HIGHER LEVEL

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HIGHER LEVEL

Physics

for the IB Diploma Programme

3rd Edition

Pearson

CHRIS HAMPER
EMMA MITCHELL

HIGHER LEVEL

Physics

for the IB Diploma Programme

Chris Hamper, Emma Mitchell

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Contents

Syllabus roadmap

The aim of the syllabus is to integrate concepts, topic content and the NOS through inquiry. Students and teachers are encouraged to personalize their approach to the syllabus according to their circumstances and interests.

Skills in the study of physics should be integrated into the syllabus content.

A. Space, time and motion	**B. The particulate nature of matter**	**C. Wave behaviour**	**D. Fields**	**E. Nuclear and quantum physics**
A.1 Kinematics* A.2 Forces and momentum* A.3 Work, energy and power* A.4 Rigid body mechanics*** A.5 Galilean and special relativity***	B.1 Thermal energy transfers* B.2 Greenhouse effect* B.3 Gas laws* B.4 Thermodynamics*** B.5 Current and circuits*	C.1 Simple harmonic motion** C.2 Wave model* C.3 Wave phenomena** C.4 Standing waves and resonance* C.5 Doppler effect**	D.1 Gravitational fields** D.2 Electric and magnetic fields** D.3 Motion in electromagnetic fields* D.4 Induction***	E.1 Structure of the atom** E.2 Quantum physics*** E.3 Radioactive decay** E.4 Fission* E.5 Fusion and stars*

* Topics with content that should be taught to all students

** Topics with additional HL content

*** Topics with content for HL students only

Authors' introduction to the third edition

Welcome to your study of IB Diploma Programme (DP) Higher Level (HL) physics! This textbook has been written to match the specifications of the new physics curriculum for first assessments in 2025 and gives comprehensive coverage of the course.

Content

The book covers the content that is common to all DP physics students and the additional material for HL students.

HL The additional HL material is labeled as such, and the sequence of the chapters matches the sequence of the subject guide themes, with textbook chapter numbering matching the guide topic numbering.

Each chapter starts with a caption for the opening image, the Guiding Questions, an introduction (which gives the context of the topic and how it relates to your previous knowledge) and the Understandings for the topic. These will give a sense of what is to come, with the Understandings providing the ultimate checklists for when you are preparing for assessments.

Guiding Questions

How can the motion of a body be described quantitatively and qualitatively?

How can the position of a body in space and time be predicted?

The text covers the course content using plain language, with all scientific terms explained. We have been careful to apply the same terminology you will see in IB examinations in worked examples and questions.

Linking Questions that relate topics to one another can be found throughout, with a hint as to where the answer might be located. The purpose of Linking Questions is to connect different areas of the subject to one another – between topics and to the Nature of Science (NOS) more generally. These questions will encourage an open mind about the scope of the course during your first read through and will be superb stimuli for revision.

How does the motion of a mass (A.1) in a gravitational field (D.1) compare to the motion of a charged particle in an electric field (D.2)?

Each chapter concludes with Guiding Questions revisited and a summary of the chapter, in which we describe how we sought to present the material and what you should now know, understand and be able to do. The Guiding Question revisited bulleted lists are available as downloadable PDFs from the eBook to help you with revision.

Guiding Questions revisited

How can we use our knowledge and understanding of the torques acting on a system to predict changes in rotational motion?

If no external torque acts on a system, what physical quantity remains constant for a rotating body?

Aims

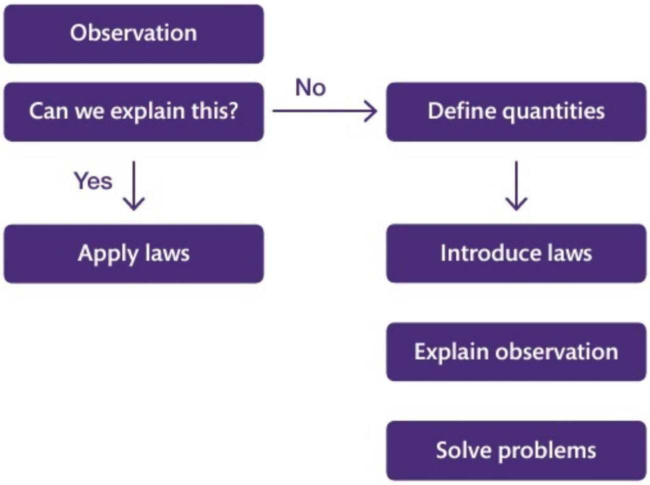
Using this textbook as part of your course will help you meet these IB DP physics aims to:

- develop conceptual understanding that allows connections to be made between different areas of the subject, and to other DP sciences subjects
- acquire and apply a body of knowledge, methods, tools and techniques that characterize science
- develop the ability to analyze, evaluate and synthesize scientific information and claims
- develop the ability to approach unfamiliar situations with creativity and resilience
- design and model solutions to local and global problems in a scientific context
- develop an appreciation of the possibilities and limitations of science
- develop technology skills in a scientific context
- develop the ability to communicate and collaborate effectively
- develop awareness of the ethical, environmental, economic, cultural and social impact of science.

Nature of physics

Physicists attempt to understand the nature of the Universe. They seek to expand knowledge through testing hypotheses and explaining observations, and by a commitment to checking and re-checking in a bid to set out basic principles. 'Doing physics' involves collecting evidence to reach partial conclusions, creating models to mediate and enable understanding, and using technology.

Physics flowchart.



You will find examples of the nature of physics throughout this book, such as the scattering experiments in E.1, the speed of light in A.5, the relationships between pressure, volume and temperature in B.3, and detecting radiation in E.3.

Nature of Science

Throughout the course, you are encouraged to think about the nature of scientific knowledge and the scientific process as it applies to physics. Examples are given of the evolution of physical theories as new information is gained, the use of models to conceptualize our understanding, and the ways in which experimental work is enhanced by modern technologies. Ethical considerations, environmental impacts, the importance of objectivity and the responsibilities regarding scientists' code of conduct are also considered here. The emphasis is not on memorization, but rather on appreciating the broader conceptual themes in context. We have included some examples but hope that you will come up with your own as you keep these ideas at the forefront of your learning.

The following table provides a comprehensive list of the elements of the Nature of Science that you should become familiar with.

Element	Details
Making observations	Using the human senses, or instruments, and identifying new fields for exploration.
Identifying patterns and trends	Using inductive reasoning (from specific cases to more general laws) and classification of bodies (in overlapping ways), and distinguishing between correlation (relationships between two variables) and causation (when one variable has an effect on another).
Suggesting and testing hypotheses	Provisional qualitative and quantitative relationships with explanations before experimentation is carried out, which can then be tested and evaluated.
Experimentation	The process of obtaining data, testing hypotheses, controlling variables, deciding the appropriate quantity of data and developing technology that requires creativity and imagination.
Measuring	Recognizing limitations in precision and accuracy, carrying out repeats for reliability, and accepting the existence of and quantifying the random errors that lead to imprecision and uncertainty and the systematic errors that lead to inaccuracy.
Using models	Artificial representations of natural phenomena that are useful when direct observation is difficult, and simplifications of complex systems in the form of physical representations, abstract diagrams, mathematical equations or algorithms, which have inherent limitations.
Collecting evidence	Used to evaluate scientific claims to support or refute scientific knowledge.
Proposing and using theories	Understanding theories (general explanations with wide applicability), deductive reasoning (from the general to the specific) when testing for corroboration or falsification of the theory, paradigm shifts (new and different ways of thinking) and laws (that allow predictions without explanation).
Falsification	Accepting that evidence can refute a claim but cannot prove truth with certainty.
Perceiving science as a shared endeavor	Making use of agreed conventions, common terminology and peer review in the spirit of global communication and collaboration.
Commitment to global impact	Assessing risk to ensure that no harm is done and the ethical, environmental, political, social, cultural, economic and unintended consequences that work may have through compliance with ethics boards and by communicating honestly and clearly with the public.

Learning physics

Approaches to learning

The IB aspires for all students to become more skilled in thinking, communicating, social activities, research and self-management.

In physics, thinking might include:

- being curious about the natural world
- asking questions and framing hypotheses based upon sensible scientific rationale
- designing procedures and models
- reflecting on the credibility of results
- providing a reasoned argument to support conclusions
- evaluating and defending ethical positions
- combining different ideas in order to create new understandings
- applying key ideas and facts in new contexts
- engaging with, and designing, linking questions
- experimenting with new strategies for learning
- reflecting at all stages of the assessment and learning cycle.

High-quality communication looks like:

- practicing active listening skills
- evaluating extended writing in terms of relevance and structure
- applying interpretive techniques to different forms of media
- reflecting on the needs of the audience when creating engaging presentations
- clearly communicating complex ideas in response to open-ended questions
- using digital media for communicating information
- using terminology, symbols and communication conventions consistently and correctly
- presenting data appropriately
- delivering constructive criticism.

The learning you will do socially could involve:

- working collaboratively to achieve a common goal
- assigning and accepting specific roles during group activities
- appreciating the diverse talents and needs of others
- resolving conflicts during collaborative work
- actively seeking and considering the perspective of others
- reflecting on the impact of personal behavior or comments on others
- constructively assessing the contribution of peers.

You will carry out research, in particular during the Internal Assessment, that includes:

- evaluating information sources for accuracy, bias, credibility and relevance
- explicitly discussing the importance of academic integrity and full acknowledgement of the ideas of others
- using a single, standard method of referencing and citation
- comparing, contrasting and validating information
- using search engines and libraries effectively.

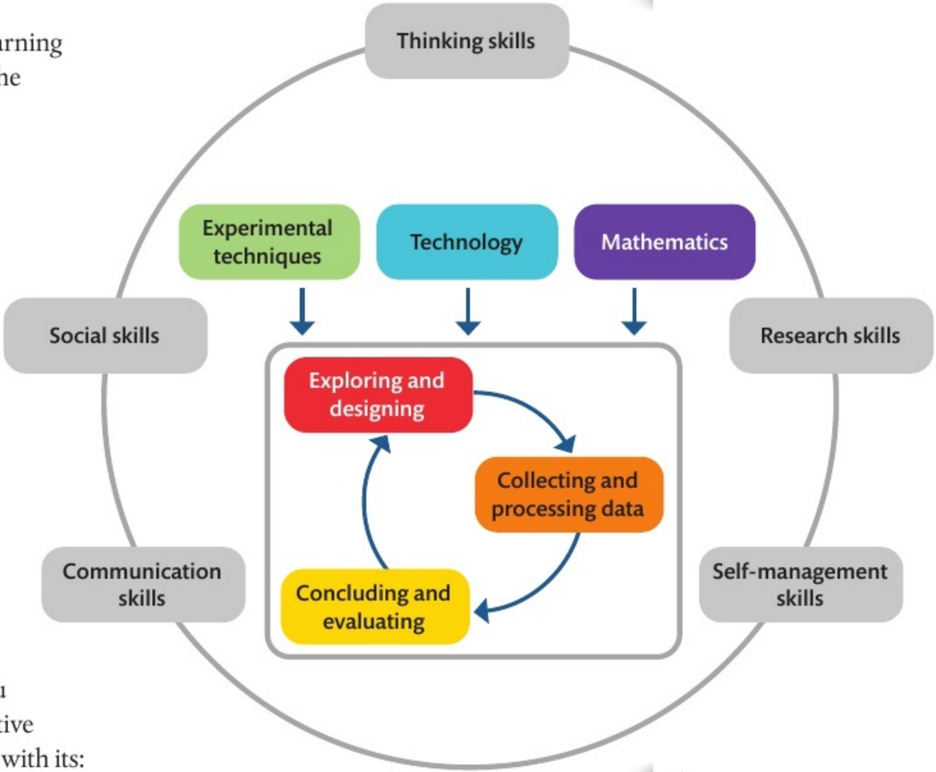
And remember that a significant component of learning comes from you. Maybe you have even reflected on your skills while reading these bullet points! How competent are you at these self-management skills?

- breaking down major tasks into a sequence of stages
- being punctual and meeting deadlines
- taking risks and regarding setbacks as opportunities for growth
- avoiding unnecessary distractions
- drafting, revising and improving academic work
- setting learning goals and adjusting them in response to experience
- seeking and acting on feedback.

Inquiry

Combining the approaches to learning above will facilitate your use of the tools in physics: experimental techniques, technology and mathematics. The next chapter specifically highlights some of these tools; the rest can be found throughout the book.

In turn, these tools will enable you to thrive in the inquiry process, which involves exploring and designing, collecting and processing data, and concluding and evaluating. There are opportunities to practice the inquiry process in this book, and the Internal Assessment chapter includes an eBook link to exemplar work. You are also sure to find the collaborative sciences project to be a highlight, with its:



Tools for physics.

- inclusion of real-world problems
- integration of factual, procedural and conceptual knowledge through study of scientific disciplines
- understanding of interrelated systems, mechanisms and processes
- solution-focused strategies
- critical lens for evaluation and reflection
- global interconnectedness (regional, national and local)
- appreciation of collective action and international cooperation.

Learner profile

There is an abundance of ways in which your physics course will support your all-round growth as an IB learner.

Learning attribute	Advice on how to develop
Inquirer	• Be curious, conduct research and try to become more independent. • Ask questions about the world, search for answers and experiment. • Extend your scientific knowledge and engage with existing research.
Knowledgeable	• Explore concepts, ideas and issues, and seek to deepen your understanding of facts and procedures. • Access a variety of resources. • Apply your knowledge to unfamiliar contexts.
Thinker	• Solve complex problems while reflecting on your strategies. • Analyze methods critically and embrace creativity when seeking solutions. • Practice reasoning and critical thinking (testing assumptions, formulating hypotheses, interpreting data and drawing conclusions from evidence).
Communicator	• Accept opportunities to collaborate. • Step out of your comfort zone during group work, for example, by opening discussions or using scientific language. • Listen to others and share your ideas.
Principled	• Take responsibility for your work, promoting shared values and acting in an ethical manner. • Acknowledge the work of others, cite your sources and reduce waste. • To show integrity during data collection, consider all data, including that which does not match your hypothesis.
Open-minded	• Be aware of the existence of different perspectives and models. • Reject or refine your models due to reasoning, deduction or falsification. • Challenge perspectives and ideas.
Caring	• Protect your environment and aim to improve the lives of others. • Choose sustainable practices. • Connect topics to global challenges (like healthcare, energy supply, food production).
Risk-taker	• Seek opportunities for learning and challenge. • Recognize your freedom to try different techniques or methods of learning. • Collect experimental data in a bid to falsify (not just validate) ideas.
Balanced	• Look holistically at your own development and consider how attentive you are to your tasks. • Have a balanced perspective on scientific issues. • Organize your time to avoid negative impacts on the emotional or social aspects of your life.
Reflective	• Consider why and how success is achieved, and how you might change your approach when learning becomes difficult. • Review your strategies, methods, techniques and approaches, for example, using success criteria. • Reflect on your internal network of knowledge.

How to use this book

The book is written according to the following approach, in which we use electric fields as an example.

Observation →

- Two rubbed balloons move apart

Explanation →

- Acceleration
- Unbalanced forces
- Charge

Laws →

- Coulomb's law
- Work done and potential energy

Solving problems

- Exploring field strength and potential gradient
- Interpreting further observations of attraction or current electricity
- Anticipating the model of the atom

Observation

The aim of the course is to be able to model the physical Universe, so first we must consider a physical process.

A student observes two rubbed balloons moving apart and wonders why they repel. They realize that there must be an unbalanced force. That is the beauty of physical laws; they are always right. The student recognizes a similarity with gravity, which is related to the mass of a body. But gravitational forces are weak and only attractive.

So what is the key property of the body and what is the force? The student does not know, so they have to add something to their model of the Universe.

Explanation

Having studied mechanics and particles, the student has some knowledge of the fundamentals of physics. They know that a body will only accelerate if there is an unbalanced force. We could stop there if this was enough to explain everything, but it is not.

The student reads about a new property, charge. Using what they know about gravitational fields, they expect to learn about field strength (in this case, electric) and wonder if electric forces follow an inverse square law. They carry out an experiment to confirm this.

Laws

Some research reveals that electric forces (like all forces) are vectors, that Coulomb's law applies to point charges, and that moving a charge in an electric field requires a force (so work is done).

They then become curious about the energies involved and read about electric potential energy. They know, using the tool of mathematics, that the area of a graph is the integral of the function and that the reverse of integration is differentiation, so the gradient of a graph of potential energy vs position could be force.

The student is unclear about how field strength can be zero when potential energy is non-zero. They use a simulation and apply the definitions of field strength and potential to a point midway between two equal charges to explore these ideas.

Solving problems

The student makes two further observations. The first is of the attraction between a balloon and a sweater. What might they determine from this? The student then observes their teacher demonstrating a simple electric circuit. What is the connection between the balloons and the circuit?

Based on observations, physicists define quantities and make up a series of rules and laws that fit the observations. They then use these laws to explain further observations, make predictions and solve problems. And it goes on! Having added to their knowledge, the student could now use what they know about mechanics and electricity to develop an understanding of atomic structure.

This example shows how the structure of the book connects factual, procedural and metacognitive knowledge and recognizes the importance of connecting learning with conceptual understanding. Learning physics is a non-linear, ongoing process of adding new knowledge, evolving understanding and identifying misconceptions.

Key to boxes

A popular feature of the book is the different colored boxes interspersed through each chapter. These are used to enhance your learning as explained below.

Nature of Science

This is an overarching theme in the course to promote concept-based learning. Through the book, you should recognize some similar themes emerging across different topics. We hope they help you to develop your own skills in scientific literacy.

Nature of Science

The principle of conservation of momentum is a consequence of Newton's laws of motion applied to the collision between two bodies. If this applies to two isolated bodies, we can generalize that it applies to any number of isolated bodies. Here we will consider colliding balls but it also applies to collisions between microscopic particles such as atoms.

Dynamic friction is less than static friction so once a car starts to skid on a corner it will continue. This is also why it is not a good idea to spin the wheels of a car while going round a corner.

Global context

The impact of the study of physics is global, and includes environmental, political and socio-economic considerations. Examples of this are given here to help you to see the importance of physics in an international context.

Negative time does not mean going back in time – it means the time before you started the clock.

Interesting facts

These give background information that will add to your wider knowledge of the topic and make links with other topics and subjects. Aspects such as historic notes on the life of scientists and origins of names are included here.

Skills

These indicate links to eBook resources that include ideas for experiments, technology and mathematics that will support your learning in the course, and help you prepare for the Internal Assessment. Look out for the grey eBook icons.

SKILLS

To find the decay constant and hence half-life of short-lived isotopes, the change in activity can be measured over a period of time using a GM tube.

Theory of Knowledge

These stimulate thought and consideration of knowledge issues as they arise in context. Each box contains open questions to help trigger critical thinking and discussion.

TOK

Color is perceived but wavelength is measured.

Key fact

These key facts are drawn out of the main text and highlighted in bold. This will help you to identify the core learning points within each section. They also act as a quick summary for review.

$$\textbf{velocity} = \frac{\textbf{displacement}}{\textbf{time}}$$

Hint

These give hints on how to approach questions, and suggest approaches that examiners like to see. They also identify common pitfalls in understanding, and omissions made in answering questions.

It is very important to realize that Newton's third law is about two bodies. Avoid statements of this law that do not mention anything about there being two bodies.

Challenge yourself

These boxes contain open questions that encourage you to think about the topic in more depth, or to make detailed connections with other topics. They are designed to be challenging and to make you think. The answers to challenge yourself questions can be found with the exercise and practice question answers.

Challenge yourself

1. A projectile is launched perpendicular to a 30° slope at $20\,\text{m}\,\text{s}^{-1}$. Calculate the distance between the launching position and landing position.

Toward the end of the book, there are four appendix chapters: Theory of Knowledge as it relates to physics, and advice on the Internal Assessment, External Assessment and Extended Essay.

Questions

In addition to the Guiding Questions and Linking Questions, there are three types of problems in this book.

1. Worked examples with solutions

These appear at intervals in the text and are used to illustrate the concepts covered. They are followed by the solution, which shows the thinking and the steps used in solving the problem.

Worked example

A body with a constant acceleration of $-5\,\mathrm{m\,s^{-2}}$ is traveling to the right with a velocity of $20\,\mathrm{m\,s^{-1}}$. What will its displacement be after 20 s?

Solution

$s = ?$

$u = 20\,\mathrm{m\,s^{-1}}$

$v = ?$

$a = -5\,\mathrm{m\,s^{-2}}$

$t = 20\,\mathrm{s}$

To calculate s, we can use the equation: $s = ut + \frac{1}{2}at^2$

$$s = 20 \times 20 + \tfrac{1}{2}(-5) \times 20^2 = 400 - 1000 = -600\,\mathrm{m}$$

This means that the final displacement of the body is to the left of the starting point. It has gone forward, stopped, and then gone backward.

2. Exercises

Exercise questions are found throughout the text. They allow you to apply your knowledge and test your understanding of what you have just been reading. The answers to these (in PDF format) are accessed via icons in the eBook at the start of each chapter. Exercise answers can also be found at the end of the eBook.

Exercise

Q1. Convert the following speeds into $\mathrm{m\,s^{-1}}$:

- **(a)** a car traveling at $100\,\mathrm{km\,h^{-1}}$
- **(b)** a runner running at $20\,\mathrm{km\,h^{-1}}$.

3. Practice questions

These questions are found at the end of each chapter. They are mostly taken from previous years' IB examination papers. The mark schemes used by examiners when marking these questions (in PDF format) are accessed via icons in the eBook at the start of each chapter. Practice question answers can also be found at the end of the eBook.

Practice questions

1. Police car P is stationary by the side of a road. Car S passes car P at a constant speed of $18\,\text{m s}^{-1}$. Car P sets off to catch car S just as car S passes car P. Car P accelerates at $4.5\,\text{m s}^{-2}$ for 6.0 s and then continues at a constant speed. Car P takes *t* seconds to draw level with car S.

(**a**) State an expression, in terms of *t*, for the distance car S travels in *t* seconds. (1)

(**b**) Calculate the distance traveled by car P during the first 6.0 s of its motion. (1)

(Total 2 marks)

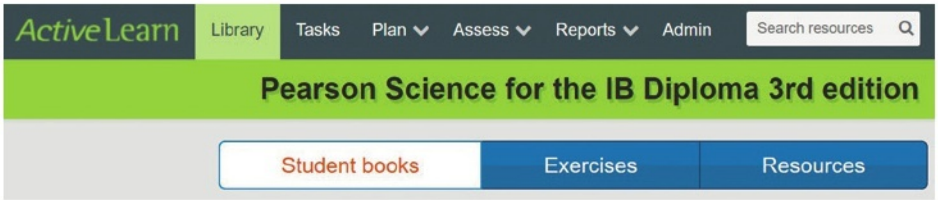
Worked solutions

Full worked solutions to all exercises and practice questions can also be found in the eBook using the grey icons at the start of each chapter.

eBook

In the eBook you will find the following:

- answers and worked solutions to all exercises and practice questions
- links to downloadable lab, activity and recommended simulation worksheets
- interactive quizzes (in the Exercises tab of your eBook account – see screenshot below)
- and links to videos (in the Resources tab of your eBook account – see screenshot below).

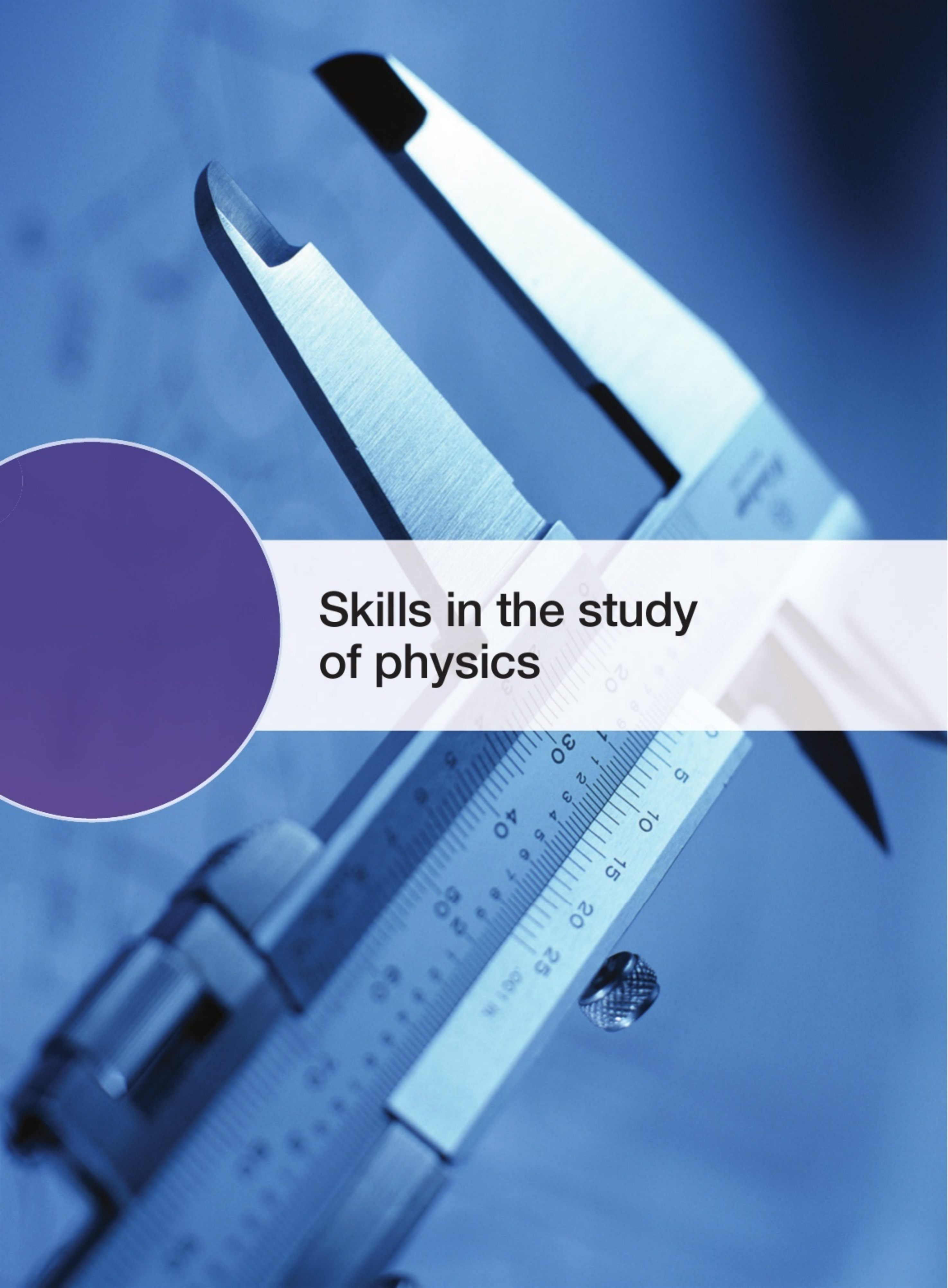


Extra eBook resources such as videos and interactive quizzes can be found in the Resources and Exercises tabs of your eBook account.

We hope you enjoy your study of IB physics.

Chris Hamper and Emma Mitchell

Skills in the study of physics



◀ A vernier caliper is a device that relates to all three aspects of the tools in physics: experimental techniques, technology and mathematics.

As discussed in the Introduction, an excellent IB physicist should be aware of the course aims, appreciate the nature of physics (and science more broadly), and know how to learn and how to inquire.

The skills associated with inquiry have already been discussed and will be referred to once again in the Internal Assessment and Extended Essay chapters. In this chapter, you will find out about the three tools that physicists benefit most from: experimental techniques, technology and mathematics.

Read this chapter before embarking on your studies and continue to refer back to the skills addressed, as almost all elements could be required in any of the topics that follow. When preparing for External Assessment (in particular Paper 1B), you may wish to attempt the practice questions that are located in the eBook.

Tool 1: Experimental techniques

Physics is about modeling the physical Universe so that we can predict outcomes, but before we can develop models, we need to define quantities and measure them. To measure a quantity, we first need to invent a measuring device and define a unit. When measuring, we should try to be as accurate as possible but we can never be exact – measurements will always have uncertainties. This could be due to the instrument or the way we use it, or it might be that the quantity we are trying to measure is changing.

Making observations

Before we can try to understand the Universe, we have to observe it. Imagine you are a cave person looking up into the sky at night. You would see lots of bright points scattered about (assuming it is not cloudy). The points are not the same but how can you describe the differences between them? One of the main differences is that you have to move your head to see different examples. This might lead you to define their position. Occasionally, you might notice a star flashing so would realize that there are also differences not associated with position, leading to the concept of time. If you shift your attention to the world around you, you will be able to make further close-range observations. Picking up rocks, you notice some are easy to pick up while others are more difficult, some are hot and some are cold, and different rocks are different colors. These observations are just the start: to be able to understand how these quantities are related, you need to measure them, and before you do that, you need to be able to count.

▲ **Figure 1** Making observations came before science.

Standard notation

In this course, we will use some numbers that are very big and some that are very small. 602 000 000 000 000 000 000 000 is a commonly used number, as is 0.000 000 000 000 000 000 160. To make life easier, we write these in standard form. This means that we write the number with only one digit to the left of the decimal place and represent the number of zeros with powers of 10.

It is also acceptable to use a prefix to denote powers of 10.

Prefix	Value
T (tera)	10^{12}
G (giga)	10^{9}
M (mega)	10^{6}
k (kilo)	10^{3}
c (centi)	10^{-2}
m (milli)	10^{-3}
μ (micro)	10^{-6}
n (nano)	10^{-9}
p (pico)	10^{-12}
f (femto)	10^{-15}

So:

602 000 000 000 000 000 000 000 = 6.02×10^{23} (decimal place must be shifted right 23 places)

0.000 000 000 000 000 000 160 = 1.60×10^{-19} (decimal place must be shifted left 19 places).

A number's order of magnitude is the closest whole power of ten. 10^{-2}, 10^{-1}, 10^{0}, 10^{1}, 10^{2} and so on are all orders of magnitude.

Exercise

Q1. Write the following in standard form.

(a) 48 000

(b) 0.000 036

(c) 14 500

(d) 0.000 000 48

If you set up your calculator properly, it will always give your answers in standard form.

Measuring variables

We have seen that there are certain fundamental quantities that define our Universe from which all other quantities can be derived or explained. These include position, time and mass.

Length and distance

Realization that the speed of light in a vacuum is the same no matter who measures it led to the speed of light being the basis of our unit of length.

Before we take any measurements, we need to define the quantity. The quantities that we use to define the position of different objects are **length** and **distance**. To measure distance, we need to make a scale and to do that we need two fixed points. We take our fixed points to be two points that never change position, for example, the ends of a stick. If everyone used the same stick, we will all end up with the same measurement. However, we cannot all use the same stick so we make copies of the stick and assume that they are all the same. The problem is that sticks are not all the same length, so our unit of length is now based on one of the few things we know to be the same for everyone: the speed of light in a vacuum. Once we have defined the unit, in this case, the meter, it is important that we all use it (or at least make it very clear if we are using a different one). There is more than one system of units but the one used in this course is the Système International d'Unités (SI units). Here are some examples of distances measured in meters:

The meter was originally defined in terms of several pieces of metal positioned around Paris. This was not very accurate so now one meter is defined as the distance traveled by light in a vacuum in $\frac{1}{299792458}$ of a second.

distance from the Earth to the Sun = 1.5×10^{11} m

diameter of a grain of sand = 2×10^{-4} m

the distance to the nearest star = 4×10^{16} m

radius of the Earth = 6.378×10^{6} m

Exercise

Q2. Convert the following into meters (m) and write in standard form:

- (**a**) Distance from London to New York = 5585 km
- (**b**) Height of Einstein = 175 cm
- (**c**) Thickness of a human hair = 25.4 µm
- (**d**) Distance to furthest part of the observable Universe = 100 000 million million million km.

Time

When something happens, we call it an **event**. To distinguish between different events, we use time. The time between two events is measured by comparing to some fixed value, the second. Time is also a fundamental quantity.

The second was originally defined as a fraction of a day but today's definition is 'the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom'.

TOK If nothing ever happened, would there be time?

Some examples of times:

time between beats of a human heart = 1 s
time for the Moon to go around the Earth = 1 month
time for the Earth to go around the Sun = 1 year

Exercise

Q3. Convert the following times into seconds (s) and write in standard form:

- (**a**) 85 years, how long Newton lived
- (**b**) 2.5 ms, the time taken for a mosquito's wing to go up and down
- (**c**) 4 days, the time it took Apollo 11 to travel to the Moon
- (**d**) 2 hours 52 min 59 s, the time it took for Concorde to fly from London to New York.

Mass

If we pick up different objects, we find another difference. Some objects are easy to lift up and others are difficult. This seems to be related to how much matter the objects consist of. To quantify this, we define mass measured by comparing different objects to the standard kilogram.

TOK The kilogram was the last fundamental quantity to be based on an object kept in Paris. It is now defined using Planck's constant. What are the benefits of using physical constants instead of physical objects?

Some examples of mass:

approximate mass of a human = 75 kg
mass of the Earth = 5.97×10^{24} kg
mass of the Sun = 1.98×10^{30} kg

Exercise

Q4. Convert the following masses to kilograms (kg) and write in standard form:

- (**a**) The mass of an apple = 200 g
- (**b**) The mass of a grain of sand = 0.00001 g
- (**c**) The mass of a family car = 2 tonnes.

Area and volume

The two dimensional space taken up by an object is defined by the area and the three dimensional space is volume. Area is measured in square meters (m^2) and volume is measured in cubic meters (m^3). Area and volume are not fundamental units since they can be split into smaller units (m × m or m × m × m). We call units like these derived units.

A list of useful area and volume equations is located in your data booklet.

Exercise

Q5. Calculate the volume of a room of length 5 m, width 10 m and height 3 m.

Q6. Using the information from pages xviii–xix, calculate:

(**a**) the volume of a human hair of length 20 cm

(**b**) the volume of the Earth.

Density

By measuring the mass and volume of many different objects, we find that if the objects are made of the same material, the ratio $\frac{\text{mass}}{\text{volume}}$ is the same. This quantity is called the **density**. The unit of density is kg m^{-3}. This is another derived unit.

Examples include:

$$\text{density of water} = 1.0 \times 10^3\,\text{kg m}^{-3}$$
$$\text{density of air} = 1.2\,\text{kg m}^{-3}$$
$$\text{density of gold} = 1.93 \times 10^4\,\text{kg m}^{-3}$$

Exercise

Q7. Calculate the mass of air in a room of length 5 m, width 10 m and height 3 m.

Q8. Calculate the mass of a gold bar of length 30 cm, width 15 cm and height 10 cm.

Q9. Calculate the average density of the Earth.

Displacement

So far, all that we have modeled is the position of objects and when events take place, but what if something moves from one place to another? To describe the movement of a body, we define the quantity **displacement**. This is the distance moved in a particular direction.

The unit of displacement is the same as length: the meter.

Referring to the map in Figure 2:
If you move from B to C, your displacement will be 5 km north.
If you move from A to B, your displacement will be 4 km west.

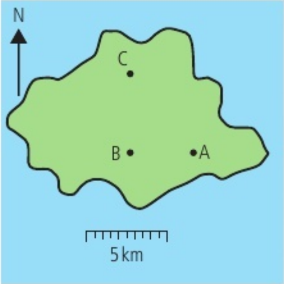


Figure 2 Displacements on a map.

Angle

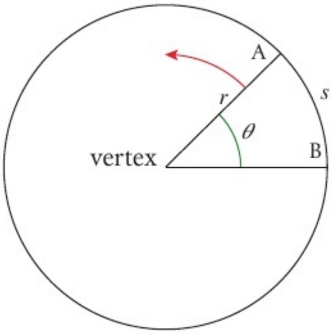


Figure 3 The angle between two lines.

When two straight lines join, an angle is formed. The size of the angle can be increased by rotating one of the lines about the point where they join (the vertex) as shown in Figure 3. To measure angles, we often use degrees. Taking the full circle to be 360° is very convenient because 360 has many whole number factors it can be easily divided by e.g., 4, 6, and 8. However, it is an arbitrary unit not related to the circle itself.

If the angle is increased by rotating line A, the arc lengths will also increase. So for this circle, we could use the arc length as a measure of angle. The problem is that if we take a bigger circle, then the arc length for the same angle will be greater. We therefore define the angle by using the ratio $\frac{s}{r}$, which will be the same for all circles. This unit is the radian.

For one complete circle, the arc length is the circumference = $2\pi r$ so the angle 360° in radians = $\frac{2\pi r}{r} = 2\pi$.

So 360° is equivalent to 2π.

Since the radian is a ratio of two lengths, it has no units.

Summary – Tool 1: Experimental techniques

So far, you will have become familiar with a range of experimental techniques, including measurements of:

- length
- time
- mass
- volume
- angle.

These tools are prescribed in your subject guide.

There are others still to come throughout the textbook. These include measurements of:

- force (A.2)
- temperature (B.1)
- electric current (B.5)
- electric potential difference (B.5)
- sound intensity (C.2)
- and light intensity (C.2).

You should also be aware of how to recognize and address safety, ethical and environmental issues. Try to spot these throughout the textbook, such as the risks of high-temperature fluids (B.3) or ionizing radiation (E.3), or the environmental impact of using electricity (B.5) or water (C.2) for experimentation.

Tool 2: Technology

Technology and physics are closely linked. Technology enables the advancement of physics, and the pursuit of scientific understanding stimulates improvements in technology. The fields impacted are as wide-ranging as communication, medicine and environmental sustainability.

Every measurement requires an instrument, which is itself inherently technological. Technology facilitates collaboration, which is to the benefit of international teams of scientists and IB physicists alike. Technology makes the processes carried out by physicists much faster, for example, when collecting data or performing calculations. Humans can sense light intensity, temperature, sounds, smells, tastes and applied pressure. How might technology replicate or improve upon these senses? What else does technology enable us to measure?

A model is a representation of reality. It can be as concise as a single word (e.g. the brain is like a 'computer') or an equation (e.g. speed is the ratio of distance traveled to time taken). Technology supports physicists in forming new models during exploratory experimental work (e.g. by making it easy to compare the 'fit' of a range of mathematical relationships) and in creating simulations that enable experimentation without need for a lab.

The ear is an example of a sensor. Look out for human-made sensors throughout this book.

Algodoo® is software that enables the simulation of ideas that may or may not be possible in the lab. Gravity can be altered (or removed altogether) and materials or any desired properties can be tested.

Summary – Tool 2: Technology

Technology can be used to good effect in physics. The Tool 3: Mathematics section of this chapter will reveal that technology can be used to display graphs for representing data. In the remainder of the textbook, you can expect to learn about:

- using sensors (A.2, B.1, B.3, C.1, C.4)
- models and simulations for generation of data (B.2, C.4)
- spreadsheets for manipulation of data (B.5)
- computer modeling for processing data (C.1)
- image analysis of motion (C.5, E.1)
- databases for data extraction (C.5, E.5)
- video analysis of motion (E.3)

TOK

If the system of numbers had been totally different, would our models of the Universe be the same?

Tool 3: Mathematics

When counting apples, we can say there are exactly six apples, but if we measure the length of a piece of paper, we cannot say that it is exactly 21 cm wide. All measurements have an associated uncertainty and it is important that this is also quoted with the value. Uncertainties cannot be avoided, but by carefully using accurate instruments, they can be minimized. Physics is all about relationships between different quantities. If the uncertainties in measurement are too big, then relationships are difficult to identify. Throughout the practical part of this course, you will be trying to find out what causes the uncertainties in your measurements. Sometimes, you will be able to reduce them and at other times not. It is quite alright to have big uncertainties but completely unacceptable to manipulate data so that the numbers appear to fit a predicted relationship.

In physics experiments, we always quote the uncertainties in our measurements. Shops also have to work within given uncertainties and could be prosecuted if they overestimate the weight of something. An approximation is similar, but not exactly equal, to something else (for example, a rounded number). An estimate is a simplification of a quantity (such as assuming that an apple has a mass of 100 g).

Summary of SI units

The SI system of units is the set of units that are internationally agreed to be used in science. It is still OK to use other systems in everyday life (miles, pounds, Fahrenheit), but in science, we must always use SI. There are seven fundamental (or base) quantities.

Base quantity	Quantity symbol	Unit	Unit symbol
length	x or l	meter	m
mass	m	kilogram	kg
time	t	second	s
electric current	I	ampere	A
thermodynamic temperature	T	kelvin	K
amount of substance	n	mole	mol
luminous intensity	I	candela	cd

The candela will not be used in this course.

All other SI units are derived units. These are based on the fundamental units and will be introduced and defined where relevant. So far we have come across just three.

Derived quantity	Symbol	Base units
area	m^2	$m \times m$
volume	m^3	$m \times m \times m$
density	$kg\,m^{-3}$	$\frac{kg}{m \times m \times m}$

By breaking down the units of derived quantities into base quantity units, it is possible to check whether an equation could be correct. This technique is an informal version of dimensional analysis, in which the 'powers of' quantities are compared on either side of an equation. Note, however, that dimensional analysis provides no insights into the constant of proportionality.

Processing uncertainties

The SI system of units is defined so that we all use the same sized units when building our models of the physical world. However, before we can understand the relationship between different quantities, we must measure how big they are. To make measurements, we use a variety of instruments. To measure length, we can use a ruler and to measure time, a clock. If our findings are to be trusted, then our measurements must be accurate, and the accuracy of our measurement depends on the instrument used and how we use it. Consider the following examples.

▲ Even this sophisticated device at CERN has uncertainties.

Measuring length using a ruler

Example 1

A good straight ruler marked in mm is used to measure the length of a rectangular piece of paper as in Figure 4.

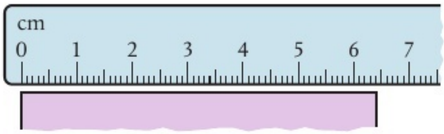


Figure 4 Length = 6.40 ± 0.05 cm.

The ruler measures to within 0.5 mm (we call this the **uncertainty** in the measurement) so the length in cm is quoted to 2 d.p. This measurement is precise and accurate. This can be written as 6.40 ± 0.05 cm, which tells us that the actual value is somewhere between 6.35 and 6.45 cm.

When using a scale such as a ruler, the uncertainty in the reading is half of the smallest division. In this case, the smallest division is 1 mm so the uncertainty is 0.5 mm. When using a digital device such as a balance, we take the uncertainty as the smallest digit. So if the measurement is 20.5 g, the uncertainty is ±0.1 g.

Example 2

Figure 5 shows how a ruler with a broken end is used to measure the length of the same piece of paper. When using the ruler, you might fail to notice the end is broken and think that the 0.5 cm mark is the zero mark.

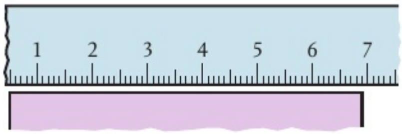


Figure 5 Length ≠ 6.90 ± 0.05 cm.

This measurement is precise since the uncertainty is small but is not accurate since the value 6.90 cm is wrong.

In Examples 1 and 2, we are assuming that there is no uncertainty at the 'zero' end of the ruler because it might be possible to line up paper with the long ruler marking. In reality, the uncertainty for Example 1 may be ±0.1 cm, which is the combination of the 0.05 cm uncertainties at each end of the length.

Example 3

A ruler marked only in $\frac{1}{2}$ cm is used to measure the length of the paper as in Figure 6.

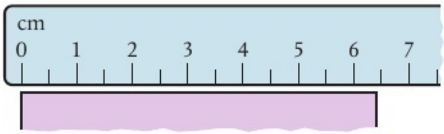


Figure 6 Length = 6.5 ± 0.3 cm.

These measurements are precise and accurate, but the scale is not very sensitive.

Notice that uncertainties are generally quoted to one significant figure. The uncertainty then dictates the number of decimal places to which the measurement is written.

Example 4

In Figure 7, a ruler is used to measure the maximum height of a bouncing ball. The ruler has more markings, but it is very difficult to measure the height of the bouncing ball. Even though you can use the scale to within 0.5 mm, the results are not precise (the base of the ball may be at about 4.2 cm). However, if you do enough runs of the same experiment, your final answer could be accurate.

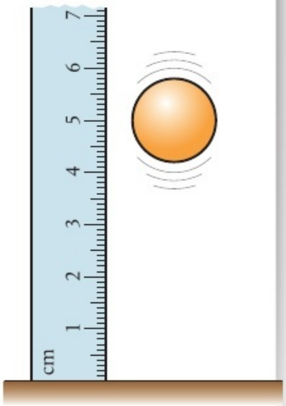


Figure 7
Height = 4.2 ± 0.2 cm.

Precision and accuracy

To help understand the difference between precision and accuracy, consider the four attempts to hit the center of a target with three arrows shown in Figure 8.

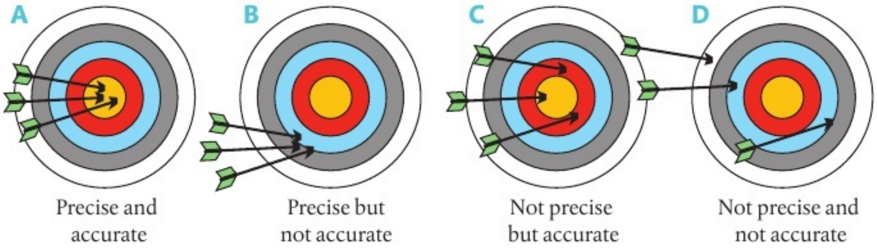


Figure 8 Precision and accuracy

A The arrows were fired accurately at the center with great precision.
B The arrows were fired with great precision as they all landed near one another, but not very accurately since they are not near the center.
C The arrows were not fired very precisely since they were not close to each other. However, they were accurate since they are evenly spread around the center. The average of these would be quite good.
D The arrows were not fired accurately and the aim was not precise since they are far from the center and not evenly spread.

So **precision** is how close to each other a set of measurements are (related to the resolution of the measuring instrument) and the **accuracy** is how close they are to the actual value (often based on an average).

If you measure the same thing many times and get the same value, then the measurement is precise.
If the measured value is close to the expected value, then the measurement is accurate. If a football player hits the post ten times in a row when trying to score a goal, you could say the shots are precise but not accurate.

Errors in measurement

There are two types of measurement error – random and systematic.

Random error

If you measure a quantity many times and get lots of slightly different readings, then this called a random error. For example, when measuring the bounce of a ball, it is very difficult to get the same value every time even if the ball is doing the same thing.

Systematic error

A systematic error is when there is something wrong with the measuring device or method. Using a ruler with a broken end can lead to a 'zero error' as in Example 2 on page xxiv. Even with no random error in the results, you would still get the wrong answer.

TOK

It is not possible to measure anything exactly. This is not because our instruments are not exact enough but because the quantities themselves do not exist as exact quantities. What measurements could you make in the space around you? What might makes these quantities inexact?

Reducing errors

To reduce random errors, you can repeat your measurements. If the uncertainty is truly random, your measurements will lie either side of the true reading and the mean of these values will be close to the actual value. To reduce a systematic error, you need to find out what is causing it and correct your measurements accordingly. A systematic error is not easy to spot by looking at the measurements, but is sometimes apparent when you look at the graph of your results or the final calculated value.

Adding uncertainties

If two values are added together, then the uncertainties also add. For example, if we measure two lengths, $L_1 = 5.0 \pm 0.1$ cm and $L_2 = 6.5 \pm 0.1$ cm, then the maximum value of L_1 is 5.1 cm and the maximum value of L_2 is 6.6 cm, so the maximum value of $L_1 + L_2 = 11.7$ cm. Similarly, the minimum value is 11.3 cm. We can therefore say that $L_1 + L_2 = 11.5 \pm 0.2$ cm.

If $\quad y = a \pm b \quad$ then $\quad \Delta y = \Delta a + \Delta b$

If you multiply a value by a constant, then the uncertainty is also multiplied by the same number.

So $\quad 2L_1 = 10.0 \pm 0.2$ cm and $\frac{1}{2}L_1 = 2.50 \pm 0.05$ cm.

Example of measurement and uncertainties

▲ Ball of modeling clay measured with a ruler.

Let us consider an experiment to measure the mass and volume of a piece of modeling clay. To measure mass, we can use a top pan balance so we take a lump of clay and weigh it. The result is 24.8 g. We can repeat this measurement many times and get the same answer. There is no variation in the mass so the uncertainty in this measurement is the same as the uncertainty in the scale. The smallest division on the balance used is 0.1 g so the uncertainty is ± 0.1 g.

So: $\quad$ mass = 24.8 ± 0.1 g

To measure the volume of the modeling clay, we first need to mold it into a uniform shape: let us roll it into a sphere. To measure the volume of the sphere, we measure its diameter from which we can calculate its radius ($V = \frac{4\pi r^3}{3}$).

Making an exact sphere out of the modeling clay is not easy. If we do it many times, we will get different-shaped balls with different diameters so let us try rolling the ball five times and measuring the diameter each time with a ruler.

Using the ruler, we can only judge the diameter to the nearest mm so we can say that the diameter is 3.5 ± 0.1 cm. It is actually even worse than this since we also have to line up the zero at the other end, so 3.5 ± 0.2 cm might be a more reasonable estimate. If we turn the ball round, we get the same value for *d*. If we squash the ball and make a new one, we might still get a value of 3.5 ± 0.2 cm. This is not because the ball is a perfect sphere every time but because our method of measurement is not **sensitive** enough to measure the difference.

Let us now try measuring the ball with a vernier caliper.

A vernier caliper has sliding jaws, which are moved so they touch both sides of the ball.

The vernier caliper can measure to the nearest 0.002 cm. Repeating measurements of the diameter of the same lump of modeling clay might give the results in Table 1.

Table 1

Diameter/cm								
3.640	3.450	3.472	3.500	3.520	3.520	3.530	3.530	3.432
3.540	3.550	3.550	3.560	3.560	3.570	3.572	3.582	3.582

The reason these measurements are not all the same is because the ball is not perfectly uniform and, if made several times, will not be exactly the same. We can see that there is a spread of data from 3.400 cm to 3.570 cm, with most lying around the middle. This can be shown on a graph but first we need to group the values as in Table 2.

Range/cm	No. of values within range
3.400–3.449	1
3.450–3.499	2
3.500–3.549	6
3.550–3.599	8
3.600–3.649	1

Table 2

Distribution of measurements

Even with this small sample of measurements, you can see in Figure 9 that there is a spread of data: some measurements are too big and some too small but most are in the middle. With a much larger sample, the shape would be closer to a 'normal distribution' as in Figure 10.

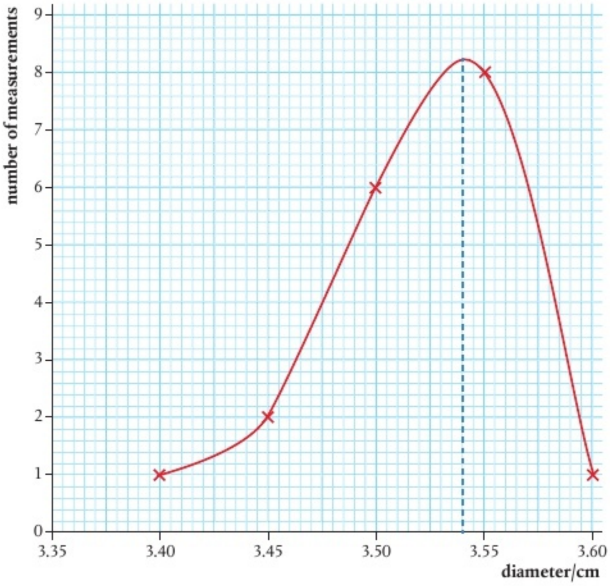
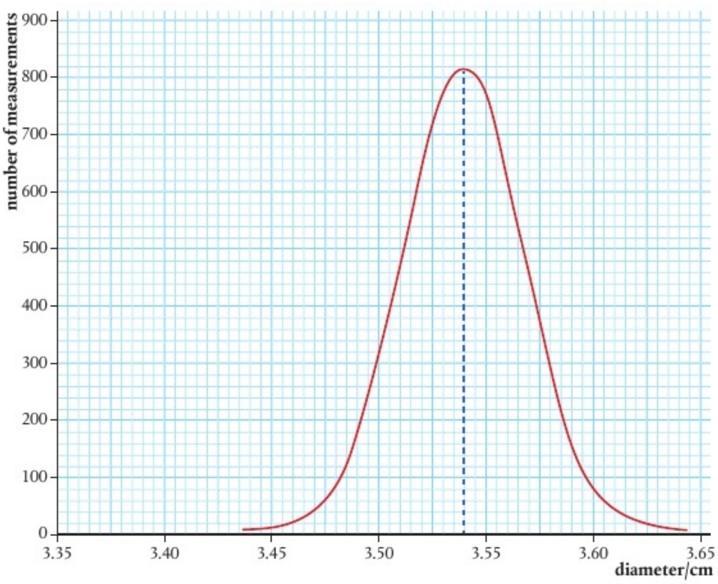


Figure 9 Distribution of measurements of diameter.

Figure 10 Normal distribution curve.



The mean

At this stage, you may be wondering what the point is of trying to measure something that does not have a definite value. Well, we are trying to find the volume of the modeling clay using the formula $V = \frac{4\pi r^3}{3}$. This is the formula for the volume of a perfect sphere. The problem is we cannot make a perfect sphere. It is probably more like the shape of an egg, so depending on which way we measure it, sometimes the diameter will be too big and sometimes too small. It is, however, just as likely to be too big as too small, so if we take the mean of all our measurements, we should be close to the 'perfect sphere' value which will give us the correct volume of the modeling clay.

The mean or average is found by adding all the values and dividing by the number of values. In this case, the mean = 3.537 cm. This is the same as the peak in the distribution. We can check this by measuring the volume in another way, for example, sinking it in water and measuring the volume displaced. Using this method gives a volume = 23 cm^3. Rearranging the formula gives: $r = \sqrt[3]{\frac{3V}{4\pi}}$

Substituting for V gives $d = 3.53$ cm, which is fairly close to the mean. Calculating the mean reduces the random error in our measurement.

There is a very nice example of this that you might like to try. Fill a jar with jelly beans and get your classmates to guess how many there are. Assuming that they really try to make an estimate rather than randomly saying a number, the guesses are just as likely to be too high as too low. So, if after you collect all the data you find the average value, it should be quite close to the actual number of beans.

If the data follows a normal distribution, 68% of the values should be within one standard deviation of the mean.

Knowing the mean of data enables a calculation of the standard deviation to be performed. Standard deviation gives an idea of the spread of the data.

Smaller samples

You will be collecting a lot of different types of data throughout the course but you will not often have time to repeat your measurements enough to get a normal distribution. With only four values, the uncertainty is not reduced significantly by taking the mean so *half* the range of values is used instead. This often gives a slightly exaggerated value for the uncertainty – for the example above, it would be ± 0.1 cm – but it is an approach accepted by the IB.

Relationships

In physics, we are very interested in the relationships between two quantities, for example, the distance traveled by a ball and the time taken. To understand how we represent relationships by equations and graphs, let us consider a simple relationship regarding fruit.

Linear relationships

Let us imagine that all apples have the same mass, 100 g. To find the relationship between number of apples and their mass, we would need to measure the mass of different numbers of apples. These results could be put into a table as in Table 3.

Number (N)	Mass (m)/g
1	100
2	200
3	300
4	400
5	500
6	600

Table 3

In this example, we can clearly see that the mass of the apples increases by the same amount every time we add an apple. We say that the mass of apples is **proportional** to the number. If we draw a graph of mass vs number, we get a straight line passing through the origin as in Figure 11.

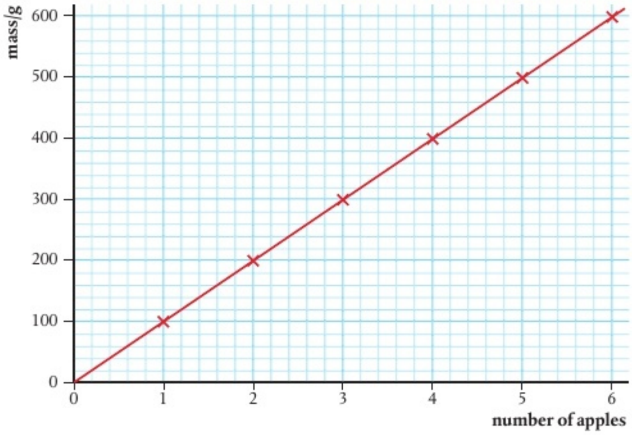


Figure 11 Graph of mass vs number of apples.

The gradient of this line is given by $\frac{\Delta y}{\Delta x}$ = 100 g/apple. The fact that the line is straight and passing through the origin can be used to test if two quantities are proportional to each other.

The equation of the line is $y = mx$, where m is the gradient, so in this case $y = 100x$ and $m = 100\,\text{g apple}^{-1}$.

This equation can be used to calculate the mass of any given number of apples. This is a simple example of what we will spend a lot of time doing in this course.

To make things a little more complicated, let us consider apples in a basket with mass 500 g. The table of masses is shown in Table 4.

Number (N)	Mass (m)/g
1	600
2	700
3	800
4	900
5	1000
6	1100

Table 4

The slope in Figure 12 is still 100 g/apple, indicating that each apple still has a mass of 100 g, but the intercept is no longer (0, 0). We say that the mass is linearly related to the number of apples but they are *not* directly proportional.