards to reach those values. Control-click on your trendline and choose "Format Trendline." Then, under "Options," you can forecast forwards or backwards however many units are needed. Then click "OK."

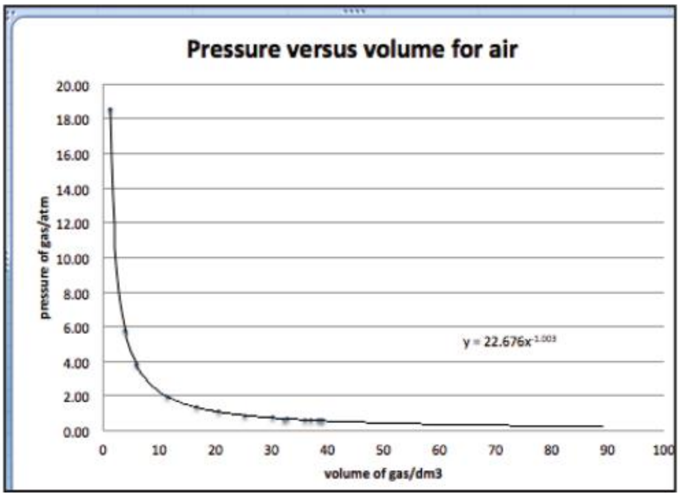


Figure 814 Gas law data with a forward forecast of 50 units

You can change the numbering system on your axes and add extra tick marks to your axes by formatting each axis. Put your cursor on the axis you want to format and Control-click, and choose "Format axis." See *Figure 814*.

You can choose to add additional tick marks to your scale by clicking on the "Colors and Lines" tab and clicking on the "Minor tick mark type" button of your choice. You can also choose the manner in which the tick marks are labeled. You can change the way the axes are labeled by choosing the "Scale" tab.

8.6 Using the Internet for research

8.6.1 Searching

The Internet is a vast store of scientific information that can be highly relevant, detailed and up to date. It can provide information ranging from data on atmospheric carbon dioxide levels and stem cell medical research to photographs from the Hubble space telescope.

Unfortunately, much information can also be irrelevant, and you can waste much time on unproductive searches. Search engines such as Yahoo, Google, Altavista and Ask Jeeves produce best results when the search request is made as specific as possible, using their advanced search facilities.

Many search engines, such as Google, use a + sign to link words in a single site together, or contain advanced search buttons to match the site with all the words that are being searched for.

For example, typing in 'nanotechnology research + singapore' will only report web sites that contain information about nanotechnology research in Singapore.

9.1 Stages of the Group 4 Project

The implementation of the Group 4 Project can be divided into three stages: the Planning stage, the Action stage and the Evaluation stage. The highlights of each stage are shown below in *Figure 901*. Note that the time allocation for the Group 4 Project is 10 hours. Remember that the project does not need to include a hands-on experiment.

Project Stage	Suggested Time Allocation (hrs)	Emphasis
Planning	2	All IB students meet together. Students brainstorm and decide on a central theme. It is also possible that the IB teacher will decide on the central theme. The central theme must give opportunities for students to raise their awareness of the moral, ethical, social, economic and environmental implications of using science and technology. In smaller sub-groups, students identify a problem to be investigated that is related to the central theme. Each group decides on the investigations that can be conducted to address the problem identified. The investigations must give opportunities for students to apply their ICT skills. Having decided on the investigations, students submit a plan listing the materials and equipment and methodology to the teacher. If applicable, a risk assessment form may also be submitted.
Action	6	In small groups, students conduct the investigation. The groups can be a mixed subject group or a single subject group. Students must collaborate effectively during this stage. Students must pay close attention to safety, ethical and environmental considerations during this stage.
Evaluation	2	Students document their findings, successes and failures by utilizing one of the following media: a poster, web pages, power point presentation. Students share with other students highlighting their group's findings, successes and failures. Special guests (e.g. parents, school board, officials of local communities) may be invited during the presentation.

Figure 901 The stages of the Group 4 Project

9.2 Examples of Group 4 Project themes

An example of a central theme is "The science of cooking." One sub-group can investigate the properties of different cooking oils e.g. olive oil, corn oil, lard. **Physics** students can investigate the cooking efficiency of the different types of oil by measuring the specific heat capacity, the thermal conductivity and boiling temperature of different types of oil. **Chemistry** students can analyse food fried from different oils and measure the amount of saturated fats transferred to it. **Biology** and **Environmental Systems and Societies** students can investigate the effect of discarded cooking oils on the environment. In this example, the students can decide which is the best cooking oil based on energy efficiency, healthiness and environmental friendliness. Note that the best cooking oil is decided from different perspectives.

Figure 902 shows other examples of Group 4 investigations.

Topic/theme/ context	Chemistry	Physics	Biology
School swimming pool	Determination of chlorine content via redox titration; study of the decomposition of chlorine water in the presence of sunlight; study of chemicals used to chlorinate pool water; relationship between free chlorine and pH; effect of urine in pool water	Determination of physical properties of chlorinated water, e.g. density, specific heat capacity, refractive index; surface tension, boiling point, melting point; change in pressure with depth, heat loss due to evaporation; measurement of heat gain during day, heat loss at night	Culturing of bacteria, algae (effect on pH) and fungi; effect of changes in chloric(I) acid concentration and pH on microorganism growth; pathogens present in polluted pool water from faeces
Keeping cool	Determination of the amount of sodium chloride and urea in sweat; investigation of the reactions in cool packs. Study of chemicals used in air conditioners: CFC, HFC, impact on global warming	Investigating the ability of different surfaces and colours in reflecting solar energy; studying the design and effectiveness of a cool box, air conditioner and thermos flask.	Investigation of the changes that occur in the souring of milk or red wine; measuring the transpiration rate under different environmental conditions

Figure 902 Some ideas for Group 4 Projects

9.3 Self motivation

Listed below are some ways by which you can demonstrate your self motivation and perseverance.

9.3.1 Planning Stage

- arriving to meetings or brainstorming sessions on time.
- coming to meetings or brainstorming sessions prepared. Once you have discovered the general theme of your Group 4 project you are expected to conduct some research about the topic.
- contributing positively to the brainstorming session. Be supportive of ideas.
- staying focused during the meeting. When you are not speaking, be an active listener. Take down notes if you hear something important.
- submitting the planning sheet on time (if applicable).

9.3.2 Action Stage

- Ensuring that the apparatus chosen and methodology for the project will give precise and reliable results.
- Presenting a creative approach to the problem.
- Making sure that you know and understand the methodology to be performed during the investigation. This includes being able to identify the data to be collected and how these data are to be collected.
- Finding and suggesting ways to solve the problem if the team is encountering difficulties with the project.
- Adapting to new circumstances. If an unexpected result is obtained, then you must try to make sense of this result or perform additional measurements to verify the reliability of this result.

9.3.3 Evaluation

- Approaching the Project with integrity. This includes acknowledging resources that were used and not altering the data to fit a preconceived **hypothesis**.
- Presenting or contributing positively towards an effective method to present your findings, successes and failures to other teams.
- Being available to other teams to help them better understand your Group 4 Project.

9.4 Working within a team

A good team will work more effectively than individuals.

9.4.1 Planning Stage

During the Planning Stage of the Group 4 Project, your ability to work with a team can be demonstrated by:

- Arriving to the meetings and planning sessions on time. This suggests that you value the time of your team mates.
- Responding to a different idea in a supportive fashion. Look at the strength of the idea first before stating its perceived weaknesses. This shows you value your team mates' ideas and this can encourage further exchange of ideas.
- Readily sharing ideas and asking questions.
- Listening to and not interrupting the speaker.
- Accepting and following the collective decision of the team even if you do not agree with it.
- Taking the initiative to contact other members of the team to update yourself should you miss a planning session.

9.4.2 Action stage

During the Action Stage of the Group 4 Project, your ability to work with a team can be demonstrated by:

- Leading by example.
- Completing the task assigned to you to the best of your ability and, if necessary, seeking assistance from other members of the team.
- Readily assisting other members of the team to the best of your ability.
- Acting responsibly and not performing any action that will place the other members of the team or the other teams in unnecessary danger. This includes seeking assistance from your IB teacher in matters involving a breach of safety.

Due to some personal differences, it is possible that your team or a few members of the team do not work well together. This will prevent your team from completing the Group 4 project well. It is suggested that you take time to discuss the problem as a team. During the discussion, it is important that the team stick to the issues and avoid personal attacks. Everyone should be courteous, respectful of other people's opinions, and open to other people's ideas. If a problem concerns one or two individuals only, then someone can act as a moderator and discuss the issues privately with this individual(s).

As much as possible, the team must resolve the issues amongst themselves quickly. Discussing the problem with your IB teacher should be the last resort. Also, requesting to be transferred to another group suggests poor collaborative skills on your part.

9.4.3 Evaluation stage

During the Evaluation stage of the Group 4 Project, your ability to work with a team can be demonstrated by:

- recognizing the strengths of the team and of the individual members of the team. This can be done by contributing positively to the presentation of the team's successes.
- Suggesting ways and methods by which the weaknesses of the team are eliminated or reduced. This includes proposing ways which will prevent the same mistakes being committed again.

9.5 Self-reflection

You will be asked to reflect and write a self evaluation report. Below are suggested questions that can help you conduct a thorough self-reflection.

The Group 4 Project is a valuable collaborative task and evidence of your involvement will be in the form of a short personal statement and a declaration on the IA coversheet.

9.5.1 Planning stage

- Did you contribute positively towards the planning of the investigation? If yes, what preparations did you do? Could you have contributed more? What prevented you from doing so? How can you overcome these obstacles?
- If you did not contribute positively, what prevented you from doing so? How can you overcome these obstacles next time?
- Were you able to accept differing ideas easily? Did you attempt to look at both the strengths and weaknesses of a proposal? Did you analyse the proposal objectively? If not, what prevented you from doing so? How can you overcome these obstacles?

9.5.2 Action stage

- Did you have the necessary skills to conduct the investigation efficiently and safely? Which skills were you good at? Which skills do you need to improve on? What do you need to do to improve these skills?
- Did your actions help promote effective collaboration amongst the different members of the team? What could you have done better for the team to improve collaboration amongst the members?
- What went well for the team? Why did the team encounter such difficulties? What could you have done better for the team to help it complete the investigation effectively?
- Did you help the team manage the time effectively?

9.5.3 Evaluation

- What insight(s) did you gain from the conclusions obtained?
- Was the team able to present its findings accurately and clearly? If yes, how was team able to do it? If not, what prevented the team from doing so?
- Did you contribute positively towards the team's presentation? What could you have done better to help the team present its findings more accurately and clearly?

10.1 Uncertainties and errors

No measurement is perfectly accurate or exact. There is always an uncertainty associated with an experimental measurement, no matter how carefully the measurement is recorded. The **uncertainty** in a measurement is the doubt that exists in its value. The uncertainty is equal to the range within which the measurement is likely to lie. A later section in this chapter will describe how the uncertainty in a measurement can be quantified.

In *Figure 1001* below, the length of the object is measured to be 2.15 cm. Note that the last digit '5' is only an estimate and it is therefore doubtful. The reading can be anywhere between 2.14 cm and 2.16 cm. Therefore there is a doubt or an uncertainty of 0.01 in the measurement.

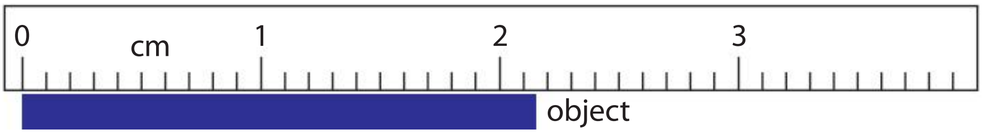


Figure 1001 The measurement of the length has an uncertainty

In many investigations in Physics, the measurements will be used later to obtain some other physical quantity. For example, measurements of lengths could be used to calculate the area of a surface. The area obtained could be used to determine the pressure exerted by a force. The area and pressure obtained are examples of derived values. Therefore, the derived values will also have their corresponding uncertainties.

In many instances, you will also be required to utilize the measurements taken to obtain a value for a physical constant. An example of this physical constant is g which is the gravitational field strength on the Earth's surface. The correct value of g is 9.8 m s^{-2}. If your experimental value is 9.6 m s^{-2}, then the experimental value has an error. The **error** of a derived experimental value refers to the difference between the derived experimental value and the true value of a physical quantity being measured. In this case, the experimental error is equal to 0.2 m s^{-2}.

Note that an experimental error is not a blunder or mistake that is committed during the experiment or during the processing of results. Instead, it is an estimate of how much that measurement is likely to deviate from the true value of the quantity.

The estimates of errors and uncertainties are important because they are essential in drawing valid conclusions from measurements and experimental results. For example, when investigating whether the mass of a simple pendulum has an effect on its period, the following values were obtained:

Period = 1.15 s at mass = 40 g

Period = 1.19 s at mass = 60 g

Is the difference between the two periods significant? Without knowing the uncertainty, it is not possible to know.

If the uncertainty in the first period measurement is 0.04 seconds or more then the difference in the two values of the period is insignificant. This is because the range of values for the first measurement is 1.11 s to 1.19 s. Therefore, the range covers the value of the second measurement. However, if the uncertainty in the period is 0.03 s or less, then the difference is significant.

In many Investigations, you will be measuring many primary quantities and using these measurements to calculate the required physical quantity. The error in the required physical quantity will depend on the uncertainties in the measurement of the primary quantities. It is therefore important that you are able to estimate the uncertainties in the different measurements and calculate the ensuing errors in the derived values.

10.1.1 Accuracy and precision

The **accuracy** of a measurement describes how close this measurement is to the correct value of the physical quantity. If the measurements are close to the correct value, then they are described as being **accurate**. The accuracy of the measured value would depend on the instrument used, the level of manipulative skills of the experimenter and the methods or techniques utilized by the experimenter. As an example, the accepted correct value of *g* (gravitational field strength) near the Earth's surface is 9.8 m s^{-2}. A measured value of 9.7 m s^{-2} is more accurate than 9.5 m s^{-2}, the first measurement being closer to the correct value.

The **precision** of the measurement describes how close this measurement is to other similar measurements when the process is repeated. If a series of measurements is repeated during an experiment and the values that are obtained are close together, then the results are described as being precise. The lower the uncertainty is in the measurement, the more precise is its value. As an example, a measured *g* value of (9.7 ± 0.5) m/s^2 is less precise than a *g* value of (9.5 ± 0.1) m/s^2, since the uncertainty in the first measurement is larger.

The type of measuring instrument used can affect the precision of a set of measurements. For example, a ruler can measure up to the nearest millimetre (1 mm), a vernier caliper can measure up to the nearest 0.1 mm and the micrometer screw gauge can measure up to the nearest 0.01 mm.

The precision of the measurement will also depend on the skill of the experimenter. Two students may use the same instrument but use them with varying levels of skill which could result in measurements of different precision.

If the same procedure is carried out by a number of different students and the results are similar to the original one, the procedure is described as being **reproducible**.

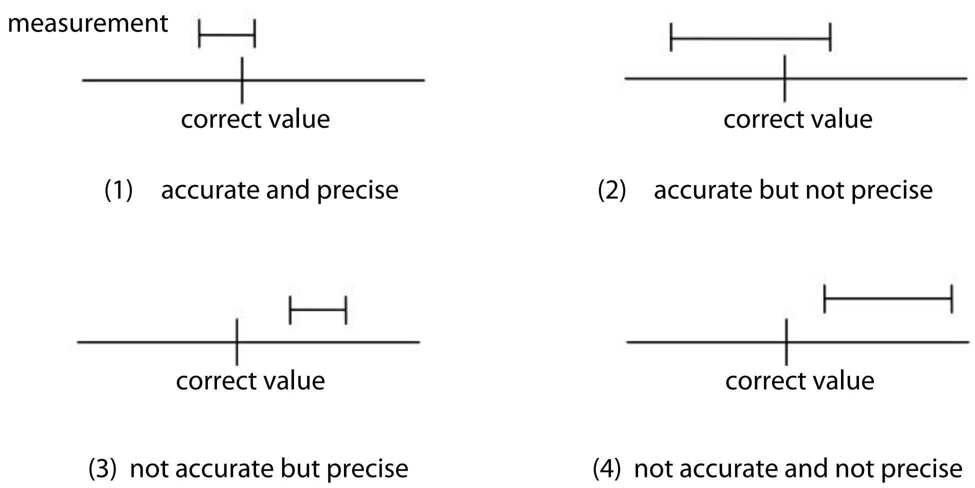


Figure 1002 The difference between accuracy and precision

In *Figure 1002*, measurements (1) and (2) are both accurate since the correct value is within the limits of their uncertainties. Measurement (1) is more precise than measurement (2) because of its smaller uncertainty. Measurement (3) is not accurate but is precise. This is because the correct value is outside of the range of its uncertainty but the uncertainty is very small. Measurement (4) is neither accurate or precise.

The difference between precision and accuracy is further illustrated in *Figure 1003* (overpage). The Figure shows numerous darts that were thrown at the centre of the board (or the bull's eye) which represents the target and thus, is the correct value. In Figure (a), the darts are closely clustered at the centre and the average position is near the centre of the board. The darts then form a pattern that is both accurate and precise. In (b), the darts are tightly clustered but the average position is far from the centre of the board. The pattern formed by the darts is then precise but not accurate. Figure (c) represents positions which are spread out far from one another. However, the average position of the darts is close to the centre of the board. Therefore the pattern formed by the darts is accurate but not precise. Finally, Figure (d) represents a pattern that is neither accurate nor precise. The darts are spread out and the average position is far from the centre of the board.

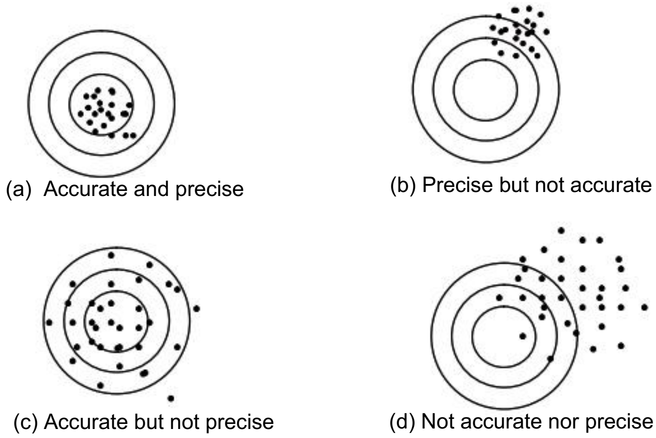


Figure 1003 An illustration of the difference between accuracy and precision

10.1.2 Reliability and validity

A measurement is **valid** if it is relevant to the investigation. For example, when determining the focal length of a convex lens experimentally, the distances from the lens to the image and from the object to the lens are valid data. The data are valid because through the lens equation ($\frac{1}{v}+\frac{1}{u}=\frac{1}{f}$, where v = image distance, u = object distance and f = focal length) the focal length can be determined. The volume of the lens and the thickness of the lens are not necessary to obtain the focal length of the lens. Therefore in this case, the volume and thickness of the lens are invalid data.

The **reliability** of a measurement is used to describe its consistency and stability and therefore, its trustworthiness. When the same measuring instrument and the same measuring technique produce a measurement that is consistent and stable when repeated over time, then the measurement is reliable and trustworthy. As an example, a reliable method to determine the period (*time for one oscillation*) of a simple pendulum is by measuring the time for 20 oscillations and then dividing the time obtained by 20. This is a better method than measuring the time for one oscillation 20 times. This is because there would be a greater chance of obtaining similar results if the first procedure is repeated.

Another way of improving the reliability of a measurement is by doing repeat measurements. A set of measurements obtained is usually distributed evenly around the correct value and when averaged, would result in a value that is close to the correct value. The mean value is then more reliable than a single measurement.

10.1.3 The origins of measurement uncertainties and experimental errors

The measurement process can be improved but uncertainties and errors cannot be eliminated completely. Instrumental errors, procedural errors, human limitations and external factors can cause measurements to have an uncertainty and derived quantities to have errors. There are two basic sources of uncertainty in experimental measurements: random errors and equipment calibrations. The rationale for two significant figures in an uncertainty is derived from a complex statistical analyses that are beyond the scope of high school work. However, when precision and accuracy differ we can be justified in stating an uncertainty to two significant figures.

In most high school physics investigations, the precision and the uncertainty will be expressed to one significant figure only. Although the digital thermometer has a resolution of 0.1 C° the manufacture's specification sheet tells us that it has an accuracy of ±1 C°. Hence, the best estimated temperature is (20.8 ± 1.0)°C.

Instrumental limitation

Every instrument has a limit to its precision. As an example, a metre rule can accurately measure only up to 1 mm. If the measurement is between the 1 mm divisions, the reading is estimated. It is not possible to keep dividing this 1 mm into smaller divisions; the dividing lines would be so close to each other that it might not be possible to differentiate one line from the other. There is a limit to what we humans can optically resolve and this, in a way, places a limitation on the measuring instrument.

Procedural error

Sometimes, the very act of measurement can cause the quantity that we are measuring to change. Thus the measurement deviates from the correct value.

An example of this is the measurement of temperature. Heat flows from one object to another due to temperature differences. When the temperature of hot water is measured, heat flows to the thermometer and this alters the temperature of the hot water that is being measured. As small as it seems, this heat that flowed into the thermometer will slightly cool down the water and cause a deviation in the measurement of the temperature.

Therefore, the introduction of the thermometer or the very act of measurement altered the quantity that is being measured.

Another example is the use of ammeters to measure the current flowing in a circuit. The ammeter, being an electrical device, has resistance. When an ammeter is connected in series to the circuit, the total resistance of the circuit increases. This causes the current in the circuit to decrease. Thus, the introduction of the ammeter causes the current value to deviate from the true value. Again, the deviation is small but it still produces an uncertainty.

Human limitation

This should not be confused with mistakes or blunders. Rather, this refers to uncertainties due to human limitations.

An example is reaction time. Whatever action we perform, there will always be some time interval between receiving the stimulus and reacting to it. There are also some situations when an experimenter anticipates the stimulus and reacts too early to it. The time that is measured will have some degree of uncertainty.

Another example is when we have to estimate a reading between graduations in a scale of an analogue device. It is possible that some people will be better at this than others and thus have different estimations.

External influences

Experimental results may be affected by factors that are beyond the experimenter's control. Fluctuations in the temperature or humidity may cause changes in the measuring instrument, i.e. expansion and contraction, change the resistance of the wire in an electronic device. These changes may be small but will still cause uncertainties in the measurement.

Computational error

Measurements will frequently be subjected to calculation. As such, when one measurement is mathematically operated on by another measurement, the error from each value is propagated to the final answer. Furthermore, rounding off figures from intermediate answers increases the error in the final value.

Note that the term 'computational error' does not refer to mistakes committed during calculations.

Theoretical assumptions

In many of the investigations that you will be conducting, there will be certain assumptions that need to be made in order to make problems possible to solve. In many mechanics investigations, the effects of air resistance and friction are neglected. Friction and air resistance slow down the motion of a moving object. Thus, when timing the motion of a trolley, a longer time is measured because of friction. This longer time will have an effect in the calculation of the trolley's speed and acceleration.

In heat investigations, it is always assumed that there is no heat transferred to the environment. But in reality, because of a temperature difference between the environment and the system being investigated; heat would flow from or into the system. When the latent heat of fusion of ice is measured, it is assumed that the temperature of ice is 0 ^{0}C. In reality, the temperature of ice can be below 0 ^{0}C.

10.1.4 Types of errors

Random errors

Errors of this type result in measurements that are either slightly too high or too low. They introduce a chance variation in the measurements.

The causes of random errors are not identifiable, hence the experimenter has no control over these.

Random errors are usually small in nature. The chances of the measurements being higher or lower than the correct value are approximately equal. With a large sample, the algebraic sum of the errors will approach zero. Therefore, random errors can be reduced by repeating the measurements and calculating the mean or average of the measurements. Thus the mean value is a good estimate of the correct value.

Note that random errors can be reduced but not eliminated completely.

Systematic errors

Errors of this type result in measured values that are consistently too high or consistently too low. They introduce an uncertainty in the measurements, but always in the *same* direction. See *Figure 1004*.

Systematic errors are due to identifiable causes and can, in principle, be identified, quantified and reduced, if not eliminated. A systematic error *cannot* be eliminated by repeating readings and then averaging. Instead, systematic error can be reduced only by improving experimental techniques.

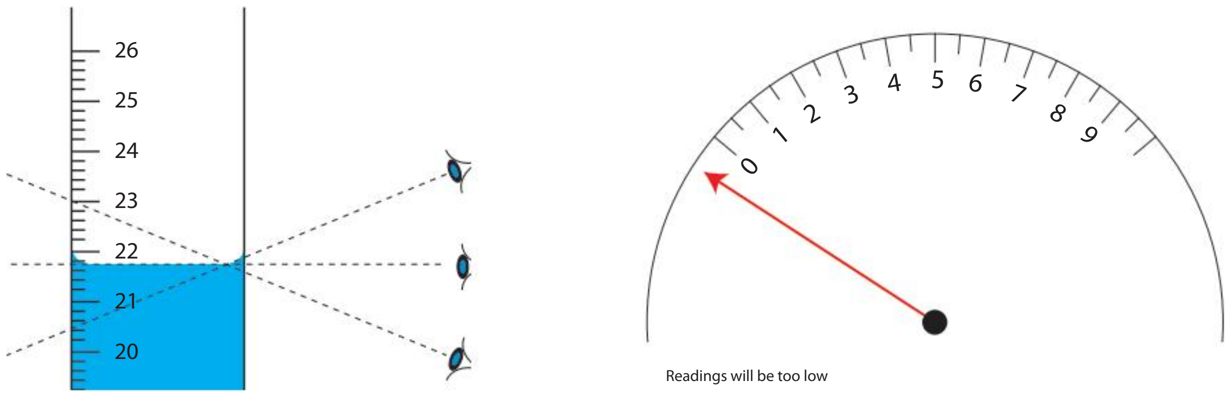


Figure 1004 (a) and (b) Examples of systematic errors

Common causes of systematic errors are instrumental or procedural in nature. Examples of systematic errors include:

- zero error on an instrumental scale – the scale reading is not "zeroed" before measurements are recorded
- a parallax error – the scale is viewed obliquely when a reading is recorded
- wrongly calibrated instrument, e.g. a stopwatch that runs slow will cause all time measurements to be too low
- a slow reaction time of the student performing the investigation – this will cause all time readings to be too high
- friction between the trolley and the inclined plane – this will slow down the trolley and cause its speed and acceleration to be too low.

Theoretically, systematic errors can always be eliminated by changing the way in which the experiment was conducted. In actual fact though, identifying all the systematic errors in an experiment is not always easy. You may not even know that the error exists, but it is always something you should attempt to do.

The concepts of systematic and random errors are shown in *Figure 1005*. In (a), all the measurements are shifted away from the correct value in the same direction. This is the effect of a systematic error. In (b), the measurements are distributed randomly around the correct value. This is due to random error.

(a) Systematic error (b) Random error

Figure 1005 (a) and (b) Effect of random and systematic errors

10.1.5 Estimating uncertainties in measurements

For an experimental result to be meaningful, the precision of the measurements must be known. This can be achieved only if the uncertainties in the data that were used to obtain the result are known. Thus it is important for you learn how to determine the nature and size of the experimental uncertainties and to determine how these uncertainties affect the accuracy and reliability of the result.

Uncertainty due to instrument limitation

The **least count** is the smallest division that is marked on the instrument. A metre rule has a least count of 1.0 mm. A protractor may have a least count of 1°. An electronic balance that can produce readings up to two decimal places may have a least count of 0.01 g.

In general, the uncertainty in a measurement due to instrument limitation is equal to or smaller than the least count.

Uncertainty in analogue devices

There are no hard and fast rules on determining the uncertainty in a single reading due to scale limitation of analogue devices. Instead you must be guided by common sense. If the space between the smallest scale divisions is large, it may be possible to estimate up to $\frac{1}{5}$ of the least count. In this case, the uncertainty in the reading is $\frac{1}{5}$ of the least count.

If the smallest scale divisions are closer together, the uncertainty can be estimated to be equal to $\frac{1}{2}$ of the least count. And if the smallest scale divisions are very close together, the uncertainty can be estimated to equal the least count.

Figure 1006 shows the length of an object being measured by scales of different precision. The ruler in *Figure 1006(a)* has a least count of 1 cm. The measurement using this scale can be estimated reasonably up to 0.2 cm. Therefore the length is (7.8 ± 0.2) cm. The ruler in *Figure 1006* (b) has a least count of 0.2 cm. The length can be estimated reasonably to half of the least count that is 0.1 cm. Therefore, the length is (7.8 ± 0.1) cm.

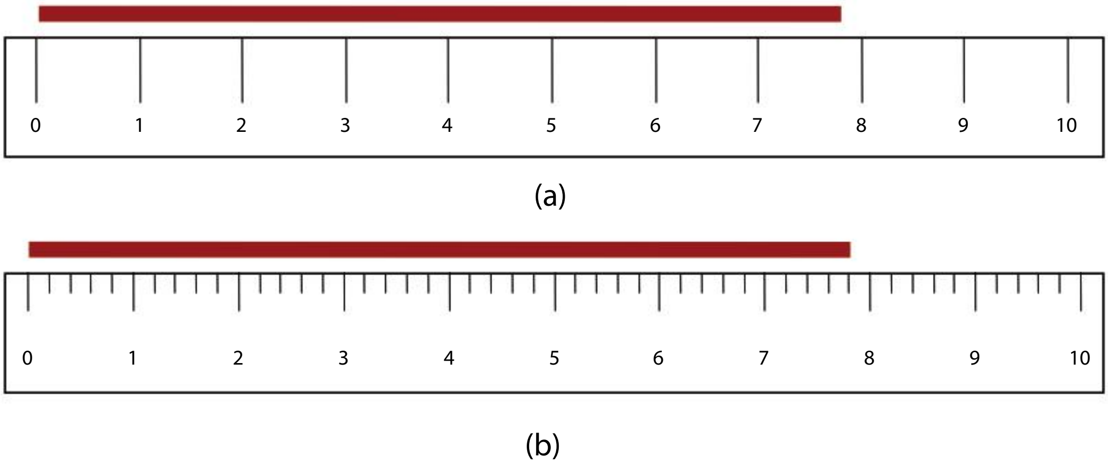


Figure 1006 (a) and (b)   Different scales have different uncertainties

Uncertainty in digital instruments

The uncertainty in a digital instrument is often stated in its operational manual. For example, an electronic balance may have a stated uncertainty of ±1% ± 3 digits. The 1% applies to the uncertainty in the scale reading and the ± 3 means an additional uncertainty equal to 3 × the least count.

Thus, for an electronic balance with a stated uncertainty of ±1% ± 3, the reading of 52.76 g will have an uncertainty of

$$(1\% \times 52.76 + 3 \times 0.01)\text{g} = 0.56\text{ g} = 0.6\text{ g}$$

In light of this uncertainty, the first decimal place in the reading becomes uncertain and this makes the second decimal place in the reading insignificant. Therefore the reading can be rounded off to (52.8 ± 0.6) g.

If the uncertainty is not given in the operational manual, then the uncertainty can be estimated to be equal to ± 1 of the least unit displayed. If an electronic device shows the mass of an object to be 5.67 g, then the mass can be anywhere between 5.66 g and 5.67 g. Note also that the smallest unit that can be measured is 0.01 g. Hence the uncertainty is 0.01 g.

Uncertainty in the vernier caliper

The uncertainty in the reading in the vernier scale is equal to the least count in the vernier scale.

This can be obtained by following these steps: See *Figure 1007***.**

- Determine the least count in the main scale.
- Count the number of divisions in the vernier scale.
- $\text{Least count in the vernier scale} = \dfrac{\text{least count in the main scale}}{\text{number of divisions in the vernier scale}}$

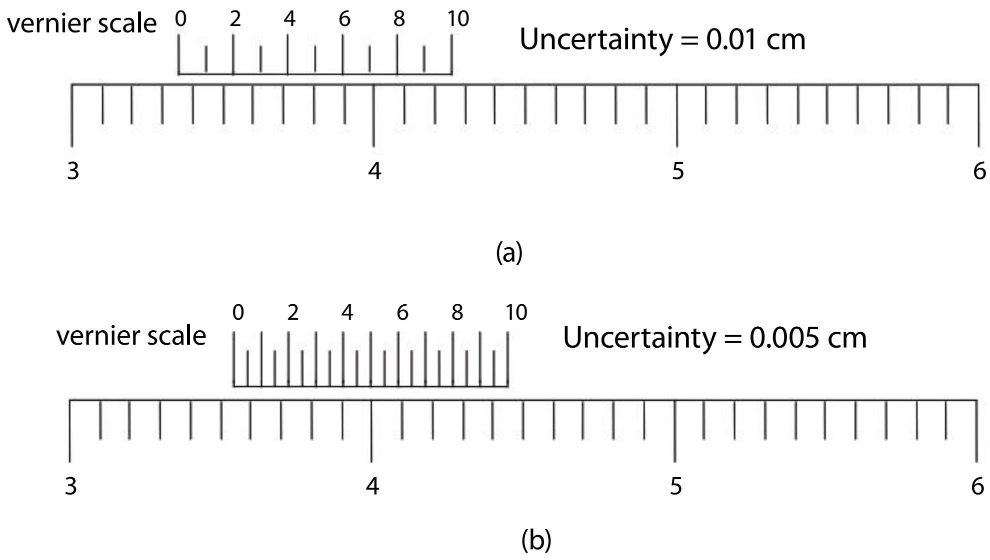


Figure 1007(a) and (b) What is the associated uncertainty in these vernier scales?

Uncertainty in the micrometer screw gauge

The uncertainty in the micrometer screw gauge is equal to half of the least count in the circular scale.

- Determine the least count in the linear scale. This is usually equal to 0.5 mm.
- Count the number of divisions in the circular scale. This is usually 50.
- $\text{Least count in the circular scale} = \dfrac{\text{least count in the linear scale}}{\text{number of divisions in the circular scale}}$
- $\text{Least count in the circular scale} = \dfrac{0.5\,\text{mm}}{50} = 0.01\,\text{mm}$

In this case the uncertainty in the reading is 0.005 mm.

Uncertainty due to procedural difficulty

In some investigations, the conditions surrounding the measurement do not allow the experimenter to exploit the full scale precision of the instrument.

As an example, a stopwatch may be accurate up to 0.01 seconds but because of reaction time, the uncertainty in the time measurement will be greater than 0.01 s. It is estimated that reaction time introduces an uncertainty of at least 0.2 seconds. Therefore the uncertainty due to instrument limitation becomes insignificant compared to that due to the reaction time. If the original reading was 2.38 seconds, then the reading, because of the uncertainty, must be reported as (2.4 ± 0.2) s.

Another example where the methodology introduces uncertainty is in the investigation titled '*Uniform circular motion.*' In this investigation, a rubber bung is whirled in a horizontal circle, as shown in *Figure 1008*. The method suggests that the rubber bung must be whirled with a constant radius of revolution but this is difficult to achieve. While the rubber bung is being whirled around, there will be slight changes in the radius of revolution. You need to estimate the range of the radius changes. In this case the uncertainty in the radius of revolution would be half the range.

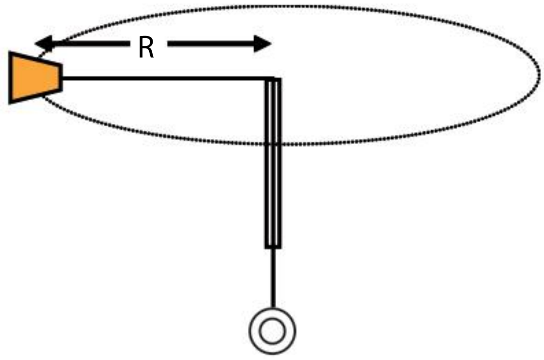


Figure 1008 Apparatus for investigating uniform circular motion

Another example is if you are investigating projectile motion and you are measuring the distance to where the projectile landed. The exact location of where the projectile landed would be difficult to determine. You may use chalk on the projectile to produce a mark on the floor when it lands, but again, the mark produced, aside from being fuzzy, will be bigger than a dot. Therefore, due to the vagueness of the landing point, the uncertainty in the distance could be around 1 cm, rather than half of the least count of the measuring instrument. In this case, the uncertainty due to the instrument limitation (e.g. metre rule: 0.05 cm) is very small compared to the uncertainty due to the fuzziness of the landing point (1 cm). Therefore, the uncertainty due to the instrument limitation is ignored.

A third example is the '*Lenses*' investigation, where the focal length of a convex lens is determined by measuring the distances from the object to the lens and from the lens to the screen. You will notice that the screen (or lens) can be moved over a certain range and the image remains focused. Again in this case, the uncertainty would be half the range at which you may move the screen while the image remains focused. If the image remains focused over a range of 24.1 cm to 26.4 cm for the lens to screen distance, then the distance can be reported as (25 ± 1) cm.

In these instances, it is good practice that you perform repeated measurements. The mean value of these measurements would be a good estimate of the correct value. The method for determining the uncertainty in repeated readings is shown elsewhere in this Handbook.

10.1.6 Expressing uncertainties

Absolute uncertainty

The absolute uncertainty of a measurement is the size of the range of values in which the correct value of the measurement probably lies. It has the same units as the measurement.

For example, if the length is expressed as:

length = 3.8 cm ± 0.5 cm, then the absolute uncertainty is 0.5 cm and 3.3 – 4.3 is the range of values in which the measurement lies.

Expressing absolute uncertainty

The rules for expressing the absolute uncertainty or error in any measurements are given below.

- The measurement and the absolute uncertainty must have the same precision. This means that they must be expressed to the same number of decimal places.
- Express the uncertainty to one significant digit.

Figure 1009 shows examples of how these two rules are used when writing measurements with uncertainties. Note that in the different examples, the measurement or the uncertainty or both needs to be rounded off to be able to satisfy the two rules above. Further to this, in example 3, an extra '0' digit is attached to the measurement so that both the measurement and the absolute uncertainty have the same precision.

Measurement value	Uncertainty	Correct format to express the measurement
55.3 g	0.5 g	55.3 g ± 0.5 g
76.4 cm	0.273 cm	76.4 cm ± 0.3 cm
56.7 ^{0}C	0.0346 ^{0}C	56.70 ^{0}C ± 0.03 ^{0}C
146 cm^2	23 cm^2	150 cm^2 ± 20 cm^2
4.8 × 10^{-4} A	7.0 × 10^{-5} A	(4.8 ± 0.7) × 10^{-4} A

Figure 1009 Correct format of expressing the absolute uncertainty

Fractional uncertainty

The fractional uncertainty is defined as the absolute uncertainty divided by the measured value. The true index of a measurement is expressed by the fractional uncertainty. Fractional uncertainty is the same as relative uncertainty.

Example:

Given below are the dimensions of a cylinder.

Height = 12.2 cm ± 0.5 cm

Radius = 5.3 cm ± 0.5 cm

What is the fractional uncertainty of each measurement?

Fractional uncertainty of height = $\frac{0.5}{12.2} = 0.04$

Fractional uncertainty of radius = $\frac{0.5}{5.3} = 0.09$

Note that although both measurements have the same absolute uncertainties, the fractional errors differ.

Percentage uncertainty

Percentage error is defined as fractional uncertainty × 100%.

In the previous example, the percentage uncertainty of the height is 0.04 × 100% = 4 %.

10.1.7 Significant Digits

Whenever measurements are recorded, the number of digits written down gives an indication of the uncertainty in the measurement. In *Figure 1010*, the length of the object can be measured as 1.85 cm. Note that in this reading, the last digit is just an estimate. It is definite that the length is more than 1.80 cm but less than 1.90 cm. But there is a margin of doubt as to whether the length is exactly halfway between those two values. Doubtful as it may be, the last digit, just like the first two digits, is still significant because it is known with some degree of certainty. Therefore, the measurement 1.85 cm has three significant digits.

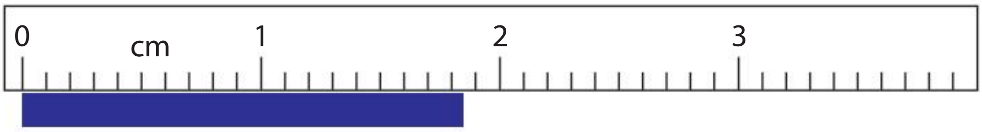


Figure 1010 The length = 1.85 cm has three significant figures

The number of significant digits in a measurement is equal to the number of digits that are known with some degree of confidence. Therefore the significant digits in a measurement are all the digits that are certain and one uncertain digit.

Aside from good experimental skills, the precision of your results will also depend on how correctly you record your measurements. When reporting a measurement, it should not appear to be more precise or less precise than the equipment used allows it to be. You can achieve this by ensuring that one and only one uncertain digit is to be reported for a measurement.

The number of significant digits necessary to express a measurement must be consistent with the precision of the measurement. This means that measurements must be recorded with all the digits that can be measured, to the limits of uncertainty of the equipment. Zeroes can be 'added' to the reading if necessary, to imply the level of precision of the instrument.

As an example, consider the lengths of lines A and B in *Figure 1011* below. If the lengths are recorded as 1.8 cm for line A and 3 cm for line B, then these readings do not reflect the level of precision of the ruler. The lengths must be recorded as 1.80 cm for line A and 3.00 cm for line B. Mathematically, 1.8 is equal to 1.80 and so is 3 to 3.00, but experimentally they are not. The length of 1.80 cm implies a more precise measurement than 1.8 cm. For this ruler, the readings must be expressed up to a hundredth of a centimetre because the uncertain digit is in the hundredth of a centimetre.

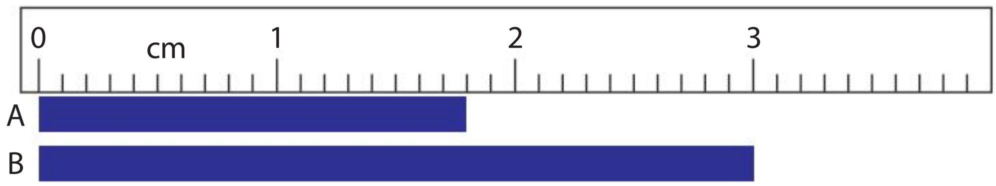


Figure 1011 What is the correct way to express the lengths of lines A and B?

As a 'rule of the thumb':

- On an analogue scale, estimate one more digit than can be actually read from the scale.
- On a digital instrument, record all the numbers, including zeros after the decimal point, exactly as displayed.

Rules concerning significant digits

In determining the number of significant digits, the problem is the zero (0) digit.

Listed below are the rules for counting the number of significant figures.

1 All non-zero digits are significant

Examples

31.81	four significant digits
549	three significant digits
23	two significant digits

2 Zeros between non-zero digits are significant

Examples

4.106	four significant digits
905	three significant digits
5002.01	six significant digits

3 For numbers with decimal points, zeros to the right of a non-zero digit are significant

Examples

4.180	four significant digits
9.00	three significant digits
59.6000	six significant digits

4 Zeros to the left of the first non-zero digit are not significant

Examples

0.0020	two significant digits
0.000500	three significant digits
0.00008	one significant digit

5 Zeros at the end of a number are ambiguous

Example

500 may have three significant figures or it may have one – the "5" – with the zeros being a place holder. Only the person who carried out the measurement would know. The ambiguity can be removed by reporting such numbers in **scientific** or **standard notation**. Writing 500 as 5×10^2 means that only one significant figure is present, while writing it as 5.00×10^2 means that three significant figures are present.

If you are not sure whether a digit is significant, then assume that it is not. For example, if the mass of an object is reported as 200 g, then assume that the mass is known up to one significant digit.

Mathematical operations with significant digits

In most cases, the measurements that you have recorded will be subjected to mathematical operations. Rounding off the calculated results to the right number of significant digits is a method of keeping track of how experimental uncertainties are propagated.

The most important ideas when doing operations with significant digits are:

- the last digit in a number is an estimate.
- the precision of an experiment **cannot** be improved by doing arithmetic with the measurements. Therefore, the derived result cannot be more precise than the primary measurements.

Significant digits in addition and subtraction

When quantities are being added or subtracted, the number of decimal places (not significant digits) in the answer should be the same as the least number of decimal places in any of the numbers being added or subtracted.

Examples:

2.32	N	(two decimal places)
+ 4.2	N	(one decimal place) least number of decimal places
0.6157	N	(four decimal places)
7.1357	N	

Final answer: 7.1 N (one decimal place)

12.587	cm	(three decimal places)
+ 4.25	cm	(two decimal places)
0.12	cm	(two decimal places) least number of decimal places
16.957	cm	

Final answer: 16.96 cm (two decimal places)

2.300×10^3 kg (three decimal places)

$+ 4.59 \times 10^3$ kg (two decimal places) least number of decimal places

6.890×10^3 kg

Final answer: 6.9×10^3 kg (two decimal places)

When adding or subtracting numbers in exponential notation, you need to make sure that the decimal place is in the same place in all the numbers, that is, the "10" must be raised to the same exponent.

$47.68 \times 10^4 \rightarrow \quad 476.8 \times 10^3$ kg

$+ 23.2 \times 10^3 \rightarrow \quad 23.2 \times 10^3$ kg

$500.0 \times 10^3 \Rightarrow$ Final answer: 5.000×10^5 kg

Significant digits in multiplication and division

When quantities are being multiplied or divided, the number of significant digits in the answer should equal the least number of significant digits (not decimal places) in the numbers being multiplied or divided.

Example:

21.45 cm (four significant digits)
× 0.023 cm (two significant digits) *least number of significant digits*
0.49335 cm^2

Final answer: 0.49 cm^2 (two significant digits)

Operations between pure numbers and significant digits

The concept of significant digits applies only to measurements because of the uncertainties associated with them. Pure numbers and counting numbers have no uncertainty and significant digits do not apply to them. Physical constants like gravitational field strength on the Earth's surface *g* and the mass of the carbon-12 atom were obtained experimentally with a high degree of precision and accuracy. Therefore, when pure numbers and physical constants are involved in the calculation, the number of significant digits in the final answer will be determined by the number of significant figures in the measured values.

Examples:

1. A motor lifted a 0.28 kg object to a height of 1.63 m in 9.78 seconds. The acceleration due to gravity (*g*) is 9.8 m s^{-2}. What is the motor's power?

$$\text{Power} = \frac{\text{weight} \times \text{height}}{\text{time}} = \frac{\text{mass} \times g \times \text{height}}{\text{time}} = \frac{0.28 \times 9.8 \times 1.63}{9.78} = 0.46 \text{ W}$$

Explanation: The final answer is rounded off to two significant digits. The measurements are the mass, the height and the time. The mass has the least number of significant digits which is two. In the formula, 'g' is a physical constant and therefore, is not covered by the rules on significant digits.

2. The radius of a sphere is measured as 2.56 cm. What is its volume?

$$\text{Volume} = \frac{4}{3}\pi r^3 = \frac{4}{3} \times \pi \times 2.56^3 = 70.3 \text{ cm}^3$$

Explanation: The final answer is rounded off to three significant digits because the radius has three significant digits. $\frac{4}{3}$ and π are pure numbers.

Significant digits in some mathematical functions

The number of significant digits in the value of any mathematical function is equal to the least number of significant digits in the numbers involved in the evaluation of the function.

Examples

sin 47.5° = 0.737 *(47.4° has three significant digits, hence sin 47.5° must have three significant figures.)*
$\log_{10} 0.2 = -0.7$ *(0.2 has one significant figure, hence $\log_{10}$ 0.2 must have one significant figure)*
$\text{antilog}_{10}\, 2.545 = 350.8$

Multi-step calculation

When doing a multi-step calculation, keep at least one more significant digit in intermediate results than needed in your final answer. For instance, if a final answer requires three significant digits, then carry at least four significant digits in calculations. If you round-off all your intermediate answers to only three digits, you are discarding the information contained in the fourth digit, and as a result, the third digit in your final answer might be incorrect. This is known as a "rounding-off error."

Example

a. Find the density of a cube if its mass is 25.3 g and the measure of one of its sides is 5.40 cm.

To find the density, the operations involved are multiplication and division. Therefore the final answer must be rounded off to two significant figures.

Volume = $s^3 = 5.40^3 = 157.5\ \text{cm}^3$

The result is rounded off to four significant figures instead of three because this is an intermediate result.

Density = $\dfrac{mass}{volume} = \dfrac{25.3}{157.5} = 0.161\ \text{g cm}^{-3}$ ← **Final answer**

b. Evaluate e^{kt} where $k = 0.2507\ \text{s}^{-1}$ and $t = 135$ s.

The result of $k \times t$ must be rounded off to four significant figures instead of three because this is an intermediate result.

$k \times t = 33.8445 \rightarrow 33.84$

Since "t" has only three significant digits, the final answer e^{kt} must be rounded off to three significant digits.

$e^{kt} = 4.97 \times 10^{14}$ ← **Final answer**

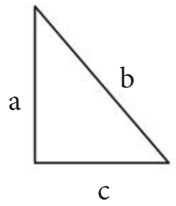
10.1.8 Propagation of uncertainties in calculated results

Measurements are usually combined to determine another quantity. For example, the area of a rectangle is obtained by multiplying the length and the width. The uncertainty in the final result depends on the uncertainty in the individual measurements and the formula used to obtain the quantity.

Addition and subtraction

When adding or subtracting measurements, add the absolute errors.

Example 1: Determine the perimeter of a triangle.



a = (4.1 ± 0.1) cm
b = (2.9 ± 0.1) cm
c = (5.2 ± 0.1) cm

Perimeter = 4.1 + 2.9 + 5.2
= 12.2 cm

Total uncertainty = 0.1 + 0.1 + 0.1
= 0.3 cm

Therefore, perimeter = (12.2 ± 0.3) cm

Example 2: Determine the change in temperature of a substance.

Final temperature = (56.3 ± 0.2)°C

Initial temperature = (20.0 ± 0.2)°C

Change in temperature = (36.3 ± 0.4)°C

In both examples the uncertainties were simply added together.

Example 3: Determine z if z = x – y + w

w = (4.52 ± 0.02) cm, x = (2.0 ± 0.2) cm and y = (3.0 ± 0.6) cm

z = x - y + w = (2.0 cm - 3.0 cm + 4.5 cm) = 3.5 cm;

the overall uncertainty or error = (0.02 + 0.2 + 0.6) = 0.82.

Therefore, z = (3.5 ± 0.8) cm

Note that that the final answer is rounded off in accordance with the rules of significant digits.

Multiplication and division

When multiplying or dividing measurements, add the fractional uncertainties.

Example Determine the final pressure using Boyle's law

In an experiment on gases conducted under constant temperature, the following measurements were obtained:

Initial pressure $p_1 = (2.03 \pm 0.02) \times 10^5$ Pa

Initial volume $V_1 = (2.33 \pm 0.02)$ cm^3

Final volume $V_2 = (4.25 \pm 0.01)$ cm^3

According to Boyle's Law, the final pressure p_2 is: $p_2 = \dfrac{p_1 V_1}{V_2}$

Final pressure = $\dfrac{2.03 \times 10^5 \times 2.33}{4.25} = 1.11 \times 10^5$ Pa

Fractional uncertainty in p_1 = $\frac{0.02}{2.03} = 0.01$

Fractional uncertainty in V_1 = $\frac{0.02}{2.33} = 0.009$

Fractional uncertainty in V_2 = $\frac{0.01}{4.25} = 0.002$

Total fractional uncertainty = 0.01 + 0.009 + 0.002 = 0.021

Absolute uncertainty in final pressure = Final Pressure × Total fractional uncertainty.

$= 1.11 \times 10^5 \times 0.021 = 0.02 \times 10^5$

Final pressure p_2 = $(1.11 \pm 0.02) \times 10^5$ Pa

Multiplying or dividing a measurement by a constant

The overall fractional uncertainty is equal to the fractional uncertainty of the measured value.

Example 1

The radius, *r*, of a copper sphere is (4.0 ± 0.2) cm. Calculate the circumference and its uncertainty.

Circumference = $2 \times \pi \times 4.0 = 25.133$ cm

fractional uncertainty of the radius = $\frac{0.2}{4.0} = 0.05$

fractional uncertainty of the circumference = 0.05

Uncertainty in circumference = $25.133 \times 0.05 = 1.3$ cm

Circumference = (25 ± 1) cm.

Note that the final answer is rounded off in accordance with the rules of significant digits

Example 2 Determining the reciprocal of a measurement

Given P = $(3.2 \pm 0.1) \times 10^5$ Pa, find $\frac{1}{P}$ and its uncertainty.

$\frac{1}{P} = 3.1 \times 10^{-6}$ Pa^{-1}

Fractional uncertainty of P = $\frac{0.1}{3.2} = 0.03$

Fractional uncertainty of $\frac{1}{P}$ = Fractional uncertainty of P

Absolute uncertainty of $\frac{1}{P} = (3.1 \times 10^{-6}) \times 0.03 = 9.0 \times 10^{-8}$ Pa^{-1}

The absolute uncertainty above can be rounded off to 1.0×10^{-7} or 0.1×10^{-6}

Therefore: $\frac{1}{P} = (3.1 \pm 0.1) \times 10^{-6}$ Pa^{-1}

Raising a measurement to a power

For a measurement raised to the power of n, the overall fractional uncertainty is equal to n multiplied by the fractional uncertainty of the measurement.

Example 1

Given that the displacement $s = \frac{1}{2} g t^2$ and t = 2.25 s ± 0.01s, find s and its uncertainty.

The value of g is 9.8 m s^{-2}.

Calculate the value of $s = \frac{1}{2} \times 9.8 \times 2.25^2$ = 24.80625 m (to be rounded off later)

Fractional uncertainty of $t = \frac{0.01}{2.25} = 0.004$

Fractional uncertainty of $t^2 = 0.004 \times 2 = 0.008$

Fractional uncertainty of $s = 0.008$

Absolute uncertainty of $s = 24.80 \times 0.008 = 0.198$ m = 0.2 m

Therefore: $s = (24.8 \pm 0.2)$ m

Example 2

The period T of a simple pendulum is given by $T = 2\pi\sqrt{\frac{L}{g}}$ where g = 9.8 ms^{-2}.

If L = 1.25 m ± 0.05 m, determine T and its uncertainty.

$T = 2\pi \times \sqrt{\frac{1.25}{9.8}} = 2.24$ s

Fractional uncertainty of L = $\frac{0.05}{1.25} = 0.04$ Note that $\sqrt{L} = L^{\frac{1}{2}}$

Fractional uncertainty of $\sqrt{L} = \frac{1}{2} \times 0.04 = 0.02$

Fractional uncertainty of $T = 0.02$

Absolute uncertainty of $T = 2.24 \times 0.02 = 0.04$

Therefore: $\boldsymbol{T}$ **= 2.24 s ± 0.04 s**

Arithmetic mean

Repeating measurements and calculating the average of these measurements provides a more reliable value. The extra readings also reduce the uncertainty of the obtained mean value.

The uncertainty in the mean value is obtained by, first, determining the difference between the largest and the smallest measurements. Then divide the difference by the number of measurements.

Example

The time for 10 oscillations of a simple pendulum was measured five times. The following data were obtained:

12.3 s ± 0.3 s, 12.6 s ± 0.3 s, 12.2 s ± 0.3 s, 12.4 s ± 0.3 s and 12.4 s ± 0.3 s

Determine the mean and its absolute uncertainty.

Mean $= \frac{12.3+12.6+12.2+12.4+12.7}{5} = 12.4$ s

$$\text{Uncertainty} = \frac{\text{largest measurement} - \text{smallest measurement}}{\text{number of measurements}}$$

$$= \frac{12.7 - 12.2}{5} = 0.1 \text{ s}$$

Therefore: mean = 12.4 s ± 0.1 s

Note that the more repetitions of the measurements are done, the smaller the uncertainty becomes.

Trigonometric and logarithmic functions

Example: Trigonometric function

If the measured angle is $35^0 \pm 1^0$, what is the uncertainty in sin 35^0?

Since the uncertainty is 1^0 then you need to look at the sines of 34^0, 35^0, and 36^0.

sin 34^0 = 0.559 193 (lower limit)

sin 35^0 = 0.573 576 (measurement)

sin 36^0 = 0.587 785 (upper limit)

Difference between the sines of the lower limit and of the measurement:

0.573 576 - 0.559 193 = 0.014 383

Difference between the sines of the upper limit and of the measurement:

0.587 785 – 0.573 576 = 0.014 209

Since the first non-zero digit in the differences appears in the second decimal place, then this is the uncertain digit in the sine value.

Therefore: sin ($35^0 \pm 1^0$) = 0.57 ± 0.01

As a working rule, if the angle is known to the nearest degree, two decimal places are appropriate in the trigonometric function. The uncertainty is equal to the difference between the sines (or cosines or tangents) of successive angles.

Example: Logarithmic function

A value y is calculated from y = $\log_{10}$ x where x is measured and found to be 15.43 ± 0.04. What is the associated error in y?

$\log_{10}$ 15.47 = 1.189 490

$\log_{10}$ 15.43 = 1.188 365

$\log_{10}$ 15.39 = 1.187 238

Since the first non-zero digit in the differences will appear in the third decimal place, you need to round off the log values up to the third decimal place.

Difference between the logs of the upper limit and of the measurement: 1.189 – 1.188 = 0.001

Difference between the logs of the lower limit and of the measurement:

1.188 – 1.187 = 0.001

Therefore y = 1.188 ± 0.001.

10.2 Graphs

A graph is a visual representation of how one quantity varies with respect to another quantity. Used properly, it is a powerful tool for data presentation and analysis and an important guide to understanding the results of an investigation. As an IB Physics student, it is important you develop good graph drawing skills and an understanding of how to use graphs.

The following are some uses of graphs in the IB Physics course:

a) Derive an equation relating the variables by looking at the trend of the experimental data.

b) Determine physical quantities represented by the gradient, the intercept of the straight line and the area under the graph.

c) Detect the need for additional readings and identify anomalous readings.

10.2.1 Elements of a good graph

1. Title

Every graph you draw must have a clear title. The title should indicate the data it represents. It must be as descriptive as possible.

As an example, a graph title "*Displacement – time graph*" is incomplete as it does not describe the conditions under which the experiment was conducted. The reader will have a better understanding of the graph if the title is "*Displacement – time graph for a trolley rolling down an inclined plane*."

2. Label each axis

Each axis must be labelled with the appropriate physical quantity and unit. Write down the whole name of the physical quantity and the corresponding unit.

Suppose that you are investigating the cooling of a copper block over a certain length of time. You have decided to plot the temperature along the y-axis and the time along the x-axis. In *Figure 812(a)*, the letter symbols of the quantities involved are used. This can be confusing as the labels T and t might be interpreted incorrectly by a reader. *Figure 812(b)* is better because writing down the complete name of the physical quantity removes any ambiguity in the labels.

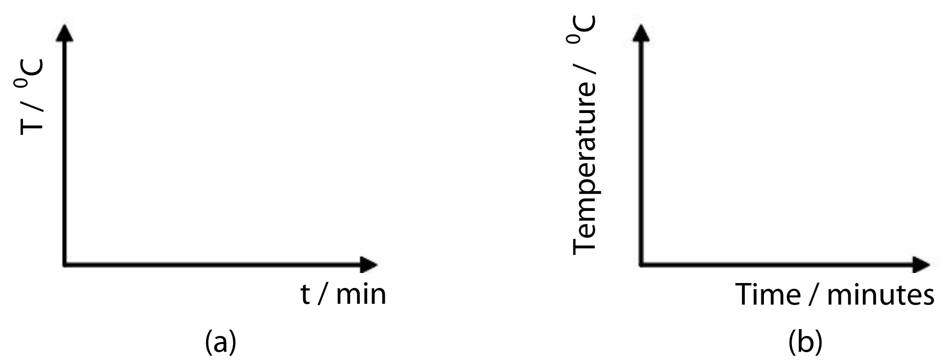


Figure 812 (a) and (b) Which axes labels are clearer?

What must be plotted on which axis?

The general rule is to plot the independent variable along the x - axis and the dependent variable along the y - axis. As an example, the distance travelled by a trolley along an inclined plane for different periods of time was measured. The independent variable, which is the time, is plotted along the x-axis and the distance travelled is plotted along the y-axis. The gradient of the line would be equal to the average speed.

In an Ohm's law experiment, the current through the resistor is varied and the voltage across it is measured. Plotting the current along the x-axis and the voltage along the y-axis will give a gradient equal to the resistance.

While this rule works well in many applications, there are a few instances where the analysis of the graph would be simplified by switching what is to be plotted along each axis.

For example, to determine the refractive index n by Snell's Law, the angle of incidence i is changed and the angle of refraction r is measured. If sin i, is plotted along the x-axis and the sin r along the y-axis, then the gradient will be equal to $\frac{\sin r}{\sin i}$. By applying Snell's law; the gradient would be equal to $1/n$. Therefore, the refractive index $\boldsymbol{n}$ is obtained from the reciprocal of the gradient.

If what is plotted along each axis is switched, then the gradient would be equal to n. While obtaining a gradient equal to $1/n$ is not impossible to deal with, switching the quantity plotted in each axis leads to the value of n and simplifies the analysis.

Therefore, what to plot on which axis depends on what information needs to be extracted from the graph. Plot the quantities in such a way that the analysis of the graph will be simplified.

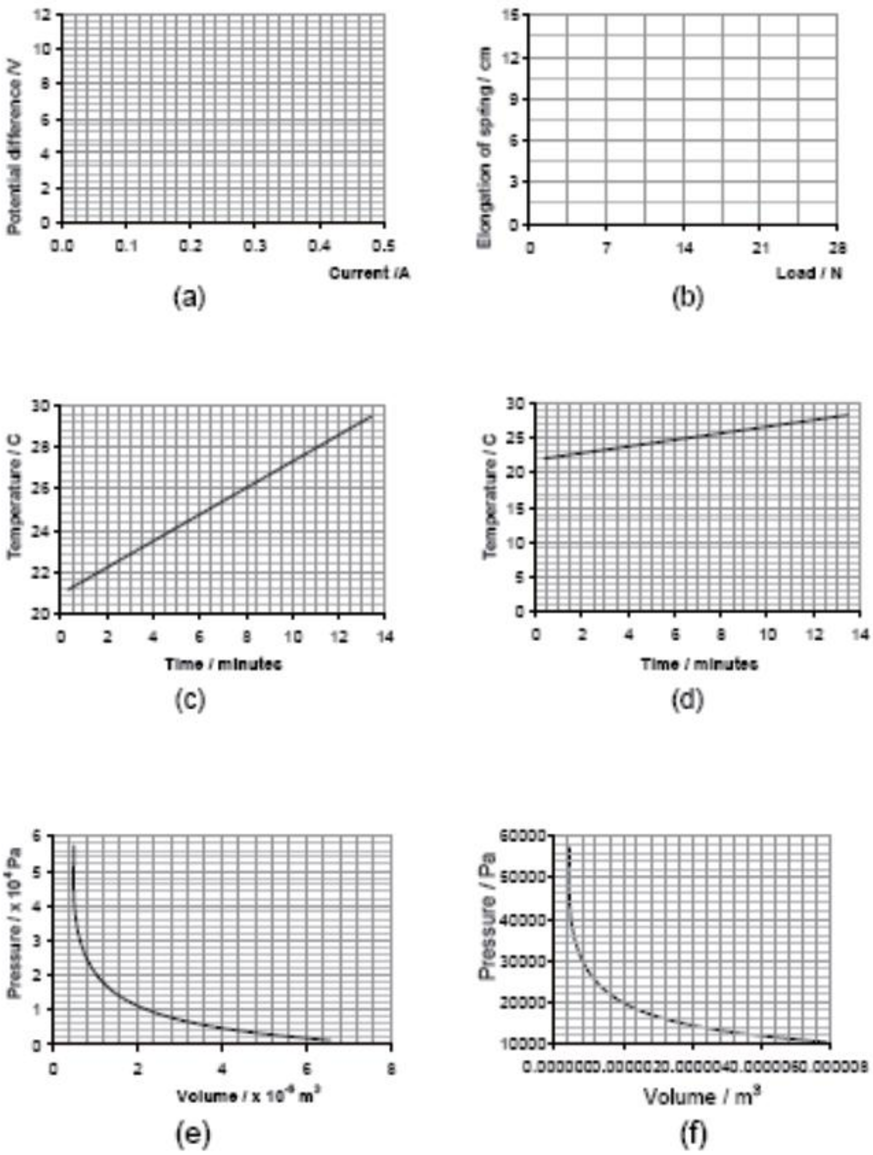


Figure 1013 Good and bad graphs

3. Scale

- Choose a suitable scale so that you make full use of the graph paper. The span of the plotted points must occupy at least half of the graph paper.
- Choose a scale that will make it easy to plot or read points between the major grid lines. Good major grid spaces should equal 1, 2, 4, 5 or 10 units or some decimal multiple of these numbers, e.g. 0.1, 0.2, 1.0×10^{-3}. Avoid scales like 3, 7 or 9.
- In order to obtain the best scales for both variables, you will sometimes need to decide on the appropriate orientation of the graph paper (i.e. landscape or portrait).

Examples of good and bad choices for scales are shown in *Figure 1013*. In graph (a), the scales on both axes make it easy to plot or read points between major grid lines. Graph (b) illustrates a bad choice of scales for both axes. With intervals of 3 and 7, it would be difficult to estimate values between the major grid lines. If the data is of a limited range, the scale need not start at zero, as shown by graph (c). If the scale starts at zero, as shown in graph (d), then the line will not make maximum use of the entire grid. Finally, if the values to be plotted are very large or very small, it would be better to use the exponential notation, as shown in graph (e). As shown in graph (f), too many zeroes produces crowding of numbers along the axes and this can lead to confusion.

4. Plotting points

- Use a sharp pencil to plot points. This improves the precision of the plotted points.
- You may indicate the location of a plotted point with a small cross × or a fine dot with a circle drawn over it, e.g ⊙. These marks make the point more visible, especially when a line is drawn over them.
- There are occasions when you may need to plot two different sets of data on the one set of axes, e.g. elongation against mass of two different springs. You can differentiate each set by using various markers like ⊙, ◆, and ✳.

5. Error bars

The uncertainty for each data point is shown on the graph as a line representing a range of possible values, with the principal value at the centre. The line is called an **error bar**.

The uncertainty in the dependent variable is shown using a vertical error bar, while that of the independent variable is shown using a horizontal error bar.

Shown in *Figure 1014* are examples of a plot with error bars. Take note that the length of the error bar must be consistent with the chosen scale.

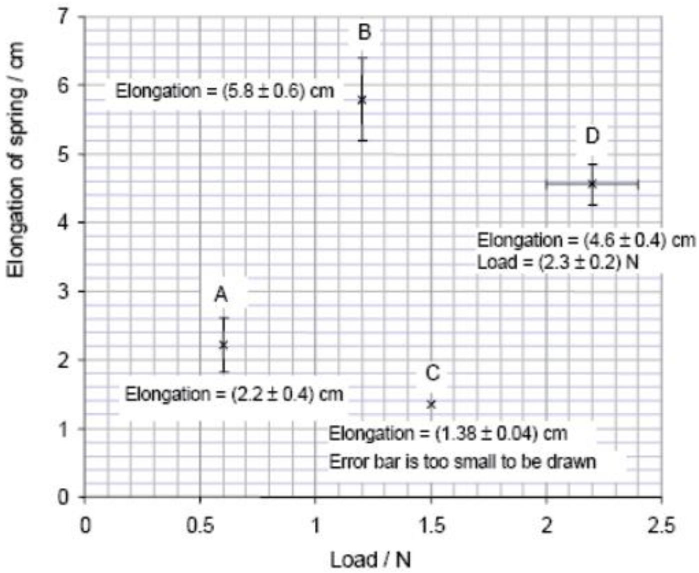


Figure 1014 Error bars

At point A, the uncertainty in the elongation is ± 0.4 cm. Since one division along the y-axis is equal to 0.2 cm, then 0.4 cm is equal to two divisions. Thus, the vertical error bar is drawn two divisions up and two divisions down. At point B, the uncertainty is 0.6 cm and this is equal to three divisions.

At point C, the uncertainty is 0.04 cm and this is equal to 1/5 of one division. This is too small to be drawn. Hence no error bar is drawn for point C. At point D, there is an uncertainty for both the elongation and the load. Along the horizontal axis, one division is equal to 0.1 N. The uncertainty in the load is 0.2 N and this is equal to two divisions. Thus, the horizontal error bar is drawn two units to the left and two units to the right.

Sometimes the uncertainty in the measurement is too small for error bars to be shown on the graph. If this is the case, then you need to state this explicitly under the graph.

In most cases, the uncertainty in the value of the set (independent) variable plotted along the x-axis is relatively small and the uncertainty bars need not be shown.

6. Drawing the line of best fit

Draw a smooth line of best fit through the region occupied by the plotted points. The line of best fit will have the following characteristics:

i) It should be as close as possible to all the plotted points, if not passing through most of the points.

ii) It is the line where the plotted points appear to be uniformly distributed on either side of the line. There will be points that will lie on the line and some that will not. The distances of those points that are not on the line must be approximately equal on either side.

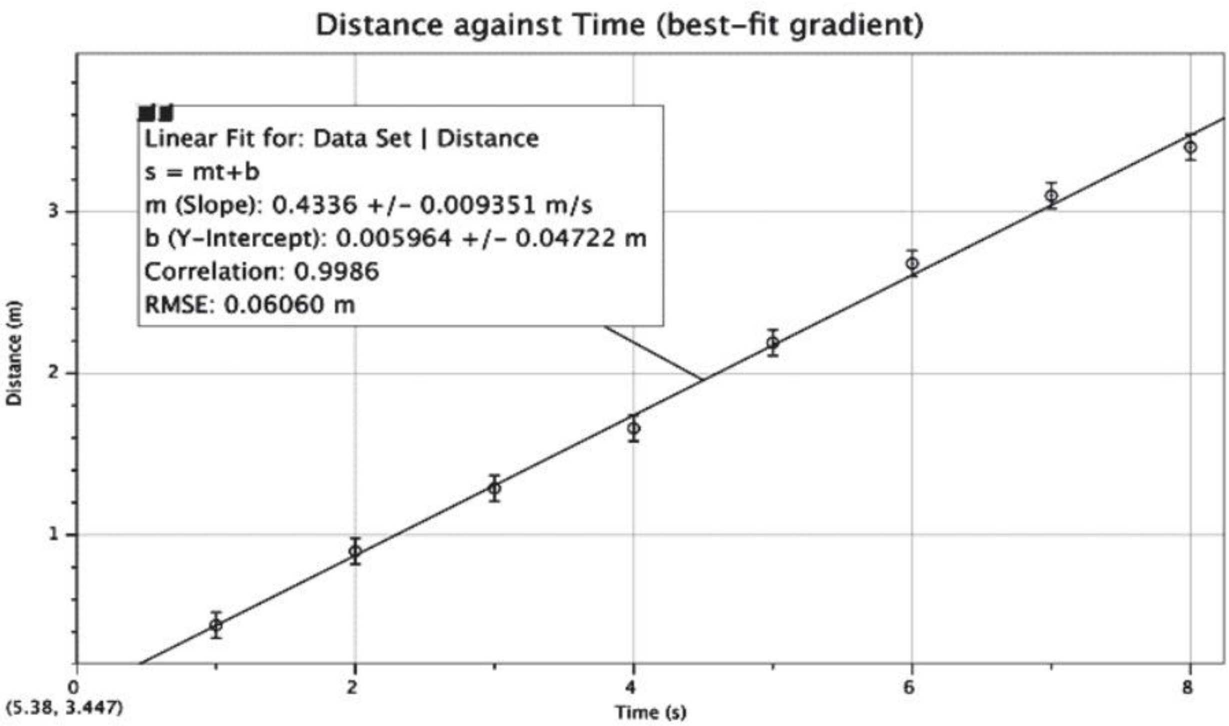


Figure 1015 The line of best fit

(Adapted from IBO OCC, where there are also other sample graphs)

It is not necessary to have the same number of points on either side. Note that it is possible that two points close to the line on the same side of the line can be balanced by one point further from the line on the opposite side of the line.

- Furthermore, you must not force the line to pass through the origin.
- When drawing a straight line, use a transparent ruler or a taut cotton thread. This allows you to have a good view of all the plotted points and to decide whether the distribution of the points around the line is uniform.
- Use a sharp pencil when drawing lines. This improves the precision of the line.
- If a straight line graph needs to be extrapolated, show the extension by using dashed lines.
- If the line is curved, do not just connect one point to another point. Instead, draw a smooth curve through the plotted points.
- If you are drawing a curved line, it is easier to form a smooth curved if you draw it from the inside of the curve, using your wrist as a pivot point.

Figure 1015 shows an example of a line of best fit.

Figure 1016 shows examples of common errors committed when drawing the line of best fit. In graph (a), the points are distributed equally around the line. However, this is not the line of best fit because the line can still be drawn so that the distances between the points and the line can be minimised. In graph (b), the problem is that there is a higher concentration of points below the line. Also, the line is forced to pass through the origin. Never draw the line by connecting the points to each other as shown in graph (c). In graph (d) the slope of the line is good. However, the line is too thick and the points plotted are too large. These errors make the line and the points imprecise.

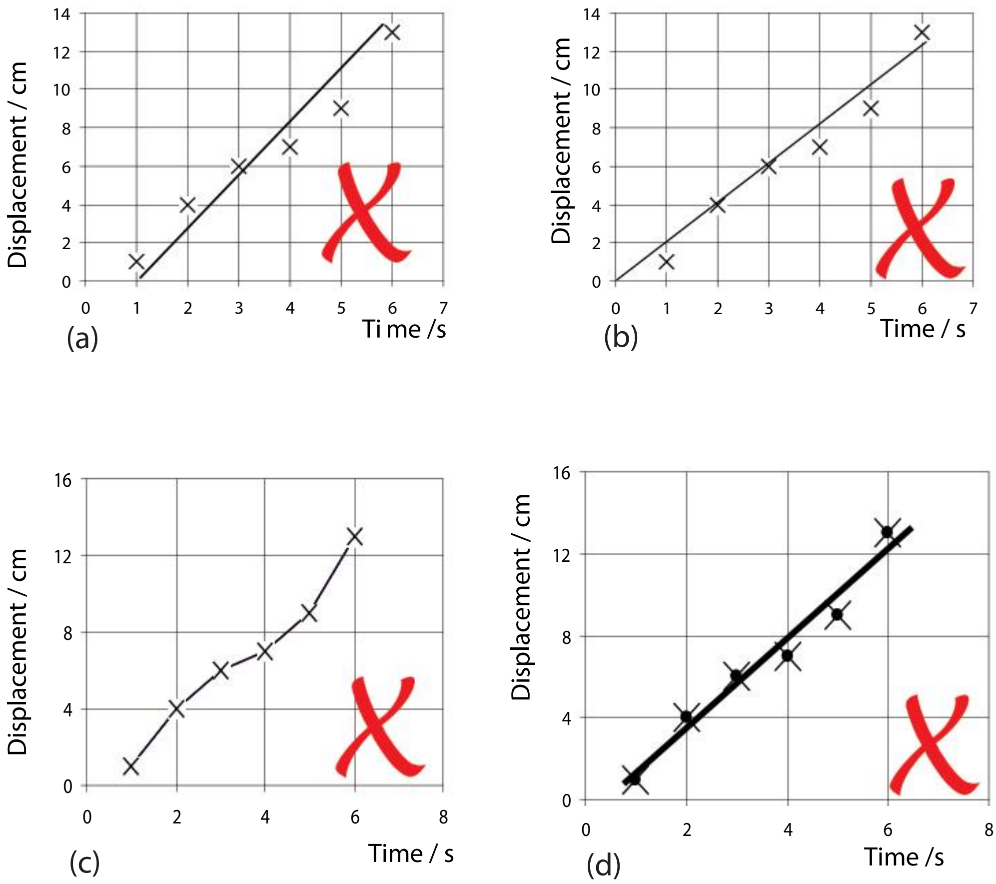


Figure 1016 Common errors when drawing the line of best fit

10.2.2 The gradient

Calculating the gradient

- Use a large triangle as shown in *Figure 1017*. Use two points that are located well apart on the graphed line. This will give a more accurate value for the gradient.
- Use sets of readings that are on the line. You need not use the data points that were plotted. Choose two points that are easy to read.
- Gradients have units. This is equal to the unit of the variable along the y-axis divided by that of the x-axis. The units of the gradients would give a hint as to what physical quantity it might represent. In *Figure 1017* the units of the gradient is $\frac{\text{V}}{\text{A}} = \Omega = \text{ohm}$ which is the unit of electrical resistance. Furthermore, since the line is straight then the gradient is constant. Therefore, the gradient represents a constant electrical resistance.
- The formula for the gradient is given by: $\text{gradient} = \frac{y_2 - y_1}{x_2 - x_1}$

Example **Calculate the gradient of the best fit line in** *Figure 1017*

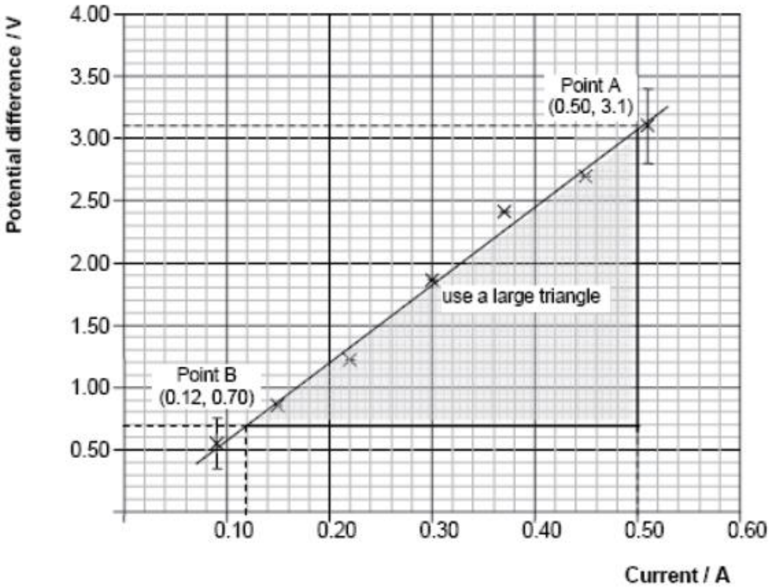


Figure 1017 Calculating the gradient

For the graph in *Figure 817*, the $\text{gradient of line of best fit} = \frac{3.1 - 0.70}{0.50 - 0.12} = 6.3\ \Omega$.

10.2.3 Uncertainty in the gradient

The gradient is calculated from data points that have uncertainties. The gradient therefore, also has an uncertainty. The uncertainty of the gradient can be obtained through the following steps:

i. Draw the lines of maximum and minimum gradient. The **line of minimum gradient** is the flattest line that can be drawn through the data points and error bars. The **line of maximum gradient** is the steepest line that can be drawn. These two lines must cross and pass through the centre of the line of best fit. Below is a *suggested* method by which these lines can be drawn.

- Locate the centre of the line of best fit.
- For the line of maximum gradient, draw the steepest possible line from the lower half of the first error bar, through the centre and to the upper half of the second error bar.

- For the line of minimum gradient, draw the flattest possible line from upper half of the first error bar through the centre of the line and to the lower half of the second error bar.
- Drawing the lines of best fit and maximum and minimum gradients by eye is a skill that you will be able to develop through constant practice. There are no rigid rules on how this is done and you need to use your best judgment every time.

ii. Calculate the maximum and minimum gradient.

iii. Uncertainty in the gradient = $\dfrac{\text{maximum gradient - minimum gradient}}{2}$

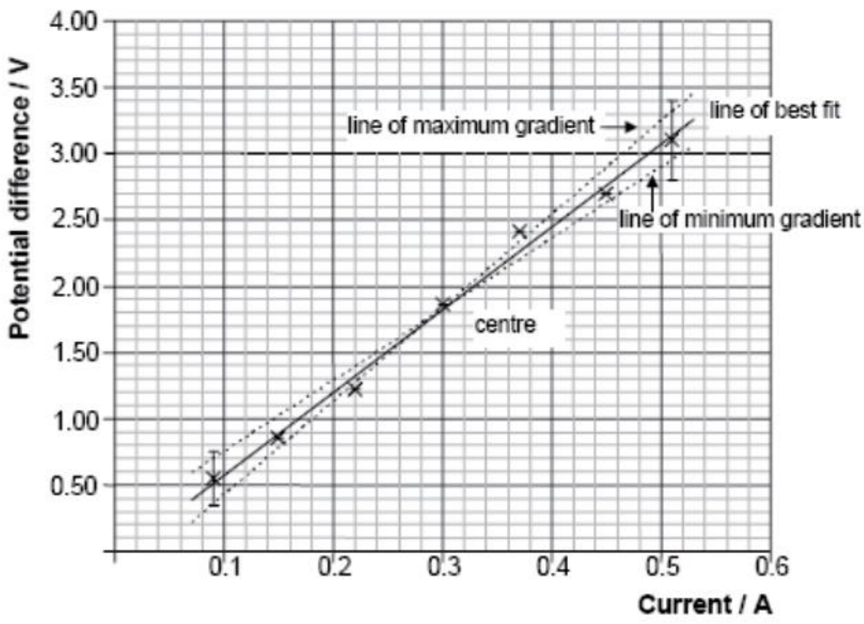


Figure 1018 The lines of maximum and minimum gradient

Example: Calculating the uncertainty in the gradient of a graph

Figure 1018 is derived from the graph in *Figure 817*. It has been shown that the gradient of the line of best fit for the graph is 6.3 Ω.

To obtain the uncertainty in the gradient, the maximum and minimum gradients need to be calculated. This can be done by selecting two convenient points on each line as shown below.

Calculating the maximum and minimum gradient

$$\text{maximum gradient} = \frac{3.10 - 0.70}{0.48 - 0.14} = 7.1\ \Omega$$

$$\text{minimum gradient} = \frac{2.80 - 1.10}{0.48 - 0.16} = 5.3\ \Omega$$

$$\text{uncertainty in the gradient} = \frac{7.1 - 5.3}{2} = 0.9\ \Omega$$

Therefore, the gradient is (6.3 ± 0.9) Ω

10.2.4 Interpreting the graph, the gradient and the y-intercept

Mathematical relationships

Drawing and interpreting graphs is an essential skill in the sciences and especially in Physics where relationships need to be derived. As an IB Diploma Physics student you need to be familiar with the common forms of graphs that appear in Physics. *Figure 1020* shows a number of typical physical relationships exhibited graphically.

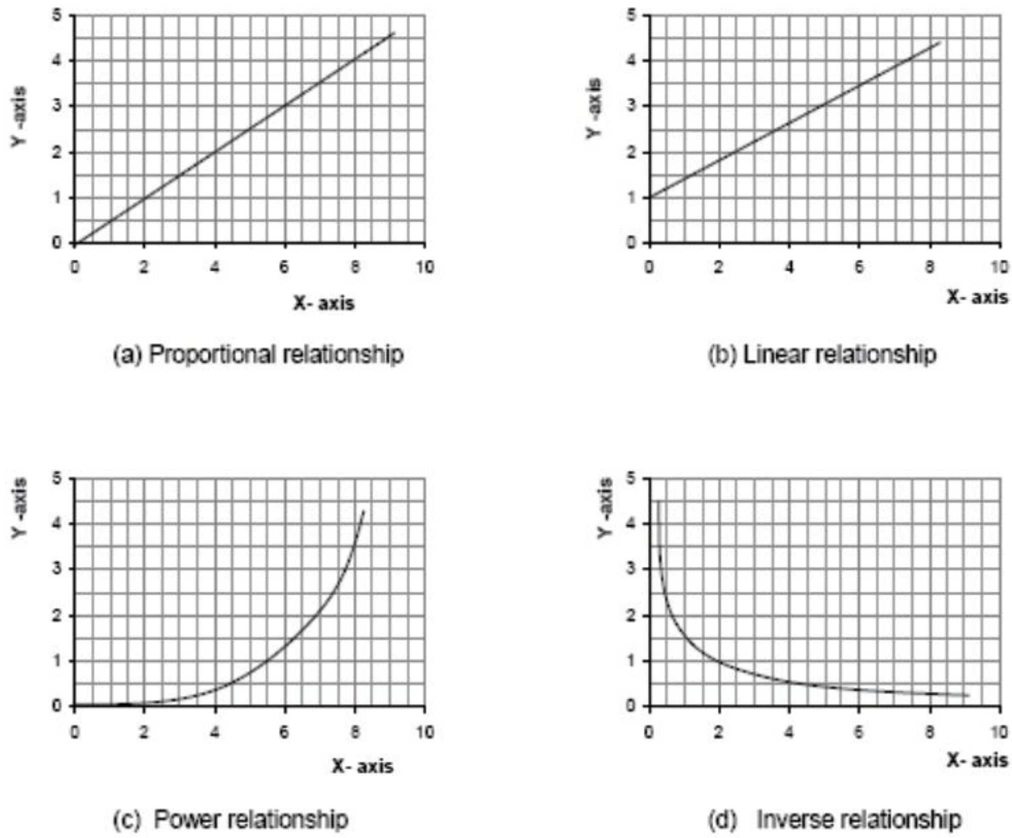


Figure 1020 Common mathematical relationships

Direct proportion

When the graph between two quantities is a straight line that passes through the origin, then the two quantities are directly proportional. Two quantities are directly proportional when one quantity is doubled, the other quantity is also doubled.

The relationship between the two quantities is expressed mathematically as y = kx where k is equal to the gradient of the line.

Examples of equations of this form, that you may verify through investigations are:

Second Law of motion $F = ma$ Charles' Law $V = kT$

Linear relationship

A linear relationship is shown by a straight line graph that does not pass through the origin. In this graph the ratio of the change in each variable is constant. This ratio is expressed as the gradient. The point where the line crosses the y-axis is called the y-intercept.

The relationship between the two quantities is expressed mathematically as $y = kx + c$ where k is equal to the gradient of the line and c is the y-intercept. (Sometimes m is used instead of k.)

Examples of equations of this form that you may verify through investigations are:

Kinematic equation: $v = u + at$

Internal resistance of a dry cell: $V = E - Ir$

Power relationship

Power relationships are of the form $y = kx^n$, where n is a constant number. In this relationship, the rate of change of one quantity with respect to the other is not constant. One quantity would be increasing faster than the other quantity. As a result, the graph is a curved line or non-linear.

Examples of equations of this form that you may verify through investigations are:

Kinematic equation: $s = \frac{at^2}{2}$

Period of a simple pendulum: $T = 2\pi\sqrt{\frac{L}{g}}$

Inverse relationship

Inverse relationships are of the form $y = \frac{k}{x^n}$ where n is a constant number. In this relationship, when one quantity increases, the other quantity decreases. This relationship results in a non-linear graph.

Example of physics equations of this form that you might verify through experimentation are:

Boyle's law: $P = \frac{k}{V}$

Coulomb force: $F = \frac{kq_1q_2}{r^2}$

The gradient

In most Physics investigations that you will be conducting, you will need to plot a graph whose gradient may be equal to a physical quantity or may be used to obtain a physical quantity. Aside from calculating the gradient, it is also necessary to determine the physical quantity it represents.

As an example, the gradient of the graph of distance against time represents speed because $\text{speed} = \frac{\text{distance}}{\text{time}}$

Other examples are shown in *Figure 1021*.

Experiment	Formula	x-axis	y-axis	Gradient
Acceleration along an inclined plane	$s = \frac{a\ t^2}{2}$	s	t^2	$\frac{a}{2}$
Second law of motion	$F = ma$	a	F	m
Simple pendulum	$T = 2\pi\sqrt{\frac{L}{g}}$	L	T^2	$\frac{4\pi^2}{g}$
Index of refraction by Snell's law	$\frac{\sin i}{\sin r} = n$	$\sin r$	$\sin i$	n
Internal resistance of a dry cell	$V = E - Ir$	I	V	$-r$

Figure 1021 Examples of experiments with a meaningful gradient

The Y-intercept

The y-intercept is the value of the quantity plotted along the y-axis, when the quantity along the x-axis is zero. *Figure 1022* shows some experiments where the y-intercept of the graph is significant.

Experiment	Formula	X-axis	Y-axis	Y-intercept
Focal length of a thin lens	$\frac{1}{f}=\frac{1}{v}+\frac{1}{u}$	$\frac{1}{u}$	$\frac{1}{v}$	$\frac{1}{f}$
Internal resistance of a dry cell	$V=E-Ir$	I	V	E

Figure 1022 Examples of experiments with a meaningful y-intercept

The uncertainty in the y intercept can be obtained by extending the lines of maximum and minimum gradients. These two lines will lead to the maximum and minimum values of the y-intercept. The uncertainty in the y-intercept is equal to half the range of the maximum and minimum y-intercepts.

$$\text{uncertainty in } y \text{ intercept} = \frac{\text{maximum } y \text{ intercept} - \text{minimum } y \text{ intercept}}{2}$$

Linear graphs with displaced origin

When the graph does not start at (0,0), the *y*-intercept can be obtained through mathematical methods. In the equation $y = mx + c$, substitute the coordinates of one point that is along the line of best fit for x and y, the calculated gradient for m (sometimes k) and solve for the constant c.

The y-intercept and systematic error

When the straight line of best fit does not pass through the origin, this may indicate the presence of a systematic error. As an example, consider an experiment designed to study the acceleration of a trolley along an inclined plane. This experiment is conducted by releasing the trolley from rest and measuring the time it takes for the trolley to travel various distances along an inclined plane. The y-intercept of the graph of distance fallen against time^2 should clearly be zero since the trolley should not take any time to travel zero distance. However, if there is a non-zero *y*-intercept on the graph, this indicates a systematic error in the results. Perhaps the times were all measured incorrectly but by the same amount and in the same direction. Depending on the value of the *y* - intercept, it could be that there was a delay in stopping the stop watch (human limitation - reaction time) or the stop watch was running slow (instrumental error – wrong **calibration**).

Note that the systematic error in this case would not affect the accuracy of the gradient obtained.

10.2.5 Linearising graphs

A straight-line graph is the most straightforward type of graph to interpret. The gradient can be easily calculated and the relationship between the two variables is easily obtained. However, not all relationships in nature produce straight-line graphs.

Linearising graphs where the relationship between variables is known

As an example, the relationship between the displacement *s* and the time of travel of a uniformly accelerating object is quadratic, that is $s = ½ at^2$. Thus, if a graph of the displacement *s* against the time *t* is plotted, a curved line results, as shown below in *Figure 1023*. The gradient at various points can be calculated using tangent lines and this process is both time-consuming and tedious.

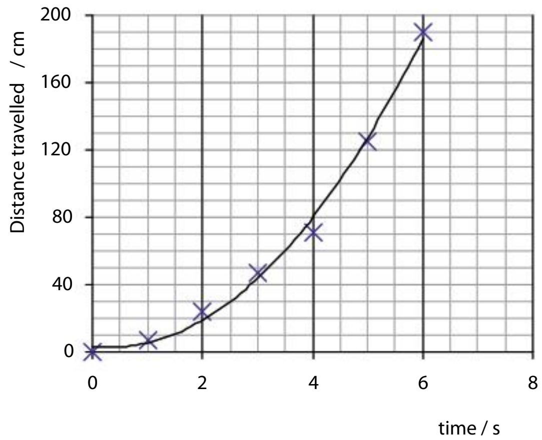
If the mathematical relationship between the two measured variables is known, the appropriate choice of function of one variable to plot can produce a straight-line graph. From the above equation, it is easy to see that $s \propto t^2$. Therefore a graph of *s versus* t^2 will produce a straight line. This method is called 'linearizing' data.

When linearizing data, any function (e.g. $y = x^2$) of the independent variable must be plotted along the x-axis.

An example is given in *Figure 1023*. The data given is for a trolley rolling down an inclined plane. The distance and time is measured using a motion sensor.

(a)

Time /s	Distance /cm
0	0.0
1	6.7
2	24.5
3	47.0
4	71.2
5	125.5
6	190.0



(b)

Time ^{2} /s ^{2}	Distance /cm
0	0.0
1	6.7
4	24.5
9	47.0
16	71.2
25	125.5
36	190.0

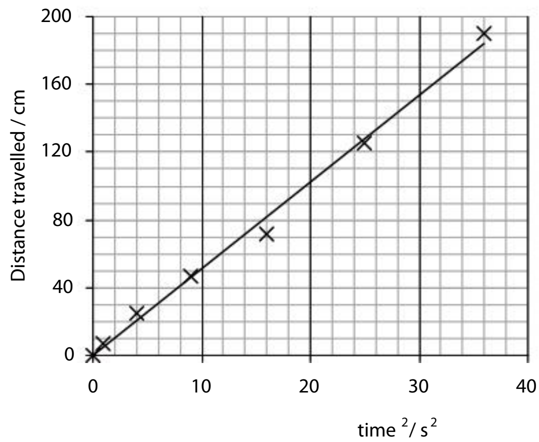


Figure 1023 Linearising a quadratic graph

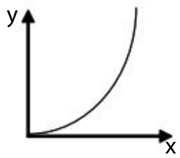
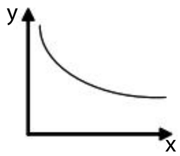
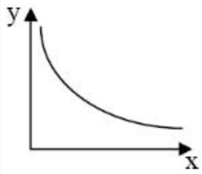
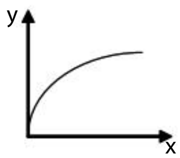
Equation	Graph shape	Example in Physics	Graph that would give a straight line through the origin
$y = kx^2$		Displacement-time relationship of uniformly accelerated motion $s = ½\,at^2$	s vs. t^2
$y = \frac{k}{x}$		Pressure-volume relationship of an ideal gas at constant temperature $P = k / V$	P vs. $1 / V$
$y = \frac{k}{x^2}$		Electrostatic force $F = k\, q_1 q_2 / r^2$	F vs. $1 / r^2$
$y = k\sqrt{x}$		Period of a simple pendulum $T = 2\pi\sqrt{\frac{L}{g}}$	T^2 vs. L

Figure 1024 Linearising some different mathematical relationships

Linearising graphs where the relationship between variables is unknown

The relationship between any two quantities can be expressed as $y = kx^n$. The value of the exponent n can be determined through the use of a logarithmic graph. The reasoning behind this is as follows:

If $y = kx^n$

- then $\log y = \log kx^n$
- $\log y = \log k + \log x^n$
- $\log y = \log k + n \log x$
- $\log y = n \log x + \log k$

Note that the equation log $y = n \log x + \log k$ is of the form $y = mx + c$. Therefore, plotting log y against log x will produce a straight line with a gradient equal to the exponent n and a y-intercept equal to the constant log k.

As an example, the data in *Figure 1023*(a) are converted into a logarithmic graph as shown below in *Figure 1025*. As shown in the table of results, the logarithm of the distance and time are determined. The plot of log s against log t produces a straight line. The equation of the line, through the use of Excel functions, shows that the gradient is 1.8 which can be rounded off to 2. Note that since the logarithm is a natural number, a logarithmic axis is unitless.

Time /s	Distance /cm	Log *t*	Log *s*
0	0.0	---	---
1	6.7	0.00	0.83
2	24.5	0.30	1.39
3	47.0	0.48	1.67
4	71.2	0.60	1.85
5	125.5	0.70	2.10
6	190.0	0.78	2.28

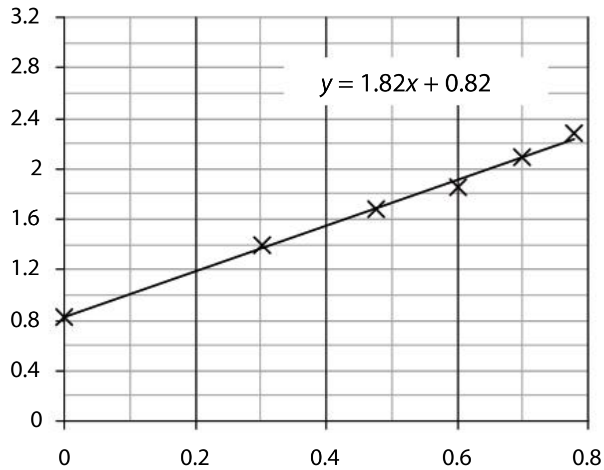
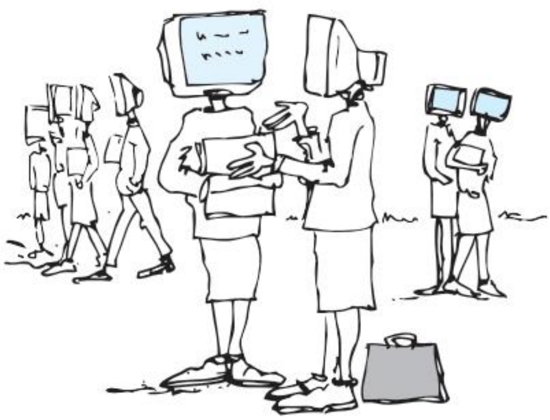


Figure 1025 Log-log graph



Example 1 Exploration

Task: Design an experiment that will investigate a property of the resonant frequency of a vibrating string.

Research Question: I will investigate how the tension in the string affects the resonant frequency of a string vibrating in its second harmonic.

Materials and apparatus

- Mechanical vibrator
- Frequency signal generator (0.1 Hz – 20 000 Hz)
- String (1.5 m)
- Pulley
- Slotted weights

Variables list

Independent Variable: tension in the string

Dependent variable: resonant frequency

Controlled variables: Length of the vibrating string, harmonic of vibration

Method

1. The set-up for the investigation is shown in Figure 1101. It is important that the string is kept horizontal when it is not vibrating. The pulley is adjusted to keep the string horizontal.

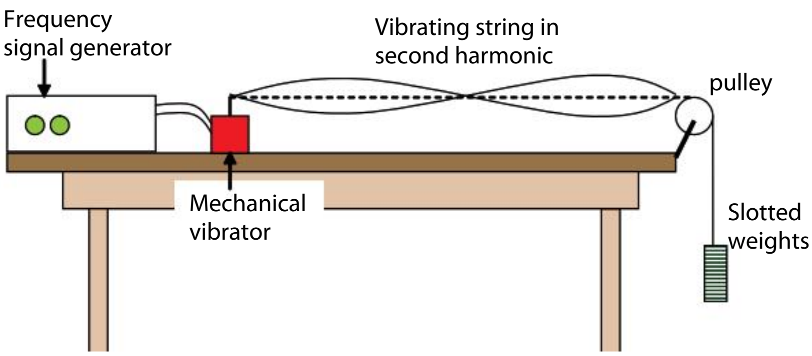


Figure 1101 Transverse waves in a string

2. *Manipulation of the independent variable*: The tension in the string will be varied by changing the mass of the hanging slotted weights. The masses that will be used are 100 g, 150 g, 200 g, 250 g, 300 g and 350 g. The tension in the string is then equal to the product of the mass and 9.8 m/s^2.

3. *Controlling variables*. The length of the vibrating string is kept constant at 1.2 metres. Only the resonant frequency for the second harmonic is to be measured.

4. *Determination of the resonant frequency*. With a 100 g mass load, the output frequency of the frequency signal generator will be adjusted until the string vibrates in two segments as shown in the diagram above. The output frequency will be fine tuned to produce the maximum amplitude. The frequency at which the amplitude of the vibrating string is a maximum is the resonant frequency. This frequency can be obtained from the settings of the signal frequency generator.

5. *Collecting sufficient data*. The process is to be repeated for the other load masses: 150 g, 200 g, 250 g, 300 g and 350 g.

6 *Collecting relevant data*. When the resonant frequency for each load is determined, the experiment will be repeated twice. The averaged value of the resonant frequencies measured for each mass will be used for the analysis.

Example 2 Analysis

Summary of Procedure

In this experiment, the circuit is set up such that the coil attracts the magnet. When the circuit is switched on, the weight of the magnet and the force of attraction between the coil and the magnet produces a moment which causes the metre stick to turn. The 50 g mass suspended from the other side of the pivot provides an opposing moment. The 50 g mass is moved so that the moments are balanced. See *Figure 1102*.

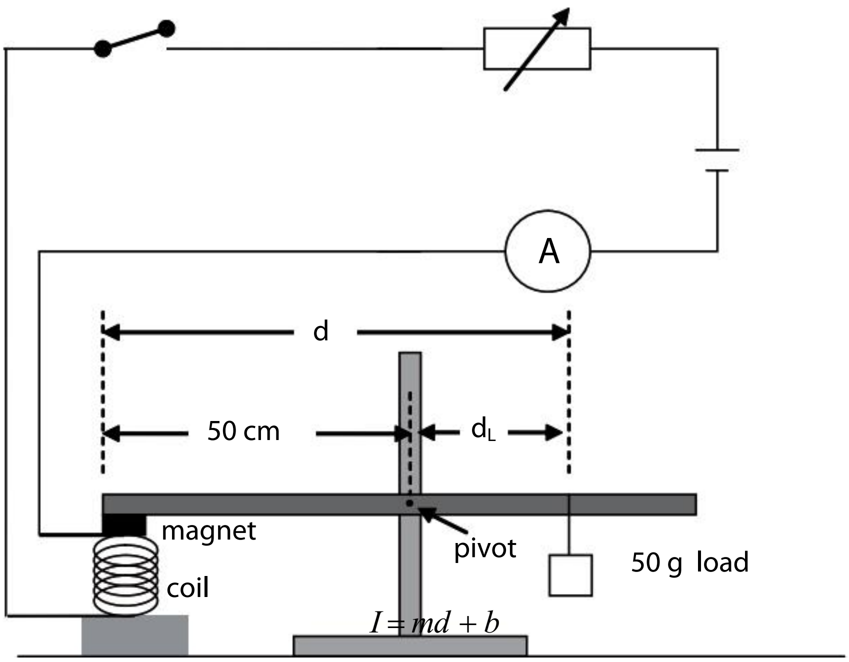


Figure 1102 Measuring the magnetic force of a current

Task

1. The current and the distance d are related by the equation

   $I = md + b$, where I = current through the coil

   d = distance from the magnet to the load

   and m and b are constants.

   Collect relevant data and use these data to prove this relationship is true. Obtain values of m and b. Include the associated uncertainties in the values.

2. The magnetic force F produced by the coil is proportional to the current I running through it, that is:

   $F = c \times I$ where c is a constant.

   Use your results to obtain a value for c. Include the associated uncertainties for c.

Data Collection

Mass of the magnet = (26.31 ± 0.01) g

Distance between the magnet and the load / m ± 0.01 m	Current through the coil / A ± 0.01 A			
	Trial 1	Trial 2	Trial 3	Average
0.70	0.31	0.25	0.23	0.26 ± 0.02
0.75	0.48	0.46	0.49	0.48
0.80	0.95	0.97	1.02	0.98
0.85	1.45	1.46	1.42	1.44
0.90	2.04	2.00	1.98	2.01
0.95	2.23	2.27	2.24	2.25
0.98	2.72	2.75	2.65	2.71± 0.03

Figure 1103 Measured currents for different distances between the magnet and the load

Data Analysis

Part 1 Proving the relationship and determining values of m and b

- The relationship $I = md + b$ is proven to be true by the graph of I against d shown in *Figure 1004*. A straight line with an equation $I = 8.85\ d + 6.05$ is obtained.
- The value of m is equal to the gradient of the line of best fit. The value of b is equal to the y-intercept of the line of best fit.
- Calculation of the uncertainties in the values of m and b is shown below.
- Uncertainty in gradient = $\frac{9.41 - 8.20}{2} = 0.6$
- Uncertainty in the y –intercept = $\frac{6.51 - 5.50}{2} = 0.5$
- $m = (8.9 \pm 0.5)$ A/m
- $b = (6.1 \pm 0.5)$ A

Moments present in the system:

Moment due to magnet's weight: magnet's mass × g × 0.50

$M \times g \times 0.50 = 0.02631 \times 9.8 \times 0.50 = 0.129$

Moment due to force by coil: $F \times 0.50 = 0.50\ c\ I$

Moment due to 50 g mass: $M \times g \times d_L = 0.050 \times g \times d_L$

$= 0.490\ d_L$, where d_L is the distance of the 50 g load from the pivot.

Sum of moments about the centre of the metre stick:

$0.129 + 0.50\ c\ I = 0.490\ d_L$

But $d_L = d - 0.50$

$0.129 + 0.50\ c\ I = 0.490\ (d - 0.50)$

$0.129 + 0.50\ c\ I = 0.490\ d - 0.245$

Solving for I

$$I = \left(\frac{0.490}{0.50\,c}\right)d - \left(\frac{0.245 + 0.129}{0.50c}\right)$$

By comparing the above equation to $I = md + b$, it can be seen that:

$$m = \frac{0.490}{0.50\,c}$$

$$c = \frac{0.490}{0.50 \times m} = \frac{0.490}{0.50 \times 8.9} = 0.11\ \text{N A}^{-1}$$

Uncertainty in c = relative error in the gradient × 0.11

$$= \frac{0.5}{8.9} \times 0.11 = 0.006$$

Therefore: $c = (0.110 \pm 0.006)\ N\ A^{-1}$

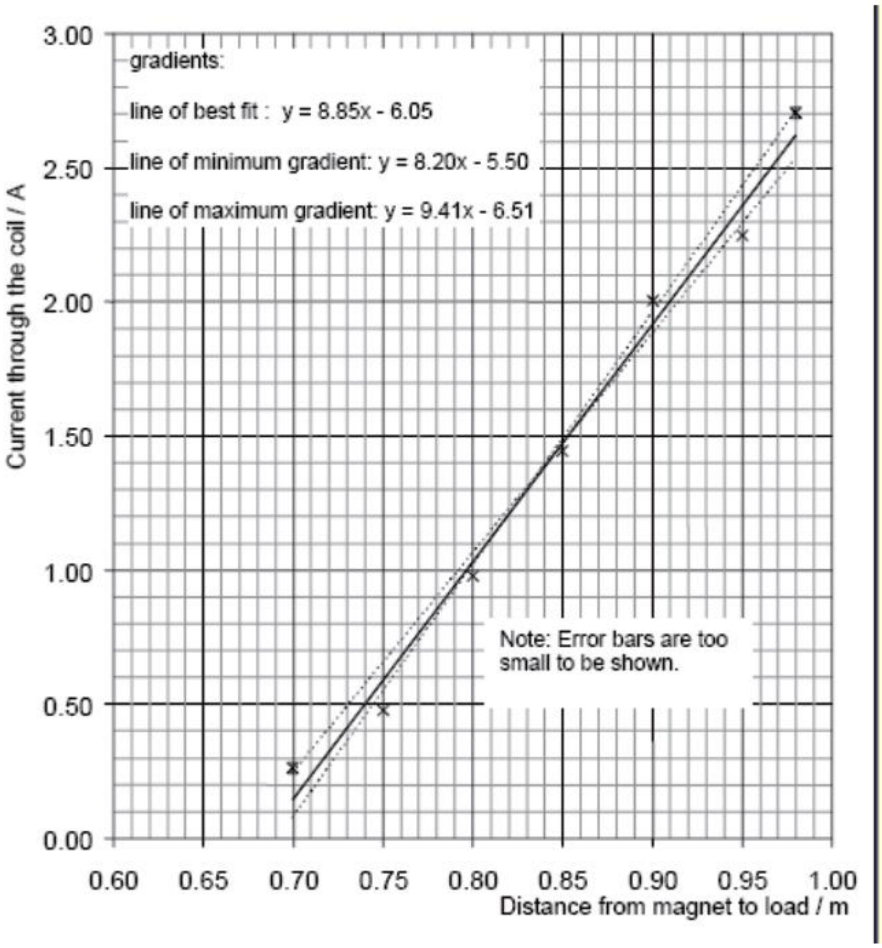


Figure 1104 Determining the gradient of a straight line

This chapter contains a range of different exercises designed to review and assess the skills related to investigative work. Answers are provided at the end of the chapter.

Questions

1. The manufacturer of a digital ammeter quotes its uncertainty as ±1.5% ± 2 digits. The 1% applies to the total reading and ± 2 digits is the uncertainty in the final figure of the display.

(a) Determine the uncertainty in a constant reading of 2.64 A.

(b) The meter is used to measure the current from a d.c. power supply. The current is found to fluctuate randomly between 1.58 A and 2.04 A. Determine the most likely value of the current, with its absolute uncertainty.

2. Suggest appropriate instruments for the measurement of:

(a) The discharge current of a capacitor (of the order of 10^{-6} A).

(b) The time for a feather to fall through the air through a distance of about 50 cm.

(c) The time taken for a ball to fall vertically through a distance of about 50 cm.

(d) The length of a simple pendulum with a period of about 1 second.

(e) The temperature of water as it cools to temperature from its boiling point.

(f) The temperature of a blue Bunsen flame.

(g) The mass of 20 small ball bearings.

(h) The mass of a house brick.

3. A student has been asked to investigate how the resistance of a thermistor varies with temperature. The table below shows the raw data and processed data. Identify the examples of bad practice.

Potential difference/V	Current when temperature increasing/ mA	Current when temperature decreasing/ mA	Average current I	Resistance kΩ	Temperature /C
3.0	96	87	91.5	3.28	4.0
3.02	120	114	117	2.58	10
3.0	134	138	136	2.21	15
3.1	175	180	177	1.75	21
1.58	114	129	122	1.3	30
0.76	170	161	165	0.461	50

4. Express each of the following quantities in SI base units.

(a) 1500 mA

(b) 750 g

(c) 250 GW

(d) 0.52 km

(e) 600 nm

(f) 150 micro seconds

(g) 5 cm

(h) 50 MW

5. How many significant figures are quoted in each of the measured quantities?

(a) 566.2 kJ

(b) 0.00032 m

(c) 602.5 kg

(d) 42.5300 s

(e) 5.6×10^3 W

(f) 0.00840 V

6.

(a) The current in a resistor is to be measured. State one source of random uncertainty and one source of systematic error.

(b) The diameter of a wire is to be measured using a micrometer screw gauge.

(i) Suggest two sources of systematic error.

(ii) Suggest why measurements are taken spirally along the whole length of the wire.

7. The attenuation of a gamma-ray beam is the reduction in intensity due to the beams' passage through a material. One way of investigating the attenutation of a gamma-ray beam is to measure the half-value thickness. The half-value thickness is the thickness of material that reduces the intensity of a parallel gamma-ray beam to half its orginal value. Design an investigation to measure the half-value thickness of a named material.

State a research question, present and classify the relevant variables and briefly outline a suitable methodology and safety precautions.

You will not be told by your physics teacher what to investigate for your Individual Investigation, or what apparatus to use, but answering this question will help you develop some of the skills necessary for a successful Invidividual Investigation.

Answers (suggested)

1. (1.5/100 × ± 2.64 A) ± 0.02 = ±0.0596, or ± 0.06 A (to two d.p.)

The median value is 2.01 A, then (1.5/100 × ± 2.01 A) ±0.02 = ± 0.05015 A, or ±0.05 A

2.

(a) Microammeter/ Multimeter with resistance range

(b) Stopwatch (manual), iPhone or Android with appropriate App

(c) Light gates and electronic stopwatch

(d) Metre rule

(e) Liquid-in-glass thermometer (alcohol) or electronic temperature probe with computer interface

(f) Calibrated thermocouple

(g) Top pan electronic balance capable of measuring 10 g to ± 0.01 g.

(h) Top pan balance capable of measuring 5 kg to ± 10g or bathroom scales.

3. Names of all units should be followed by a solidus: /. The units for Celsius are missing the degree symbol. C is the unit for Coulomb. The units of average current are milliamp, mA. *I* is the symbol for current. There is inconsistency in the number of decimal places/ significant figures for measurements of temperature, resistance, average current and potential difference. The temperature being the independent variable should be the first column. Random uncertainties (errors) should be recorded at the top of each column in the data table. The processed data cannot have more significant figures than the raw data. Resistance should be expressed in Ohms.

4.

(a) 1.5 A

(b) 0.750 kg or 7.50×10^{-1} kg

(c) 250000000000 W or 2.5×10^{11} W

(d) 5.2×10^{2} m

(e) 0.0000006 m or 6×10^{-7} m

(f) 0.00015 s or 1.5×10^{-4} s

(g) 0.05 m or 5×10^{-2} m

(h) 50000000 MW or 5×10^{7} MW

5.

(a) 4

(b) 2

(c) 4

(d) 6

(e) 2

(f) 3

6.

(a) **Random uncertainty** could be due to a parallax error when taking a reading. This can be reduced by the use of a mirror behind the scale and viewing normally.

A systematic error could be due to a zero error, or a wrongly calibrated scale. This can be reduced by checking for a 'zero reading' before recording the measurement, or using two ammeters in series and checking that the two readings agree.

(b) (i) Zero error on drum of micrometer; extraneous material between faces gripping the wire; to allow for a non-circular cross section,

(ii) Moving along its length to allow for tapering.

7.

Research Question

To investigate the relationship between the thickness of the lead blocks/sheets and the intensity of the transmitted γ radiation. and to determine the half-value thickness of lead for the γ radiation emitted by a source of cobalt-60.

Variable classification

Independent variable

The thickness of the lead blocks or sheet.

Dependent variable

Count rate recorded by Geiger-Müller counter.

Controlled variables

Nature of cobalt-60 source; nature of Geiger-Müller counter, distances between cobalt-60 source and lead block and distance between lead block/sheet and Geiger-Müller counter.

Outline of Method

1. Set up the GM tube and counter to take a background reading. This background value will be subtracted from each subsequent reading taken when using the gamma source.
2. Fix the gamma source 10–15 cm from the front window of the GM tube. The separation of the source and the counter and the orientation of the source must be fixed.
3. Take a reading of the number of gamma photons over an appropriate time interval.
4. Insert one lead block/sheet between the tube and source close to the GM tube; record the count rate for this absorber thickness
5. Increase the number of lead sheets (increasing the thickness) or use blocks of increasing thickness placed between the counter and the source and record all count rates.
6. Repeat procedure so an average count rate (for the different thicknesses) can be calculated.
7. Measure the thickness of the lead block, d, using a vernier caliper or other appropriate device.

   (*using a vernier is not appropriate for blocks*)
8. Plot a graph of corrected count rate against thickness and determine the thickness of lead for which half the incident gamma radiation is absorbed.

Safety Procedure

The cobalt-60 source is to be handled with tongs and I will wear gloves. I will not point the source at myself or any other students in the laboratory. I will replace the source in its lead-lined box immediately after use.

Absolute uncertainty

The absolute uncertainty in a measurement is due to the inherent variations in the measurement process itself.

Absolute error

The absolute error in a result is due to the combined effects of the uncertainties in the measurements that were used to obtain the result.

(The absolute uncertainty or error is expressed in the same unit as the measurement.)

Accuracy

A measure of the total error in your measured value. The accuracy of a measurement depends on the experimental techniques and equipment used. Accuracy can be improved by removing or minimising error.

Anomalous data

Data with unexpected values that do not match the relationship predicted by the hypothesis. Anomalous results can be due to experimental error.

Calibration

Standardisation of the measurement scale of an instrument or apparatus.

Conclusion

A conclusion is an interpretation of experimental data. The conclusion should, if possible, show whether the data support or reject any hypothesis put forward.

Controlled variable

Controlled variables are potential variables which are fixed and not allowed to vary during an investigation.

Data

In an experiment, data refers to the measurement or observation recorded. The singular form of data is *datum*.

Dependent variable

This is the variable that is assumed to respond to the changes the experimenter makes to the independent variable. The change in the dependent variable is not under the control of the experimenter. This is also known as the output variable.

Evaluation

This involves the consideration of all errors, random and systematic, which may affect the results, identifying weakness and limitations in the method, calculating the total error present in the results and explaining how the errors can be minimised.

Experimental error

This term refers to the incorrectness of data. It is mathematically equal to the difference between the measured value and the correct value.

Extrapolation

The process of extending the mathematical relationship between the two variables beyond the known range by assuming that the variables will continue to behave as they have in the known range.

Fair test

A test in which only one variable is manipulated or changed while keeping the other variables constant. By carrying out a fair test, the experimenter can be sure that it is only the variable that has been changed (independent variable) which is affecting what is being measured (dependent variable).

Hypothesis

A tentative or interim explanation for an observation, phenomenon, or physical problem whose predictions may be tested by further investigation. Formally, a hypothesis is made before conducting an experimental investigation.

Independent variable

An independent variable is the variable that is manipulated by the experimenter. In an experiment, this is the variable that is supposed to cause a change in the dependent variable.

Inference

An inference is a tentative conclusion drawn from a series of observations. It may lead to the formulation of a hypothesis.

Interpolation

To estimate a value for a variable between two or more known values. This is frequently done graphically.

Law

A scientific law is a generalisation that scientists make from an extensive body of research findings. A useful scientific law can be used to accurately predict what will happen in a range of situations.

Limitations

The restrictions of a particular experimental technique or set of apparatus. Limitations encountered during an investigation could influence the results and would need to be addressed in the evaluation.

Literature value

A value from the physical literature of a physical constant or experimental measurement.

Observation

Observations are changes that can be measured or described (see qualitative and quantitative data below). Changes can be seen, heard, smelt, tasted or felt during an investigation.

Precision

The precision of the measurement describes how close this measurement is to other similar measurements when the process is repeated.

Percentage error

A percentage error is an error expressed as a percentage of the value measured or of the true value.

Prediction

Predictions are a consequence of a hypothesis and descriptions of the results you expect to obtain from an investigation.

Processed data

Raw data which have been organised and/or mathematically or graphically transformed.

Propagation of errors

Calculating the overall error from a series of mathematical operations.

Qualitative data

Qualitative data refers to observations made without measurements and are described in words.

Quantitative data

Quantitative data refers to numerical measurements.

Replication

This involves repeating a test, or observation, a number of times.

Random error

Random errors are present every time a measurement is recorded. Their effects can be reduced by repeating the measurement and averaging.

Raw data

This is unanalysed data which have not yet been processed or analysed.

Reliability

A measure of the confidence that can be placed in a set of observations or measurements. The reliability of a set of observations or measurements depends on the number and accuracy of the individual observations or measurements. Reliability can be improved by replicating observations and measurements.

Risk assessment

A consideration of the possible safety hazards that could be encountered during an investigation.

Sensitivity

The ratio between the change in measurement to the change in measured quantity.

Significant figures

The significant figures in a number are those that are meaningful.

Standard deviation

A measure of dispersion, providing an estimate of the average deviation of data points from the mean.

Systematic error

An error which biases your measurements in some predictable but perhaps unknown or unrecognised way. Systematic errors can not be reduced by repeating the measurement and averaging.

Tests

Investigations are usually composed of a number of tests where one variable is manipulated or changed.

Theory

A set of statements or principles devised to explain a group of facts or phenomena, especially one that has been repeatedly tested or is widely accepted and can be used to make predictions.

Trend

The general direction, tendency or patterns shown by a set of measurements or observations.

Uncertainty

An uncertainty is the range that will likely contain the true value of whatever is being measured.

Validity

A measure of the confidence that can be placed in a conclusion. The validity depends on factors such as the range and reliability of observations and measurements. Statistical tests may be used to place a value on the reliability of data.

Variable

The conditions or factors that can vary and may be varied during an experiment. As far as possible only one variable should be changed or manipulated at a time.

Variability

The degree to which the observations or measurements differ from one another.