

STANDARD LEVEL



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Physics

for the IB Diploma Programme

3rd Edition

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EMMA MITCHELL



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Physics

for the IB Diploma Programme

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KEY (t – top, c – center, b – bottom, l – left, r – right)

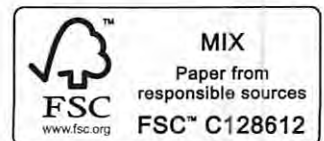
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B.4 is not included as it is for HL students only.



E.2 is not included as it is for HL students only.

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	B.1 Thermal energy transfers B.2 Greenhouse effect B.3 Gas laws 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	E.1 Structure of the atom E.3 Radioactive decay E.4 Fission E.5 Fusion and stars

Authors' introduction to the third edition

Welcome to your study of IB Diploma Programme (DP) Standard Level (SL) 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.

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.

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?

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)?

Aims

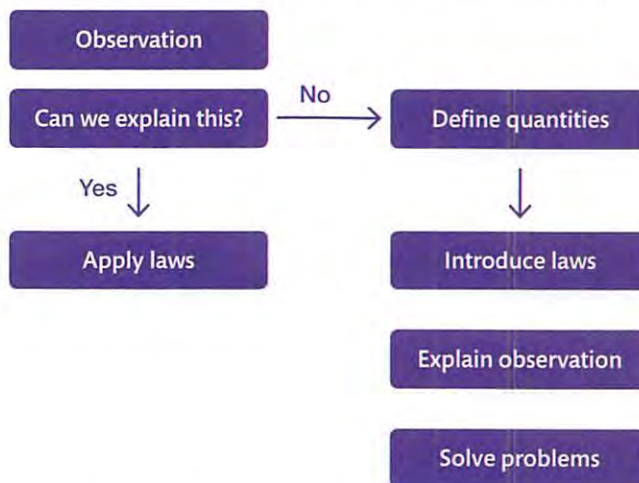
Using this textbook as part of your course will help you meet these IB DP physics aims to:

- 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 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?

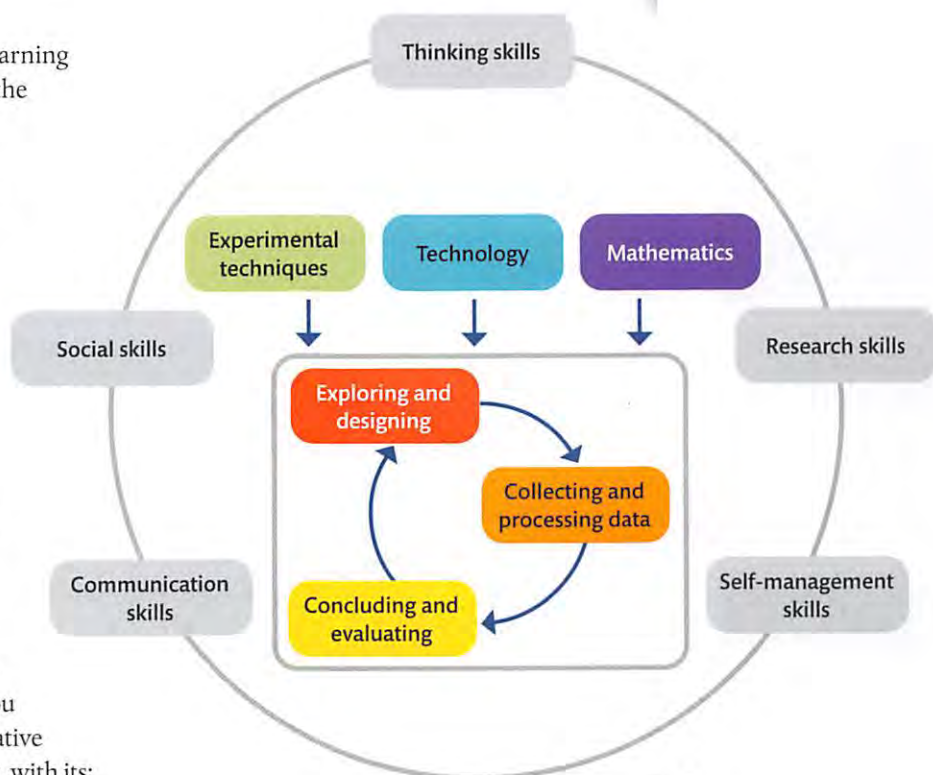
- breaking down major tasks into a sequence of stages
- being punctual and meeting deadlines
- taking risks and regarding setbacks as opportunities for growth
- avoiding unnecessary distractions
- drafting, revising and improving academic work
- setting learning goals and adjusting them in response to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

- 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.



▲
Tools for physics.

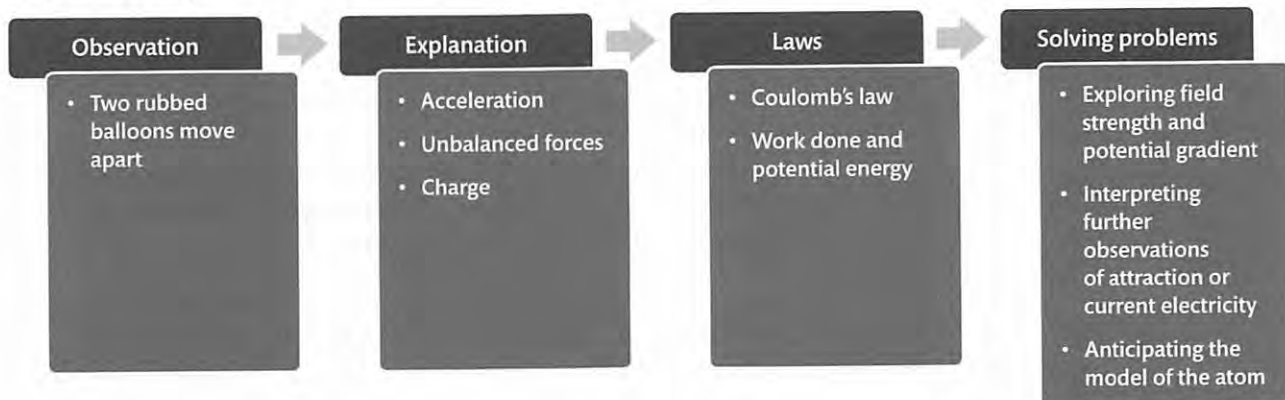
Learner profile

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	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 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

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.



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.

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

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 gray eBook icons.

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.

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.

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.

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.

Challenge yourself

1. A projectile is launched perpendicular to a 30° slope at 20 m 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 Internal Assessment, External Assessment and the Extended Essay.

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.

TOK

Color is perceived but wavelength is measured.



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



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.

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 m s^{-2} is traveling to the right with a velocity of 20 m s^{-1} . What will its displacement be after 20 s?

Solution

$$s = ?$$

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

$$v = ?$$

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

$$t = 20 \text{ s}$$

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

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

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 m s^{-1} :

- (a) a car traveling at 100 km h^{-1}
- (b) a runner running at 20 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

- Police car P is stationary by the side of a road. Car S passes car P at a constant speed of 18 m s^{-1} . Car P sets off to catch car S just as car S passes car P. Car P accelerates at 4.5 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.
 - State an expression, in terms of t , for the distance car S travels in t seconds. (1)
 - Calculate the distance traveled by car P during the first 6.0 s of its motion. (1)

Worked solutions

Full worked solutions to all exercises and practice questions can also be found in the eBook using the gray 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)
- and links to videos (in the Exercises tab of your eBook account).



We hope you enjoy your study of IB physics.

Chris Hamper and Emma Mitchell



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



**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.

Standard notation

In this course, we will use some numbers that are very big and some that are very small. $602\,000\,000\,000\,000\,000\,000\,000\,000\,000$ is a commonly used number, as is $0.000\,000\,000\,000\,000\,000\,000\,160$. 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.



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

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}

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

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.

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 $\frac{1}{299\,792\,458}$ of a second.



So:

$602\,000\,000\,000\,000\,000\,000\,000 = 6.02 \times 10^{23}$ (decimal place must be shifted right 23 places)

$0.000\,000\,000\,000\,000\,000\,000\,160 = 1.60 \times 10^{-19}$ (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



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

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:

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 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.

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.

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.

i

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?

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?

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 ($\text{m} \times \text{m}$ or $\text{m} \times \text{m} \times \text{m}$). 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 xv–xvii, calculate:
- the volume of a human hair of length 20 cm
 - 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

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.

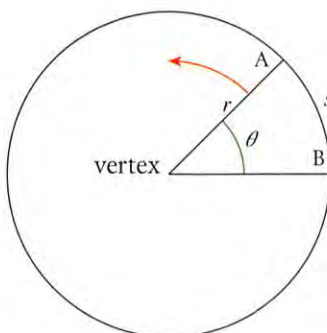


Figure 3 The angle between two lines.

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.

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.



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.



▲ 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.

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

TOK



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).

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.

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)

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.

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.

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.

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.

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.



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.

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.



▲ **Figure 4** Length = 6.40 ± 0.05 cm.



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 $\neq 6.90 \pm 0.05$ cm.

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



Example 3

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

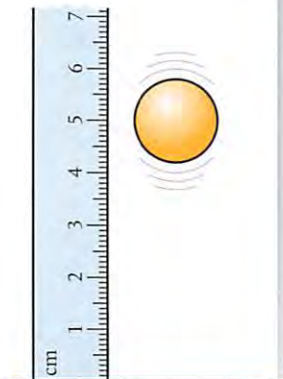


▲ **Figure 6** Length = 6.5 ± 0.3 cm.

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

Example 4

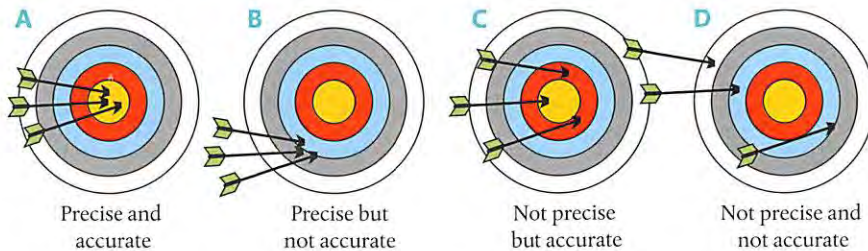
In Figure 7, a ruler is used to measure the maximum height of a bouncing ball. The ruler has more markings, but it is very difficult to measure the height of the bouncing ball. Even though you can use the scale to within 0.5 mm, the results are not precise (the base of the ball may be at about 4.2 cm). 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.



- 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).

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 is 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.

Figure 8 Precision and accuracy.



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.

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 $L_1 + L_2$ is 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 $y = a \pm b$ then $\Delta y = \Delta a + \Delta b$

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

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

Example of measurement and uncertainties

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: 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.



▲ Ball of modeling clay measured with a ruler.

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



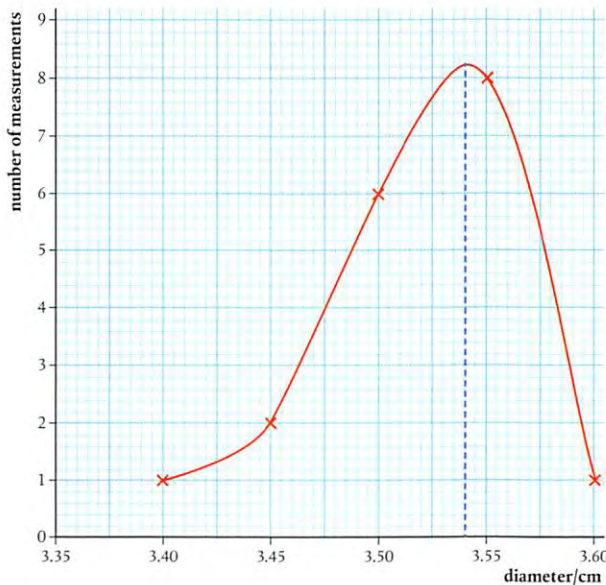
The vernier caliper can measure to the nearest 0.002 cm. Repeating measurements of the diameter of the same lump of modeling clay might give the results in Table 1.

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.

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.



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

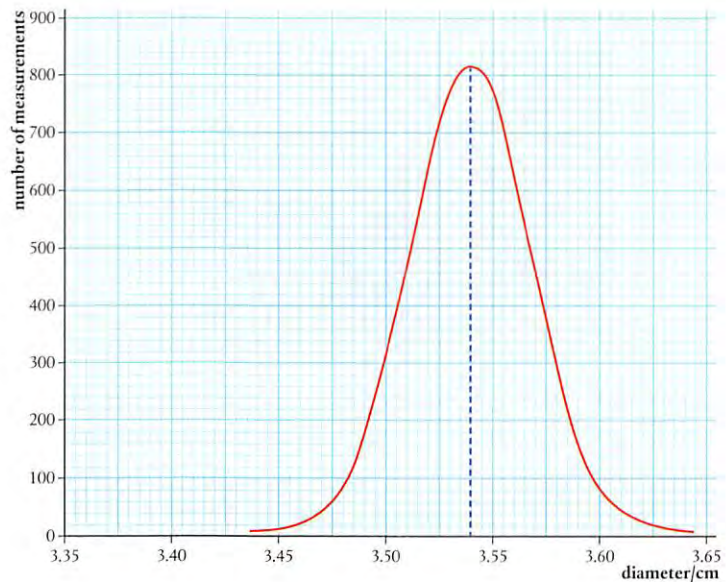
◀ Table 1

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

◀ 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 cm³. 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.

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

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

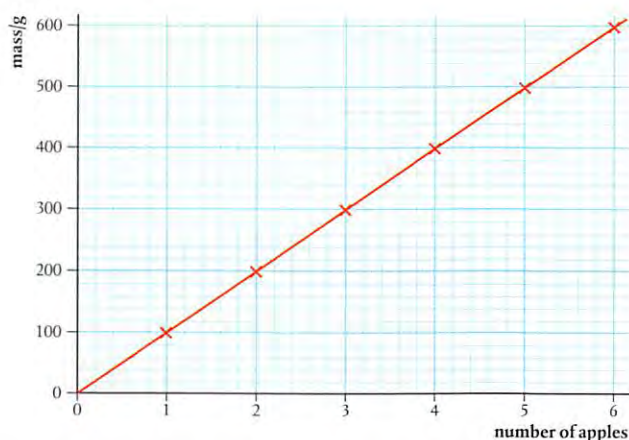
Relationships

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.

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.



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 $m = 100$ 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.

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.

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

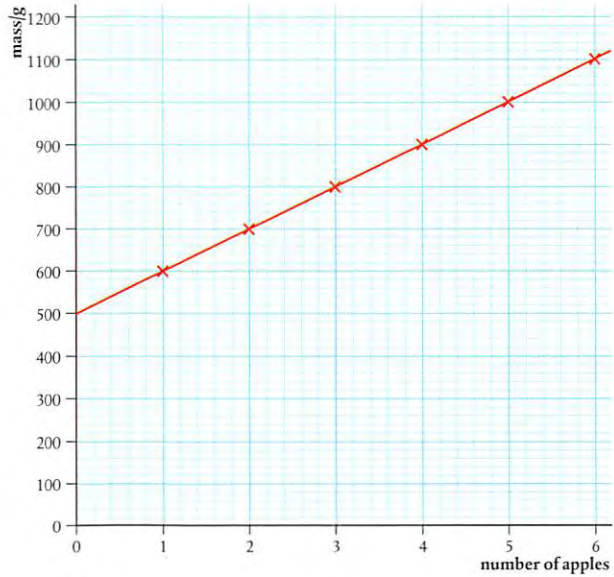
▲ Table 3

◀ Figure 11 Graph of mass vs number of apples.

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

▲ Table 4

Figure 12 Graph of mass vs number of apples in a basket.



The equation of this line is $y = mx + c$, where m is the gradient and c the intercept on the y -axis. The equation in this case is therefore $y = 100x + 500$.

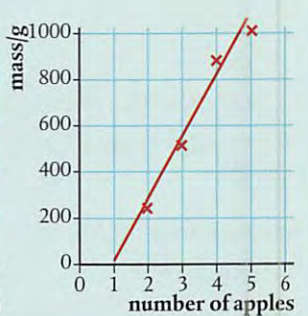
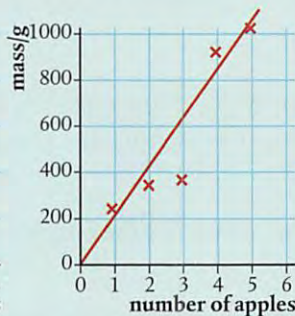
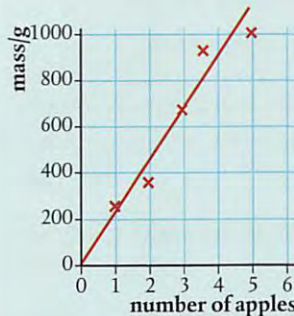
Finding the equation that relates two quantities can be useful for interpolation and extrapolation. Both techniques involve inserting a value for one of the quantities into the equation to find the corresponding value of the other. Interpolation can be performed with good confidence as it is done within the range of collected data. Extrapolation is more risky as the values are beyond the range of collected data; you are making a prediction.

It is much easier to plot data from an experiment without processing it but this will often lead to curves that are very difficult to draw conclusions from. Linear relationships are much easier to interpret so are worth the time spent processing the data.



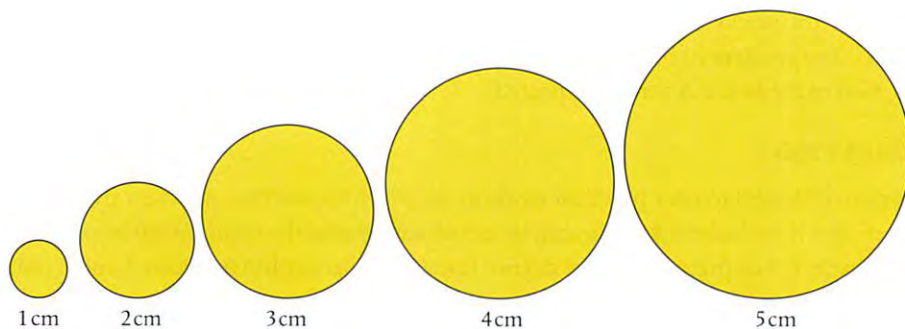
Exercise

Q10. The data displayed in the graphs below all show examples of correlation. What other conclusions can you make?



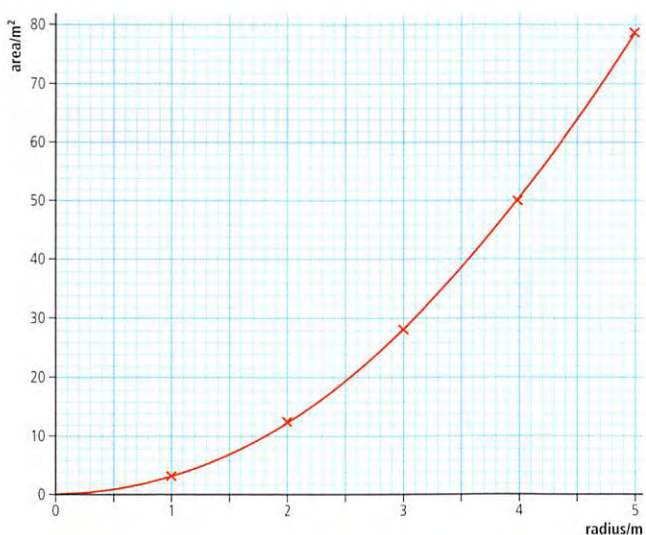
Non-linear relationships

Let us now consider the relationship between radius and the area of circles of paper as shown in Figure 13 on the following page.



The results are recorded in Table 5.

If we now graph the area vs the radius, we get the graph shown in Figure 14.



This is not a straight line so we cannot deduce that area is linearly related to radius. However, you may know that the area of a circle is given by $A = \pi r^2$, which would mean that A is proportional to r^2 . To test this, we can calculate r^2 and plot a graph of area vs r^2 . The calculations are shown in Table 6.

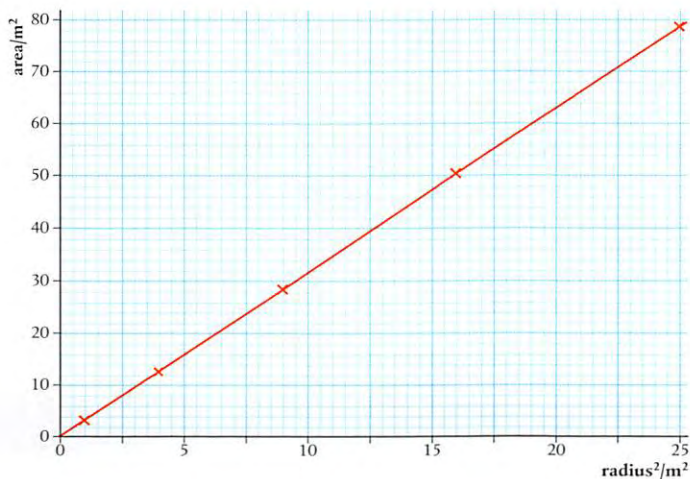


Figure 13 Five circles of green paper.

Radius/m	Area/m ²
1	3.14
2	12.57
3	28.27
4	50.27
5	78.54

Table 5

Figure 14 Graph of area of green circles vs radius.

Radius/m	r^2/m^2	Area/m ²
1	1	3.14
2	4	12.57
3	9	28.27
4	16	50.27
5	25	78.54

Table 6

Figure 15 Graph of area of green circles vs radius².

This time, the graph is linear, confirming that the area is indeed proportional to the radius². The gradient of the line is 3.1, which is π to two significant figures. So the equation of the line is $A = \pi r^2$ as expected.

Using logs

Logs can be useful in your practical work. In the previous exercise, we knew that $A = \pi r^2$, but if we had not known this, we could have found the relationship by plotting a log graph. Let us pretend that we did not know the relationship between A and r , only that they were related. So it could be $A = kr^2$ or $A = kr^3$ or even $A = k\sqrt{r}$.

We can write all of these in the form: $A = kr^n$

Now if we take logs of both sides of this equation, we get: $\log A = \log kr^n = \log k + n \log r$

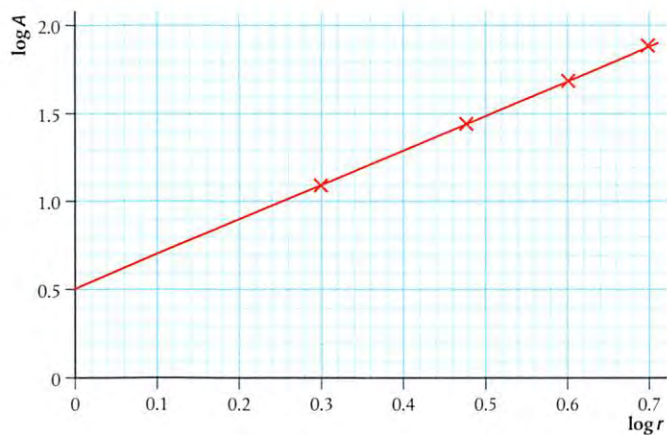
This is of the form $y = mx + c$, where $\log A$ is y and $\log r$ is x .

So if we plot $\log A$ vs $\log r$, we should get a straight line with gradient n and intercept $\log k$. This is all quite easy to do using a spreadsheet, resulting in Table 7 and the graph in Figure 16.

Table 7

Radius/m	Area/m ²	log (A/m ²)	log (r/m)
1	3.14	0.4969	0.0000
2	12.57	1.0993	0.3010
3	28.27	1.4513	0.4771
4	50.27	1.7013	0.6021
5	78.54	1.8951	0.6990

Figure 16 log A vs log r for the green paper disks.



This has gradient = 2 and intercept = 0.5, so if we compare it to the equation of the line:

$$\log A = \log k + n \log r$$

we can deduce that:

$$n = 2 \text{ and } \log k = 0.5$$

The inverse of $\log k$ is 10^k so $k = 10^{0.5} = 3.16$, which is quite close to π .

Substituting into our original equation $A = kr^n$, we get $A = \pi r^2$.

A	B
1.1	0.524
3.6	0.949
4.2	1.025
5.6	1.183
7.8	1.396
8.6	1.466
9.2	1.517
10.7	1.636

Table 8

Exercise

Q11. Use a log–log graph to find the relationship between A and B in Table 8.

Relationship between the diameter of a modeling clay ball and its mass

So far, we have only measured the diameter and mass of one ball of modeling clay. If we want to know the relationship between the diameter and mass, we should measure many balls of different sizes. This is limited by the amount of modeling clay we have, but should be from the smallest ball we can reasonably measure up to the biggest ball we can make.

Mass/g ± 0.1 g	Diameter/cm ± 0.002 cm			
	1	2	3	4
1.4	1.296	1.430	1.370	1.280
2.0	1.570	1.590	1.480	1.550
5.6	2.100	2.130	2.168	2.148
9.4	2.560	2.572	2.520	2.610
12.5	2.690	2.840	2.824	2.720
15.7	3.030	2.980	3.080	2.890
19.1	3.250	3.230	3.190	3.204
21.5	3.490	3.432	3.372	3.360
24.8	3.550	3.560	3.540	3.520

Table 9

In Table 9, the uncertainty in diameter d is given as 0.002 cm. This is the uncertainty in the vernier caliper: the actual uncertainty in diameter is *more* than this as is revealed by the spread of data which you can see in the first row, which ranges from 1.280 to 1.430, a difference of 0.150 cm. Because there are only four different measurements, we can use the approximate method using $\Delta d = \frac{(d_{\max} - d_{\min})}{2}$. This gives an uncertainty in the first measurement of ±0.08 cm. Table 10 includes the uncertainties and the mean.

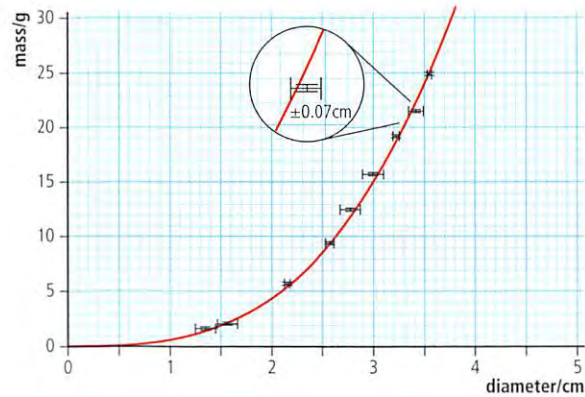
Mass/g ± 0.1 g	Diameter/cm ± 0.002 cm					
	1	2	3	4	$d_{\text{mean}}/\text{cm}$	Uncertainty $\Delta d/\text{cm}$
1.4	1.296	1.430	1.370	1.280	1.34	0.08
2.0	1.570	1.590	1.480	1.550	1.55	0.06
5.6	2.100	2.130	2.168	2.148	2.14	0.03
9.4	2.560	2.572	2.520	2.610	2.57	0.04
12.5	2.690	2.840	2.824	2.720	2.77	0.08
15.7	3.030	2.980	3.080	2.890	3.00	0.10
19.1	3.250	3.230	3.190	3.204	3.22	0.03
21.5	3.490	3.432	3.372	3.360	3.41	0.07
24.8	3.550	3.560	3.540	3.520	3.54	0.02

Table 10

Now, to reveal the relationship between the mass m and diameter d , we can draw

a graph of m vs d as shown in Figure 17. However, since the values of m and d have uncertainties, we do not plot them as points but as lines. The length of the lines equals the uncertainty in the measurement. These are called **uncertainty bars**.

Figure 17 Graph of mass of modeling clay ball vs diameter with error bars.



A worksheet with full details of how to carry out this experiment is available in the eBook.



This curve is the *best fit* for the data collected.



The curve is quite a nice fit but very difficult to analyze. It would be more convenient if we could manipulate the data to get a straight line. This is called **linearizing**. To do this, we must try to deduce the relationship using physical theory and then test the relationship by drawing a graph. In this case, we know that density, $\rho = \frac{\text{mass}}{\text{volume}}$ and the volume of a sphere = $\frac{4\pi r^3}{3}$, where r = radius.

So:
$$\rho = \frac{3m}{4\pi r^3}$$

Rearranging this equation gives:
$$r^3 = \frac{3m}{4\pi\rho}$$

But:
$$r = \frac{d}{2} \text{ so } \frac{d^3}{8} = \frac{3m}{4\pi\rho}$$

$$d^3 = \frac{6m}{\pi\rho}$$

Since $\frac{6}{\pi\rho}$ is a constant, this means that d^3 is proportional to m . So, a graph of d^3 vs m should be a straight line with gradient = $\frac{6}{\pi\rho}$. To plot this graph, we need to find d^3 and its uncertainty. The uncertainty can be found by calculating the difference between the maximum and minimum values of d^3 and dividing by 2: $\frac{(d_{\text{max}}^3 - d_{\text{min}}^3)}{2}$. This has been done in Table 11.

Table 11

Mass/g ± 0.1 g	Diameter/cm ± 0.002 cm						
	1	2	3	4	$d_{\text{mean}}/$ cm	$d^3_{\text{mean}}/$ cm ³	$d^3_{\text{unc}}/$ cm ³
1.4	1.296	1.430	1.370	1.280	1.34	2.4	0.4
2.0	1.570	1.590	1.480	1.550	1.55	3.7	0.4
5.6	2.100	2.130	2.168	2.148	2.14	9.8	0.5
9.4	2.560	2.572	2.520	2.610	2.57	17	1
12.5	2.690	2.840	2.824	2.720	2.77	21	2
15.7	3.030	2.980	3.080	2.890	3.00	27	3
19.1	3.250	3.230	3.190	3.204	3.22	33	1
21.5	3.490	3.432	3.372	3.360	3.41	40	2
24.8	3.550	3.560	3.540	3.520	3.54	44	1

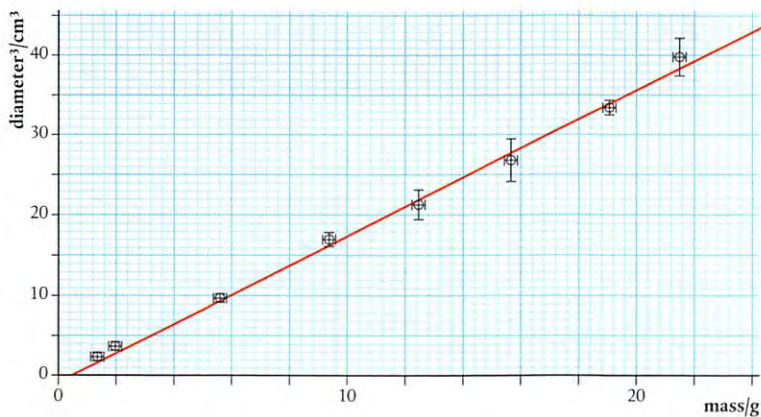


Figure 18 Graph of diameter³ of a modeling clay ball vs mass.

Looking at the line in Figure 18, we can see that due to random errors in the data, the points are not exactly on the line but close enough. What we expect to see is the line touching all of the error bars, which is the case here. The error bars should reflect the random scatter of data. In this case, they are slightly bigger, which is probably due to the approximate way that they have been calculated. Notice how the points furthest from the line have the biggest error bars.

According to the formula, d^3 should be directly proportional to m ; the line should therefore pass through the origin. Here we can see that the y -intercept is -0.3 cm^3 , which is quite close to the origin and is probably just due to the random errors in d . If the intercept had been more significant, then it might have been due to a **systematic error** in mass. For example, if the balance had not been zeroed properly and instead of displaying zero with no mass on the pan, it read 0.5 g , then each mass measurement would be 0.5 g too big. The resulting graph would be as in Figure 19.

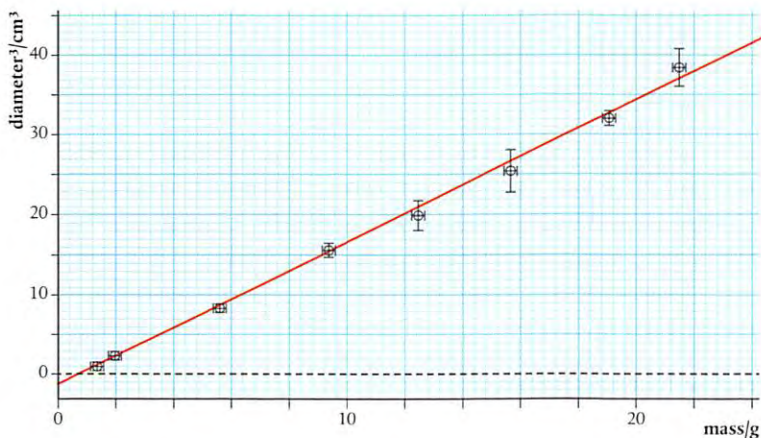


Figure 19 Graph of diameter³ of a modeling clay ball vs mass with a systematic error.

A systematic error in the diameter would not be so easy to see. Since diameter is cubed, adding a constant value to each diameter would cause the line to become curved.

Outliers

Sometimes a mistake is made in one of the measurements. This is quite difficult to spot in a table but will often lead to an outlier on a graph. For example, one of the measurements in Table 12 is incorrect.



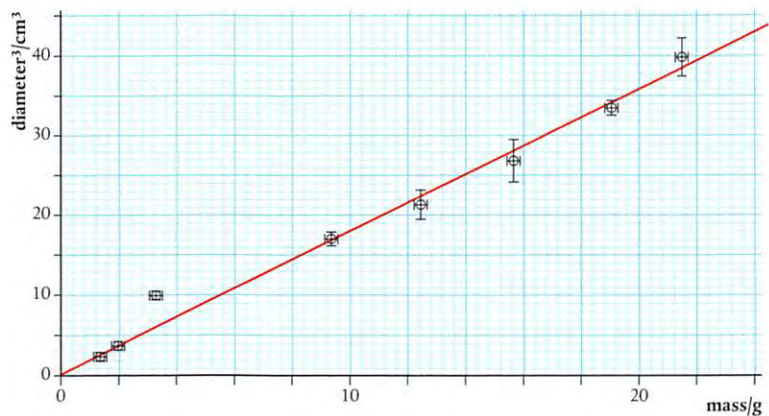
The best fit of these points is now a straight line. Over time, you will learn how to judge whether data is best represented by a linear or non-linear fit, perhaps based on the theory behind an experiment or the positions of the points.

Table 12

Mass/g ± 0.1 g	Diameter/cm ± 0.002 cm			
	1	2	3	4
1.4	1.296	1.430	1.370	1.280
2.0	1.570	1.590	1.480	1.550
5.6	2.100	2.130	2.148	3.148
9.4	2.560	2.572	2.520	2.610
12.5	2.690	2.840	2.824	2.720
15.7	3.030	2.980	3.080	2.890
19.1	3.250	3.230	3.190	3.204
21.5	3.490	3.432	3.372	3.360
24.8	3.550	3.560	3.540	3.520

This is revealed in the graph in Figure 20.

Figure 20 Graph of diameter³ of a modeling clay ball vs mass with outlier.



If asked for a sketch graph, you should consider what shape it will have and where it will cross the axes. Scales are not required.



When you find an outlier, you need to do some detective work to try to find out why the point is not closer to the line. Taking a close look at the raw data sometimes reveals that one of the measurements was incorrect. This can then be removed and the line plotted again. However, you cannot simply leave out the point because it does not fit. A sudden decrease in the level of ozone over the Antarctic was originally left out of the data since it was an outlier. Later investigation of this 'outlier' led to a significant discovery.

Uncertainty in the gradient

The general equation for a straight-line graph passing through the origin is $y = mx$. In this case, the equation of the line is $d^3 = \frac{6m}{\pi\rho}$, where d^3 is y and m is x and the gradient is $\frac{6}{\pi\rho}$. You can see that the unit of the gradient is cm^3/g . This is consistent with it representing $\frac{6}{\pi\rho}$.

From the graph, we see that gradient = $1.797 \text{ cm}^3 \text{ g}^{-1} = \frac{6}{\pi\rho}$ so $\rho = \frac{6}{1.797\pi}$
 $\frac{6}{1.797\pi} = 1.063 \text{ g cm}^{-3}$ but what is the uncertainty in this value?

There are several ways to estimate the uncertainty in a gradient. One of them is to draw the steepest and least steep lines through the error bars as shown in Figure 21.

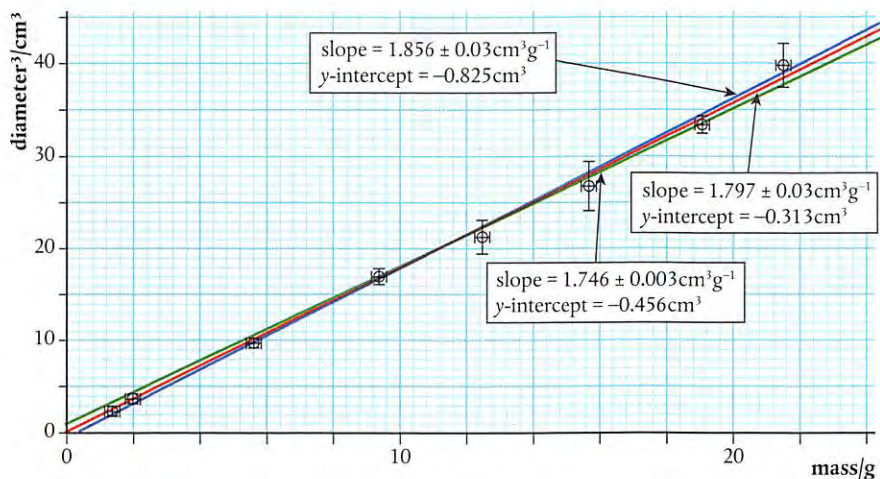


Figure 21 Graph of diameter³ of a modeling clay ball vs mass showing steepest and least steep lines.

This gives a maximum gradient = $1.856 \text{ cm}^3 \text{ g}^{-1}$ and minimum gradient = $1.746 \text{ cm}^3 \text{ g}^{-1}$.

So: uncertainty in the gradient = $\frac{(1.856 - 1.746)}{2} = 0.06 \text{ cm}^3 \text{ g}^{-1}$

Note that the program used to draw the graph (LoggerPro®) gives an uncertainty in the gradient of $\pm 0.03 \text{ cm}^3 \text{ g}^{-1}$. This is a more correct value but the steepest and least steep lines method is accepted in IB assessments.

The steepest and least steep gradients give maximum and minimum values for the density of:

$$\rho_{\max} = \frac{6}{1.746\pi} = 1.094 \text{ g cm}^{-3}$$

$$\rho_{\min} = \frac{6}{1.856\pi} = 1.029 \text{ g cm}^{-3}$$

So the uncertainty is: $\frac{(1.094 - 1.029)}{2} = 0.03 \text{ g cm}^{-3}$

The density can now be written as: $1.06 \pm 0.03 \text{ g cm}^{-3}$

Fractional uncertainties

So far, we have dealt with uncertainty as $\pm \Delta x$. This is called the **absolute uncertainty** in the value. Uncertainties can also be expressed as fractions. This has some advantages when processing data.

In the previous example, we measured the diameter of modeling clay balls then cubed this value in order to linearize the data. To make the sums simpler, let us consider a slightly bigger ball with a diameter of $10 \pm 1 \text{ cm}$.

So the measured value $d = 10 \text{ cm}$ and the absolute uncertainty $\Delta d = 1 \text{ cm}$.

The fractional uncertainty = $\frac{\Delta d}{d} = \frac{1}{10} = 0.1$ (or, expressed as a percentage, 10%).

During the processing of the data, we found $d^3 = 1000 \text{ cm}^3$.

The uncertainty in this value is not the same as in d . To find the uncertainty in d^3 , we need to know the biggest and smallest possible values of d^3 . These we can calculate by adding and subtracting the absolute uncertainty:

$$\text{maximum } d^3 = (10 + 1)^3 = 1331 \text{ cm}^3$$

$$\text{minimum } d^3 = (10 - 1)^3 = 729 \text{ cm}^3$$



If the y-intercept was of more importance, then constructing steepest and least steep lines would also allow maximum and minimum intercept values to be read off.



A value obtained from an experiment can be compared with a 'known' value by seeing if the known value lies within the uncertainty range. Additionally, you could use percentage difference. Find the difference between the experimental and known values and then divide this difference by the known value.

So the range of values is: $(1331 - 729) = 602 \text{ cm}^3$

The uncertainty is therefore $\pm 301 \text{ cm}^3$, which rounded down to one significant figure gives $\pm 300 \text{ cm}^3$.

This is not the same as $(\Delta d)^3$, which would be 1 cm^3 .

The fractional uncertainty in $d^3 = \frac{300}{1000} = 0.3$. This is the same as $3 \times$ the fractional uncertainty in d . This leads to an alternative way of finding uncertainties when raising data to the power 3.

If $\frac{\Delta x}{x}$ is the fractional uncertainty in x , then the fractional uncertainty in $x^3 = \frac{3\Delta x}{x}$.

More generally, if $\frac{\Delta x}{x}$ is the fractional uncertainty in x , then the fractional uncertainty in $x^n = \frac{n\Delta x}{x}$.

So if you square a value, the fractional uncertainty is $2 \times$ bigger.

Another way of writing this would be that, if $\frac{\Delta x}{x}$ is the fractional uncertainty in x , then the fractional uncertainty in $x^2 = \frac{\Delta x}{x} + \frac{\Delta x}{x}$. This can be extended to any multiplication.

So if $\frac{\Delta x}{x}$ is the fractional uncertainty in x and $\frac{\Delta y}{y}$ is the fractional uncertainty in y , then the fractional uncertainty in $xy = \frac{\Delta x}{x} + \frac{\Delta y}{y}$.

It seems strange but, when dividing, the fractional uncertainties also add. So if $\frac{\Delta x}{x}$ is the fractional uncertainty in x and $\frac{\Delta y}{y}$ is the fractional uncertainty in y , then the fractional uncertainty in $\frac{x}{y} = \frac{\Delta x}{x} + \frac{\Delta y}{y}$.

If you divide a quantity by a constant with no uncertainty, then the fractional uncertainty remains the same.

This is all summarized in the data booklet as:

If $y = \frac{ab}{c}$ then $\frac{\Delta y}{y} = \frac{\Delta a}{a} + \frac{\Delta b}{b} + \frac{\Delta c}{c}$

And if $y = a^n$ then $\frac{\Delta y}{y} = n \frac{\Delta a}{a}$

Challenge yourself

1. When a solid ball rolls down a slope of height h , its speed at bottom v is given by the equation:

$$v = \sqrt{\frac{10}{7}gh}$$

where g is the acceleration due to gravity.

In an experiment to determine g , the following results were achieved:

Distance between two markers at the bottom of the slope $d = 5.0 \pm 0.2 \text{ cm}$

Time taken to travel between markers $t = 0.06 \pm 0.01 \text{ s}$

Height of slope $h = 6.0 \pm 0.2 \text{ cm}$.

Given that the speed $v = \frac{d}{t}$, find a value for g and its uncertainty. How might you reduce this uncertainty?

Example

If the length of the side of a cube is quoted as 5.00 ± 0.01 m, what are its volume and the uncertainty in the volume?

$$\text{fractional uncertainty in length} = \frac{0.01}{5} = 0.002$$

$$\text{volume} = 5.00^3 = 125 \text{ m}^3$$

When a quantity is cubed, its fractional uncertainty is $3 \times$ bigger so the fractional uncertainty in volume = $0.002 \times 3 = 0.006$.

The absolute uncertainty is therefore $0.006 \times 125 = 0.75$ (approximately 1) so the volume is $125 \pm 1 \text{ m}^3$.

Exercise

Q12. The length of the sides of a cube and its mass are quoted as:

$$\text{length} = 0.050 \pm 0.001 \text{ m}$$

$$\text{mass} = 1.132 \pm 0.002 \text{ kg}$$

Calculate the density of the material and its uncertainty.

Q13. The distance around a running track is 400 ± 1 m. If a person runs around the track four times, calculate the distance traveled and its uncertainty.

Q14. The time for 10 swings of a pendulum is 11.2 ± 0.1 s. Calculate the time for one swing of the pendulum and its uncertainty.



Nature of Science

We have seen how we can use numbers to represent physical quantities. By representing those quantities by letters, we can derive mathematical equations to define relationships between them, then use graphs to verify those relationships. Some quantities cannot be represented by a number alone so a whole new area of mathematics needs to be developed to enable us to derive mathematical models relating them.

Vector and scalar quantities

So far we have dealt with six different quantities: length, time, mass, volume, density and displacement.

All of these quantities have a size, but displacement also has a direction. Quantities that have size and direction are **vectors** and those with only size are **scalars**. All quantities are either vectors or scalars. It will be apparent why it is important to make this distinction when we add displacements together.

Example

Consider two displacements one after another as shown in Figure 22.

Starting from A, walk 4 km west to B, then 5 km north to C.



Scalar

A quantity with magnitude only.

Vector

A quantity with magnitude and direction.

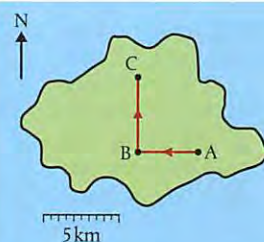


Figure 22 Displacements shown on a map.

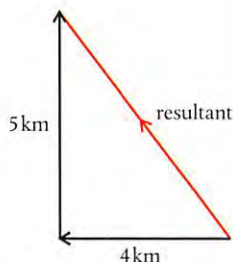
The total displacement from the start is not $5 + 4$ but can be found by drawing a line from A to C on a scale diagram.

We will find that there are many other vector quantities that can be added in the same way.

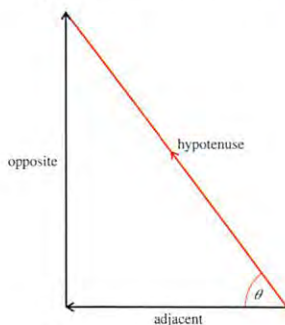
Addition of vectors

Vectors can be represented by drawing arrows. The *length* of the arrow is proportional to the magnitude of the quantity and the *direction* of the arrow is the direction of the quantity. The arrow commences at the point of application, the significance of which will become clearer in A.2.

To add vectors, the arrows are simply arranged so that the point of one touches the tail of the other. The resultant vector is found by drawing a line joining the free tail to the free point.



▲ **Figure 23** Vector addition.



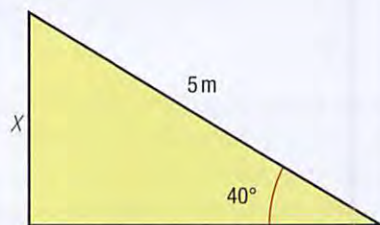
▲ **Figure 24** Triangle key terms.

To show that a quantity is a vector, we can write it in a special way. In textbooks, this is often in bold (**A**) but when you write, you can put an arrow on the top. In physics texts, the vector notation is often left out. This is because if we know that the symbol represents a displacement, then we know it is a vector and do not need the vector notation to remind us.



Worked example

Find the side X of the triangle.



Solution

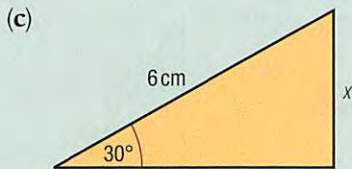
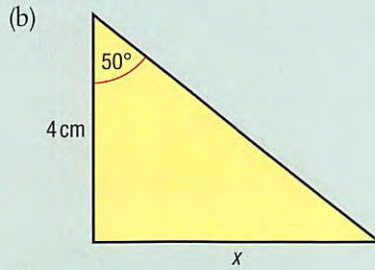
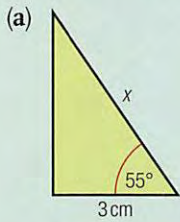
Side X is the opposite so:

$$X = 5 \times \sin 40^\circ$$

$$\sin 40^\circ = 0.6428 \text{ so } X = 3.2 \text{ m}$$

Exercise

Q15. Use your calculator to find x in each triangle.



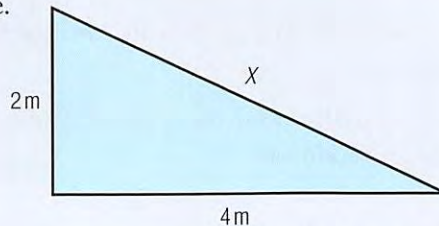
Pythagoras

The most useful mathematical relationship for finding the resultant of two perpendicular vectors is Pythagoras' theorem:

$$\text{hypotenuse}^2 = \text{adjacent}^2 + \text{opposite}^2$$

Worked example

Find the side X on the triangle.



Solution

Applying Pythagoras:

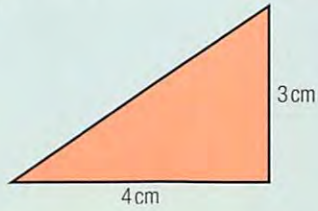
$$X^2 = 2^2 + 4^2$$

So: $X = \sqrt{2^2 + 4^2} = \sqrt{20} = 4.5\text{m}$

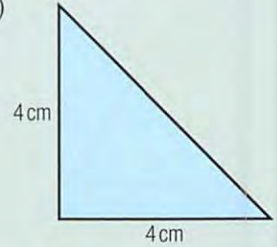
Exercise

Q16. Use Pythagoras' theorem to find the hypotenuse in each triangle.

(a)



(b)



(c)



(d)



Using trigonometry to solve vector problems

Once the vectors have been arranged point to tail, it is a simple matter of applying the trigonometrical relationships to the triangles that you get.

Exercise

Draw the vectors and solve the following problems using Pythagoras' theorem.

Q17. A boat travels 4 km west followed by 8 km north. What is the resultant displacement?

Q18. A plane flies 100 km north then changes course to fly 50 km east. What is the resultant displacement?

Vectors in one dimension

In this course, we will often consider the simplest examples where the motion is restricted to one dimension, for example, a train traveling along a straight track. In examples like this, there are only two possible directions – forward and backward. To distinguish between the two directions, we give them different signs (forward + and backward –). Adding vectors is now simply a matter of adding the magnitudes, with no need for complicated triangles.

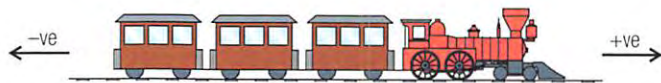


Figure 25 The train can only move forward or backward.

You can decide for yourself which you want to be positive but generally we follow the convention below.

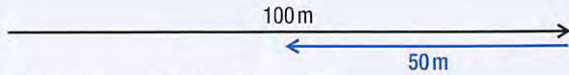


Worked example

If a train moves 100 m forward along a straight track then 50 m back, what is its final displacement?

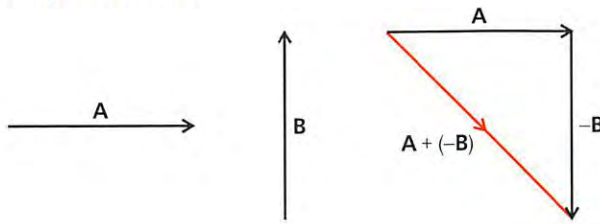
Solution

The vector diagram is as follows.



The resultant is 50 m forward.

Subtracting vectors



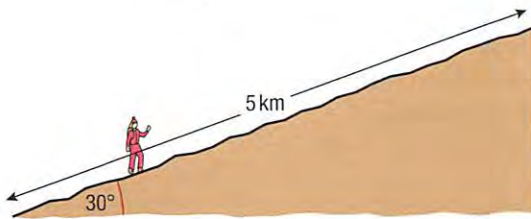
Now we know that a negative vector is simply the opposite direction to a positive vector, we can subtract vector **B** from vector **A** by changing the direction of vector **B** and adding it to **A**.

$$A - B = A + (-B)$$

Taking components of a vector

Consider someone walking up the hill in Figure 27. They walk 5 km up the slope but want to know how high they have climbed rather than how far they have walked. To calculate this, they can use trigonometry.

$$\text{height} = 5 \times \sin 30^\circ$$



The height is called the vertical component of the displacement.

The horizontal displacement can also be calculated.

$$\text{horizontal displacement} = 5 \times \cos 30^\circ$$

This process is called taking components of a vector and is often used in solving physics problems.

Figure 26 Subtracting vectors.



When a vector is multiplied by a scale factor, its alignment is unchanged. If the scale factor is negative, the vector is in the opposite direction. The magnitude is increased by the magnitude of the scale factor.

Figure 27 5 km up the hill but how high?

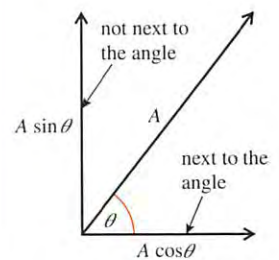


Figure 28 An easy way to remember which is cos is to say that 'it is becous it is next to the angle'.

Exercise

- Q19.** If a boat travels 10 km in a direction 30° to the east of north, how far north has it traveled?
- Q20.** On his way to the South Pole, Amundsen traveled 8 km in a direction that was 20° west of south. What was his displacement south?
- Q21.** A mountaineer climbs 500 m up a slope that is inclined at an angle of 60° to the horizontal. How high has he climbed?

Summary – Tool 3: Mathematics

In terms of mathematics, you should now be aware of:

- scientific notation
- SI prefixes and units
- orders of magnitude
- area and volume
- fundamental units
- derived units in terms of SI units
- approximation and estimation
- dimensional analysis of units for checking expressions
- the significance of uncertainties in raw and processed data
- recording uncertainties in measurements as a range to appropriate precision
- expressing measurement and processed uncertainties to appropriate significant figures or precision
- expressing values to appropriate significant figures or decimal places
- mean and range
- extrapolate and interpolate graphs
- linear and non-linear graphs with appropriate scales and axes
- linearizing graphs
- drawing and interpreting uncertainty bars
- drawing lines or curves of best fit
- constructing maximum and minimum gradient lines by considering all uncertainty bars
- determining uncertainty in gradients and intercepts
- percentage change and percentage difference
- percentage error and percentage uncertainty
- propagation of uncertainties
- scalars and vectors
- scale diagrams
- drawing and labeling vectors
- vector addition and subtraction
- decimals, fractions, percentages, ratios, reciprocals, exponents and trigonometric ratios
- multiplication of vectors by a scalar
- resolving vectors.

SKILLS



You will find practice questions and solutions in the eBook.

There are some mathematical tools that have been introduced here and will be continued, including:

- arithmetic and algebra (see worked example calculations throughout)
- tables and graphs for raw and processed data (see also Sankey diagrams (A.3) and greenhouse gas spectra (B.2))
- direct and inverse proportionality, and positive and negative relationships or correlations (A.1, A.2, B.1, B.2, C.1, D.1, D.2, D.3)
- interpreting graph features (A.1)
- sketch graphs (labeled but unscaled axes) to qualitatively describe trends (A.1).

The mathematical skills listed in the guide that will be addressed in the textbook content more generally are:

- symbols from the guide and data booklet (throughout)
- selection and manipulation of equations (throughout)
- effect of changes to variables on other variables (throughout)
- use of units (throughout)
- rates of change (A.1, A.3)
- neglecting effects and explaining why (A.1)
- free-body diagrams (A.2)
- derivations of equations (B.3, C.5, D.1)
- continuous and discrete variables (E.1)
- logarithmic and exponential functions (E.3).

Video resources

This table lists recommended videos that have been selected to help enhance your learning. The links to the videos can be found in the 'Resources' section of your eBook.

Chapter	Video	Description
Skills in the study of physics	Snooker	A vector quantity, like momentum, has both magnitude and direction.
A.1	Parachute descent	Parachutes are used to reduce the downward acceleration experienced and to enable steering. The parachute used at the end of this video has a larger surface area so that the spacecraft is decelerated.
A.2	Racing car start	The ground exerts a forward force on the tyres and the tyres exert an equal and opposite force on the ground. We can see evidence for this in the movement of the stones.
A.2	Bike riding	The banked wall exerts a force perpendicular to the velocity of the cyclists. They move (temporarily) along the arc of a circle.
A.3	Climbing	This climber, at some point, consumed an energy source and is seeking to convert this into gravitational potential energy. There is also a metaphorical lesson to be learned here about not giving up as you tackle your physics revision!
A.5	Hyperspace	Science fiction writers have long imagined what might happen if travelling at or beyond the speed of light. Physicist Michio Kaku uses the term to refer to higher dimensions in his discussions on the unification of fundamental forces and the fate of the universe.
B.1	Brownian motion	The apparently erratic movement of visible pollen grains can be explained by the presence of many invisible colliding particles in the surrounding fluid.
B.1	Heat conduction in a solid	In high temperature regions, particles vibrate quickly. They transfer energy to neighbouring particles. Eventually, the body as a whole might reach a constant temperature throughout.
B.1	Hot air balloons	These balloons use convection to rise because high temperature gases have a lower density than the surrounding fluid.
B.1	Evaporation	Evaporation of water results in the temperature of the remaining water falling. This is because the particles of highest kinetic energy are more likely to be removed from the surface, meaning that the average kinetic energy of the remaining particles decreases.
B.2	Greenhouse gas emissions	Carbon dioxide release during 2011 and 2012 is represented on this world map. Fossil fuel combustion is not uniformly distributed.
B.2	Albedo	Albedo is the ratio of reflected to incident light. Ice contributes to a higher albedo on Earth.
B.3	Boyle–Mariotte gas law	As the volume of a constant number of moles of gas decreases at constant temperature, pressure increases.
B.3	Gay–Lussac gas law	As the temperature of a constant number of moles of gas increases at constant volume, pressure increases.
B.5	Wall switch	Although the drift speed of electrons in a conductor is roughly 1 mm per second, there is no perceptible delay between pressing a switch and the bulb lighting. This is because the electric force is transmitted at close to the speed of light.

C.1	Seismograph	The recording tip on this seismograph vibrates about a fixed point. The paper moving beneath it shows a wave form.
C.2	Compression wave in a gas	Longitudinal waves are made up of compressions and rarefactions.
C.3	Dispersion	Different wavelengths of light travel at different speeds in a prism and therefore refract by different amounts. White light can be split into its constituent colours.
C.3	Light diffraction through a double slit	Light is diffracted separately at each slit, resulting in an interference pattern. Maxima form where the waves that meet are in phase; minima form where the waves are in antiphase.
C.4	Piano strings	Pianos (as with all stringed and wind instruments) use standing waves. The pitch varies with length and mass per unit length.
C.4	Damped driven pendulums	Displacements are maximized when the driving frequency approximates the natural frequency. Damping reduces the frequency at which the maximum displacement is reached and the amplitude itself.
C.5	Ultrasound imaging	The Doppler effect can be combined with ultrasound imaging to measure the speed of blood flow for diagnosis of cardiovascular conditions.
D.1	Rings of Saturn	The orbital speed of the rocks that make up the rings of Saturn depends on orbital radius but not on the mass of the rocks themselves.
D.2	Magnetic field lines	Iron filings can be used to show the 3D shape of magnetic field lines.
D.3	Aurora	The aurora results from the motion of charged particles from the Sun in the Earth's magnetic field.
E.1	Rutherford scattering experiment	The (unexpected) outcome of the Geiger–Marsden–Rutherford experiment was that most alpha particles were undeflected but a small proportion were scattered.
E.3	Ionizing radiation	Ionizing radiation can damage DNA, which means that precautions must be taken to shield and reduce exposure time by those who work with radioactive isotopes.
E.4	Pressurized water nuclear reactor	This fission reactor contains fuel rods, control rods, a turbine and a generator. Water acts both as the moderator and as the coolant for heat exchange.
E.5	Proton–proton III chain reaction	When nucleons fuse together, energy is released.
E.5	Sunlight	The Sun's light forms a spectrum. Shown here are a variety of visible light wavelengths, but the Sun also produces invisible electromagnetic radiation.
E.5	Lifecycle of the Sun	When a nebula collapses under gravity, the temperature might be sufficient for hydrogen nuclei to fuse. The main sequence concludes when the radiation pressure from hydrogen fusion is insufficient to counter gravity, resulting in collapse and then a red giant.
E.5	Milky Way	The Sun is located in the Milky Way galaxy. This time-lapse footage over observatory domes was captured at ESO's La Silla Observatory in the Atacama desert, Chile.



THEME

A Space, time and motion



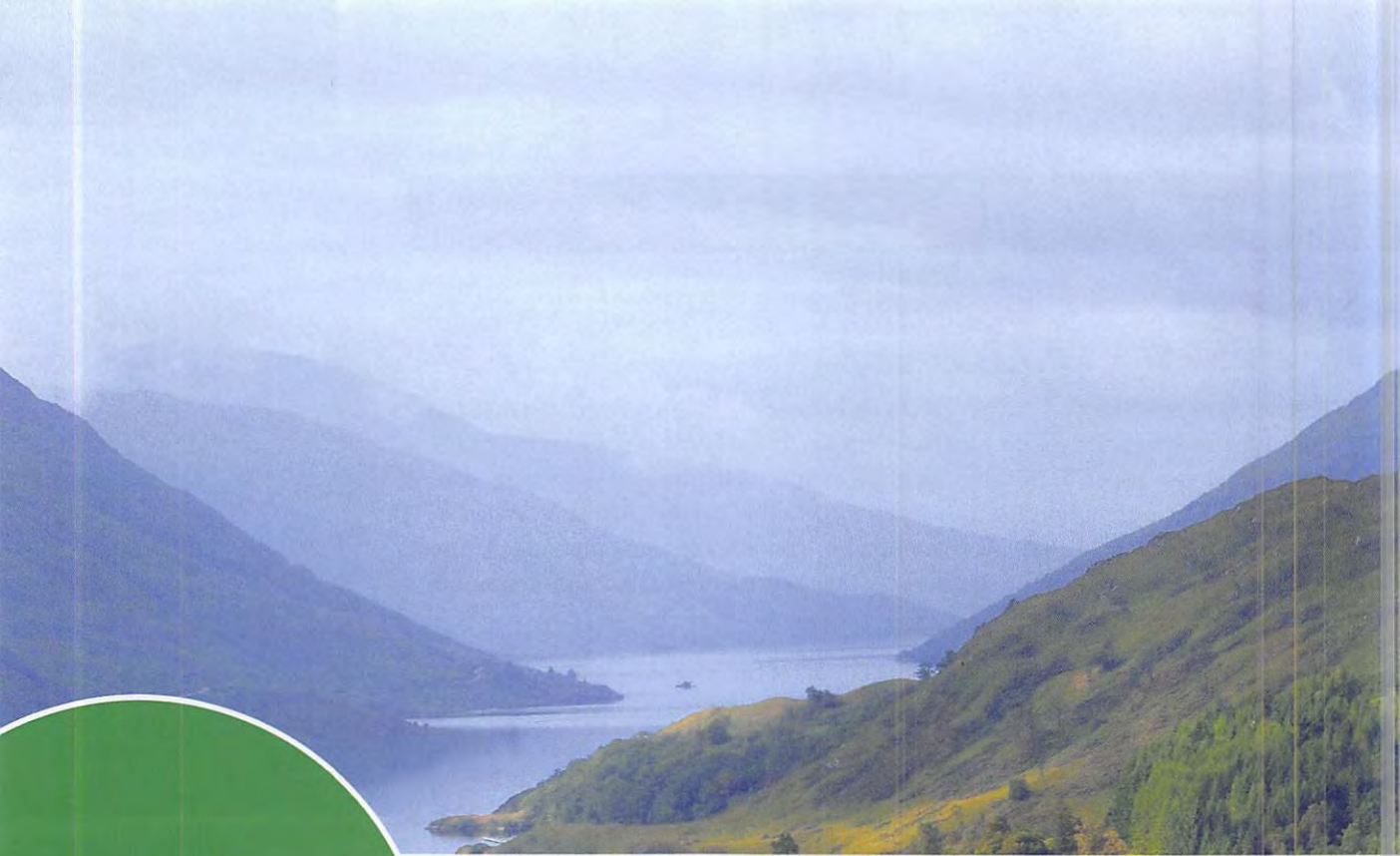
A Space, time and motion

◀ Fireworks displays encapsulate a lot of physics, including thermal energy, light and sound waves, their behavior in the Earth's gravitational field and the effects generated by particular types of atom. As you will see, they also relate to space, time and motion.

There are lots of words that can be used to describe something's motion: distance and displacement, speed and velocity, and acceleration. If you know everything about a body's motion at a specific position and time, then as an IB physicist you will be able to predict its state of motion at another position or time. This is kinematics. When simplified, the equations that govern motion horizontally and vertically can be treated separately. Fireworks are not so simple; they experience air resistance and continue to combust their fuel mid-flight.

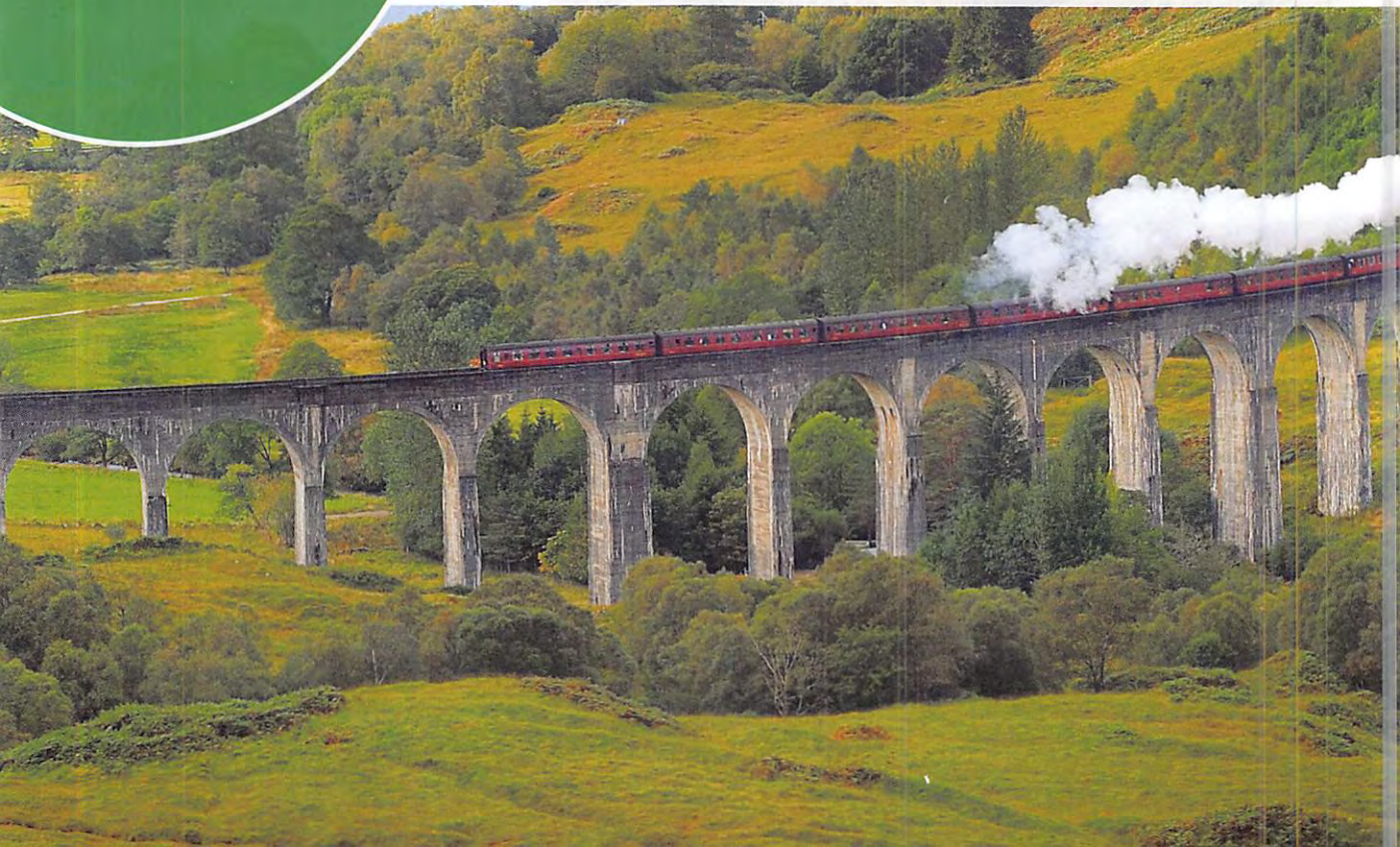
The burning of fuels to generate changes in motion relates to forces and momentum. Isaac Newton articulated three laws that describe how a lack of resultant force means there is no change in velocity, a resultant force leads to a change in momentum and the force of one body 'A' on another 'B' means that the same type and size of force must be being exerted by 'B' on 'A' in precisely the opposite direction. There are types of force to contend with, and of course not all forces act in the same direction that the body is already moving in; circular motion results from perpendicular forces and velocities and has its own set of governing equations.

If kinematics is the study of the journey, energy is the study of the start and end. Energy, along with momentum, is a conserved quantity that can be changed only if work is done. Power is another term still; it is the rate at which energy is changed or work is done. Balancing a 100 g apple in your hand requires a force of about 1 N. Lifting it vertically to arm's reach requires you to provide about 1 J of work. Doing so repeatedly every second represents 1 W of power, irrespective of how long in total you do it for.



A.1

Kinematics



◀ When can you think of a steam train as a particle?



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?

How can the analysis of motion in one and two dimensions be used to solve real-life problems?

The photograph at the start of this chapter shows a train, but we will not be dealing with complicated systems like trains in their full complexity. In physics, we try to understand everything on the most basic level. Understanding a physical system means being able to predict its final conditions given its initial conditions. To do this for a train, we would have to calculate the position and motion of every part – and there are a lot of parts. In fact, if we considered all the particles that make up all the parts, then we would have a huge number of particles to deal with.

In this course, we will be dealing with one particle of matter at a time. This is because the ability to solve problems with one particle makes us able to solve problems with many particles. We may even pretend a train is one particle.

The initial conditions of a particle describe where it is and what it is doing. These can be defined by a set of numbers, which are the results of measurements. As time passes, some of these quantities might change. What physicists try to do is predict their values at any given time in the future. To do this, they use mathematical models.

Nature of Science

From the definitions of velocity and acceleration, we can use mathematics to derive a set of equations that predict the position and velocity of a particle at any given time. We can show by experiment that these equations give the correct result for some examples, then make the generalization that the equations apply in all cases.

Students should understand:

that the motion of bodies through space and time can be described and analyzed in terms of position, velocity, and acceleration

velocity is the rate of change of position, and acceleration is the rate of change of velocity
--

the change in position is the displacement
--

the difference between distance and displacement
--

the difference between instantaneous and average values of velocity, speed and acceleration, and how to determine them
--

the equations of motion for solving problems with uniformly accelerated motion as given by:

$$s = \frac{u + v}{2} t$$

$$v = u + at$$

$$s = ut + \frac{1}{2} at^2$$

$$v^2 = u^2 + 2as$$

motion with uniform and non-uniform acceleration

the behavior of projectiles in the absence of fluid resistance, and the application of the equations of motion resolved into vertical and horizontal components

the qualitative effect of fluid resistance on projectiles, including time of flight, trajectory, velocity, acceleration, range and terminal speed.

Further information about the fluid resistance force can be found in A.2.



Nature of Science

In the Tools chapter, we observed that things move and now we are going to mathematically model that movement. Before we do that, we must define some quantities.

Displacement and distance

It is important to understand the difference between distance traveled and displacement. To explain this, consider the route marked out on the map shown in Figure 1.

Displacement is the shortest path moved in a particular direction.

The unit of displacement is the meter (m). Displacement is a vector quantity.

On the map, the displacement is the length of the straight line from A to B, which is a distance of 5 km west.

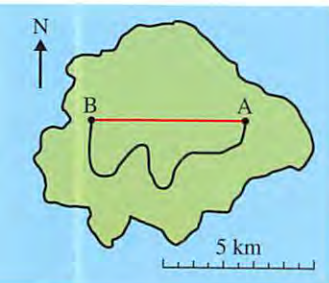
Distance is how far you have traveled from A to B.

The unit of distance is also the meter (m). Distance is a scalar quantity.

In this example, the distance traveled is the length of the path taken, which is about 10 km.

Sometimes, this difference leads to a surprising result. For example, if you run all the way round a running track, you will have traveled a distance of 400 m but your displacement will be 0 m.

In everyday life, it is often more important to know the distance traveled. For example, if you are going to travel from Paris to Lyon by road, you will want to know that the distance by road is 450 km, not that your final displacement will be 336 km southeast. However, in physics, we break everything down into its simplest parts, so we start by considering motion in a straight line only. In this case, it is more useful to know the displacement, since that also has information about which direction you have traveled in.



A.1 Figure 1

Note: since displacement is a vector, you should always say what the direction is.



Velocity and speed

Both speed and velocity are a measure of how fast a body is moving.

Velocity is defined as the rate of change of position. Since 'change of position' is displacement and 'rate of change' requires division by time taken:

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

The unit of velocity is m s^{-1} .

Velocity is a vector quantity.

Speed is defined as the distance traveled per unit time:

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

The unit of speed is also m s^{-1} .

Speed is a scalar quantity.

Exercise

Q1. Convert the following speeds into m s^{-1} :

- (a) a car traveling at 100 km h^{-1}
- (b) a runner running at 20 km h^{-1} .

Average velocity and instantaneous velocity

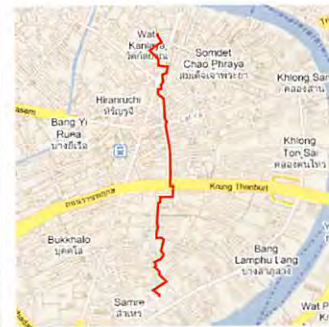
Consider traveling by car from the north of Bangkok to the south – a distance of about 16 km. If the journey takes 4 hours, you can calculate your velocity to be $\frac{16}{4} = 4 \text{ km h}^{-1}$ in a southward direction. This does not tell you anything about the journey, just the difference between the beginning and the end (unless you managed to travel at a constant speed in a straight line). The value calculated is the **average velocity** and in this example it is quite useless. If we broke the trip down into lots of small pieces, each lasting only one second, then for each second the car could be considered to be traveling in a straight line at a constant speed. For these short stages, we could quote the car's **instantaneous velocity** – which is how fast it is going at that moment in time and in which direction.



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



$$\text{speed} = \frac{\text{distance}}{\text{time}}$$



A.1 Figure 2 It is not possible to take this route across Bangkok with a constant velocity.

The bus in the photo has a constant velocity for a very short time.

Exercise

- Q2.** A runner runs once around a circular track of length 400 m with a constant speed in 96 s. Calculate:
- the average speed of the runner
 - the average velocity of the runner
 - the instantaneous velocity of the runner after 48 s
 - the displacement after 24 s.

Constant velocity

If the velocity is constant, then the instantaneous velocity is the same all the time so:

$$\text{instantaneous velocity} = \text{average velocity}$$

Since velocity is a vector, this also implies that the direction of motion is constant.

Measuring a constant velocity

From the definition of velocity, we see that:

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

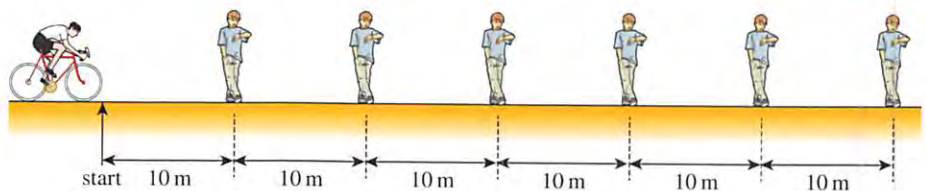
Rearranging this gives:

$$\text{displacement} = \text{velocity} \times \text{time}$$

So, if velocity is constant, displacement is proportional to time. To test this relationship and find the velocity, we can measure the displacement of a body at different times.

To do this, you either need a lot of clocks or a stop clock that records many times.

This is called a **lap timer**. In this example, a bicycle was ridden at constant speed along a straight road past six students standing 10 m apart, each operating a stop clock as in Figure 3. The clocks were all started when the bike, already moving, passed the start marker and stopped as the bike passed each student.



A.1 Figure 3 Measuring the time for a bike to pass.

What does Newton's first law tell us about the forces on a body traveling at constant velocity? (A.2)

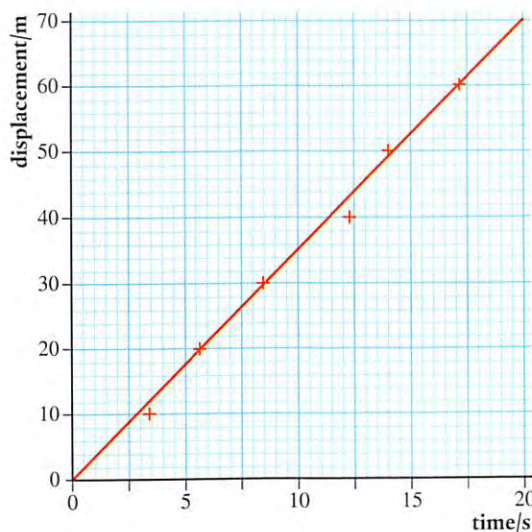


The results achieved are shown in Table 1.

The uncertainty in displacement is given as 0.1 m since it is difficult to decide exactly when the bike passed the marker.

The digital stop clock has a scale with 2 decimal places, so the uncertainty is 0.01 s. However, the uncertainty given is 0.02 s since the clocks all had to be started at the same time.

Since displacement (s) is proportional to time (t), then a graph of s vs t should give a straight line with gradient = velocity as shown in Figure 4.



A.1 Figure 4 Graph of displacement vs time for a bike.

Notice that in this graph the line does not pass through all the points. This is because the uncertainty in the measurement in time is almost certainly bigger than the uncertainty in the clock (± 0.02 s) due to the reaction time of the students stopping the clock. To get a better estimate of the uncertainty, we would need to have several students standing at each 10 m position. Repeating the experiment is not possible in this example since it is very difficult to ride at the same velocity several times.

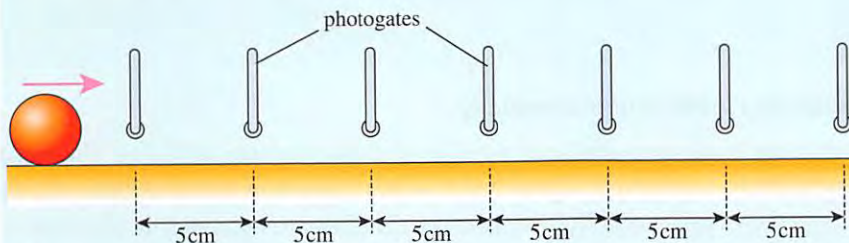
The gradient indicates that: velocity = 3.5 m s^{-1}

Displacement/m $\pm 0.1 \text{ m}$	Time/s $\pm 0.02 \text{ s}$
10.0	3.40
20.0	5.62
30.0	8.55
40.0	12.31
50.0	14.17
60.0	17.21

A.1 Table 1

SKILLS

Most school laboratories are not large enough to ride bikes in so when working indoors, we need to use shorter distances. This means that the times are going to be shorter so hand-operated stop clocks will have too great a percentage uncertainty. One way of timing in the lab is by using photogates. These are connected to a computer via an interface and record the time when a body passes in or out of the gate. So, to replicate the bike experiment in the lab using a ball, we would need seven photogates as in Figure 5, with one extra gate to represent the start.



A.1 Figure 5 How to measure the time for a rolling ball if you have seven photogates. This would be quite expensive so we compromise by using just two photogates and a motion that can be repeated. An example could be a ball moving along a horizontal section of track after it has rolled down an inclined plane. Provided the ball starts from the same point, it should have the same velocity. So, instead of using seven photogates, we can use two – one is at the start of the motion and the other is moved to different positions along the track as in Figure 6.



A.1 Figure 6 The ball interrupts the infrared light transmitted across each gate as it passes through them. The times of these interruptions are measured and recorded by a data logger.

A.1 Figure 7 Measuring the velocity of a ball with two photogates.

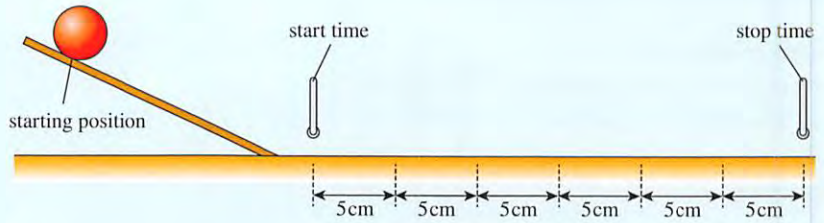
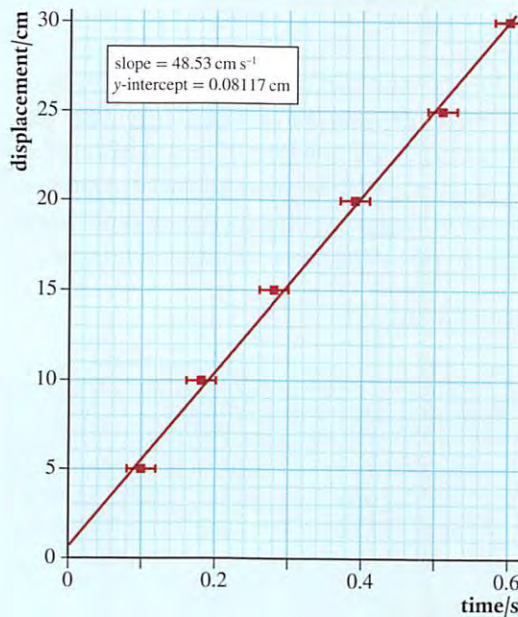


Table 2 shows the results obtained using this arrangement.

A.1 Table 2

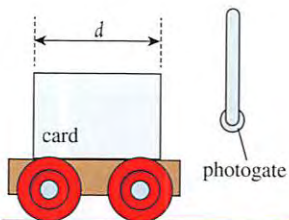
Displacement/ cm ± 0.1 cm	Time(t)/s ± 0.0001 s					Mean t/s	$\Delta t/s$
5.0	0.0997	0.0983	0.0985	0.1035	0.1040	0.101	0.003
10.0	0.1829	0.1969	0.1770	0.1824	0.1825	0.18	0.01
15.0	0.2844	0.2800	0.2810	0.2714	0.2779	0.28	0.01
20.0	0.3681	0.3890	0.3933	0.3952	0.3854	0.39	0.01
25.0	0.4879	0.5108	0.5165	0.4994	0.5403	0.51	0.03
30.0	0.6117	0.6034	0.5978	0.6040	0.5932	0.60	0.01

A.1 Figure 8 Graph of displacement vs time for a rolling ball.



Notice that the uncertainty calculated from $\frac{(\max - \min)}{2}$ is much more than the instrument uncertainty. A graph of displacement vs time gives Figure 8.

From this graph, we can see that within the limits of the experiment's uncertainties the displacement could be proportional to time, so we can conclude that the velocity may have been constant. However, if we look closely at the data, we see that there seems to be a slight curve, indicating that perhaps the ball was slowing down. To verify this, we would have to collect more data.



A.1 Figure 9 A card and photogate used to measure instantaneous velocity.

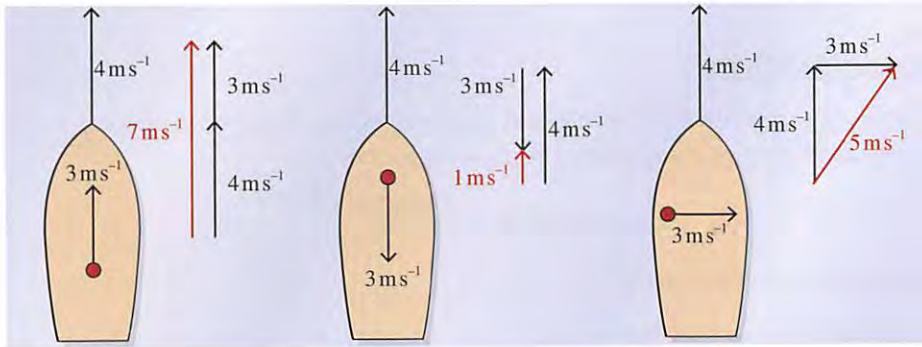
Measuring instantaneous velocity

To measure instantaneous velocity, a very small displacement must be used. This could be achieved by placing two photogates close together or attaching a piece of card to the moving body as shown in Figure 9. The time taken for the card to pass through the photogate is

recorded and the instantaneous velocity calculated from: $\frac{\text{length of card}}{\text{time taken}} \left(\frac{d}{t} \right)$

Relative velocity

Velocity is a vector so velocities must be added as vectors. Imagine you are running north at 3 m s^{-1} on a ship that is also traveling north at 4 m s^{-1} as shown in Figure 10. Your velocity relative to the ship is 3 m s^{-1} but your velocity relative to the water is 7 m s^{-1} . If you turn around and run due south, your velocity will still be 3 m s^{-1} relative to the ship but 1 m s^{-1} relative to the water. Finally, if you run toward the east, the vectors add at right angles to give a resultant velocity of magnitude 5 m s^{-1} relative to the water. You can see that the velocity vectors have been added.



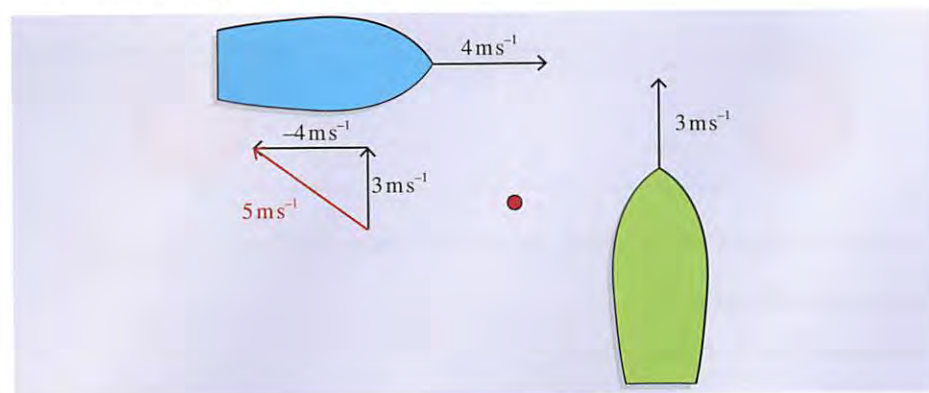
A.1 Figure 10 Running on board a ship.

Imagine that you are floating in the water watching two boats traveling toward each other as in Figure 11.



A.1 Figure 11 Two boats approach each other. The vector addition for the velocity of the green boat from the perspective of the blue boat is shown.

The blue boat is traveling east at 4 m s^{-1} and the green boat is traveling west at -3 m s^{-1} . Remember that the sign of a vector in one dimension gives the direction. So, if east is positive, then west is negative. If you were standing on the blue boat, you would see the water going past at -4 m s^{-1} so the green boat would approach with the velocity of the water plus its velocity in the water: $-4 + -3 = -7 \text{ m s}^{-1}$. This can also be done in two dimensions as in Figure 12.



A.1 Figure 12 Two boats traveling perpendicular to each other. The vector addition for the velocity of the green boat from the perspective of the blue boat is shown.

According to the swimmer floating in the water, the green boat travels north and the blue boat travels east, but an observer on the blue boat will see the water traveling toward the west and the green boat traveling due north. Adding these two velocities gives a velocity of 5 m s^{-1} in an approximately northwest direction.



How effectively do the equations of motion model Newton's laws of dynamics? (A.2)

Exercise

- Q3.** An observer standing on a road watches a bird flying east at a velocity of 10 m s^{-1} . A second observer, driving a car along the road northward at 20 m s^{-1} , sees the bird. What is the velocity of the bird relative to the driver?
- Q4.** A boat travels along a river heading north with a velocity 4 m s^{-1} as a woman walks across a bridge from east to west with velocity of 1 m s^{-1} . Calculate the velocity of the woman relative to the boat.

Acceleration

In everyday usage, the word **accelerate** means to go faster. However, in physics, acceleration is defined as the rate of change of velocity:

$$\text{acceleration} = \frac{\text{change of velocity}}{\text{time}}$$

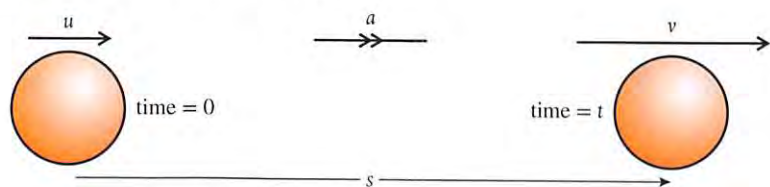
The unit of acceleration is m s^{-2} .

Acceleration is a vector quantity.

This means that whenever a body changes its velocity, it accelerates. This could be because it is getting faster, slower, or just changing direction. In the example of the journey across Bangkok, the car would have been slowing down, speeding up and going round corners almost the whole time so it would have had many different accelerations. However, this example is far too complicated for us to consider in this course (and probably any physics course). For most of this chapter, we will only consider the simplest example of accelerated motion, which is constant acceleration.

Constant acceleration in one dimension

In one-dimensional motion, acceleration, velocity and displacement are all in the same direction. This means they can be added without having to draw triangles. Figure 13 shows a body that is starting from an initial velocity u and accelerating at a constant rate a to velocity v in t seconds. The distance traveled in this time is s . Since the motion is in a straight line, this is also the displacement.



A.1 Figure 13 A red ball with constant acceleration.

Using the definitions already stated, we can write equations related to this example.

Average velocity

From the definition, average velocity = $\frac{\text{displacement}}{\text{time}}$

$$\text{average velocity} = \frac{s}{t} \quad (1)$$

Since the velocity changes at a constant rate from the beginning to the end, we can also calculate the average velocity by adding the initial and final velocities and dividing by two:

$$\text{average velocity} = \frac{(u + v)}{2} \quad (2)$$

Acceleration

Acceleration is defined as the rate of change of velocity:

$$a = \frac{(v - u)}{t} \quad (3)$$

We can use these equations to solve any problem involving constant acceleration. However, to make problem-solving easier, we can derive two more equations by substituting from one into the other.

Equating equations (1) and (2):

$$\begin{aligned} \frac{s}{t} &= \frac{(u + v)}{2} \\ s &= \frac{(u + v)t}{2} \end{aligned} \quad (4)$$

Rearranging (3) gives: $v = u + at$

If we substitute for v in equation (4), we get: $s = ut + \frac{1}{2}at^2$ (5)

Rearranging (3) again gives: $t = \frac{(v - u)}{a}$

If t is now substituted in equation (4), we get: $v^2 = u^2 + 2as$ (6)

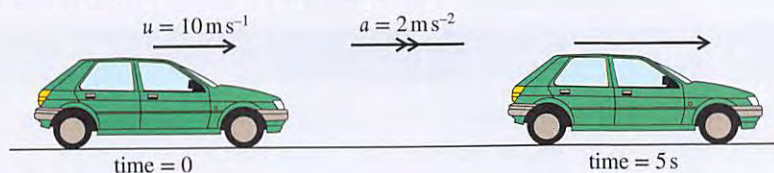
These equations are sometimes known as the *suvat* equations. If you know any three of s , u , v , a and t , you can find either of the other two in one step.

Worked example

A car traveling at 10 m s^{-1} accelerates at 2 m s^{-2} for 5 s. What is its displacement?

Solution

The first thing to do is draw a simple diagram:



This enables you to see what is happening at a glance rather than reading the text. The next stage is to make a list of *suvat*.

$$s = ?$$

$$u = 10 \text{ m s}^{-1}$$

$$v = ?$$

$$a = 2 \text{ m s}^{-2}$$

$$t = 5 \text{ s}$$

To find s , you need an equation that contains *suat*. The only equation with all four of these quantities is: $s = ut + \frac{1}{2}at^2$

Using this equation gives:

$$s = 10 \times 5 + \frac{1}{2} \times 2 \times 5^2$$

$$s = 75 \text{ m}$$



These equations are known as the *suvat* equations:

$$a = \frac{(v - u)}{t}$$

$$s = \frac{(v + u)t}{2}$$

$$s = ut + \frac{1}{2}at^2$$

$$v^2 = u^2 + 2as$$



How are the equations for circular motion related to those for linear motion? (A.2)

SKILLS



A GeoGebra worksheet linked to this topic is available in the eBook.



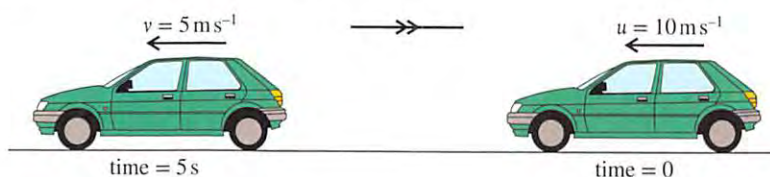
When the units are consistent, you do not need to include units in all stages of a calculation, just in the answer.

The signs of displacement, velocity and acceleration

We must not forget that displacement, velocity and acceleration are vectors. This means that they have direction. However, since this is a one-dimensional example, there are only two possible directions, forward and backward. We know which direction the vector is in from its sign.

If we take right to be positive:

- A positive displacement means that the body has moved to the right.
- A positive velocity means the body is moving to the right.
- A positive acceleration means that the body is either moving to the right and getting faster or moving to the left and getting slower. This can be confusing so consider the following example.



A.1 Figure 14 A car moves to the left with decreasing speed.

The car is traveling in a negative direction so the velocities are negative.

$$u = -10 \text{ m s}^{-1}$$

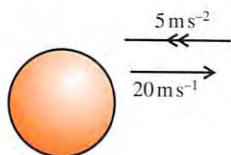
$$v = -5 \text{ m s}^{-1}$$

$$t = 5 \text{ s}$$

The acceleration is therefore given by:

$$a = \frac{(v - u)}{t} = \frac{-5 - (-10)}{5} = 1 \text{ m s}^{-2}$$

The positive sign tells us that the acceleration is in a positive direction (right) even though the car is traveling in a negative direction (left).



A.1 Figure 15 The acceleration is negative so points to the left.

The acceleration due to gravity is not constant all over the Earth. 9.81 m s^{-2} is the average value.

The acceleration also gets smaller the higher you go. However, we ignore this change when conducting experiments in the lab since labs are not that high.

To make the examples easier to follow, $g = 10 \text{ m s}^{-2}$ is used throughout. However, you should only use this approximate value in exam questions if told to do so.



Worked example

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

Solution

$$s = ?$$

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

$$v = ?$$

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

$$t = 20 \text{ s}$$

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

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

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.

Exercise

- Q5. Calculate the final velocity of a body that starts from rest and accelerates at 5 m s^{-2} for a distance of 100 m.
- Q6. A body starts with a velocity of 20 m s^{-1} and accelerates for 200 m with an acceleration of 5 m s^{-2} . What is the final velocity of the body?
- Q7. A body accelerates at 10 m s^{-2} and reaches a final velocity of 20 m s^{-1} in 5 s. What is the initial velocity of the body?

Free fall motion

Although a car has been used in the previous examples, the acceleration of a car is not usually constant so we should not use the *suvat* equations. The only example of constant acceleration that we see in everyday life is when a body is dropped. Even then, the acceleration is only constant for a short distance.

Acceleration of free fall

When a body is allowed to fall freely, we say it is in free fall. Bodies falling freely on the Earth fall with an acceleration of about 9.81 m s^{-2} (depending where you are). The body falls because of gravity. For that reason, we use the letter *g* to denote this acceleration. Since the acceleration is constant, we can use the *suvat* equations to solve problems.

Exercise

In these calculations, use $g = 10 \text{ m s}^{-2}$.

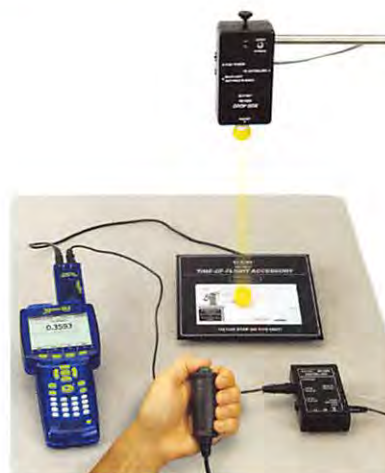
- Q8. A ball is thrown upward with a velocity of 30 m s^{-1} . What is the displacement of the ball after 2 s?
- Q9. A ball is dropped. What will its velocity be after falling 65 cm?
- Q10. A ball is thrown upward with a velocity of 20 m s^{-1} . After how many seconds will the ball return to its starting point?

Measuring the acceleration due to gravity

When a body falls freely under the influence of gravity, it accelerates at a constant rate. This means that time to fall t and distance s are related by the equation: $s = ut + \frac{1}{2}at^2$. If the body starts from rest, then $u = 0$ so the equation becomes: $s = \frac{1}{2}at^2$. Since s is directly proportional to t^2 , a graph of s vs t^2 would therefore be a straight line with gradient $\frac{1}{2}g$. It is difficult to measure the time for a ball to pass different markers, but if we assume the ball falls with the same acceleration when repeatedly dropped, we can measure the time taken for the ball to fall from different heights. There are many ways of doing this. All involve some way of starting a clock when the ball is released and stopping it when it hits the ground. Table 3 shows a set of results from a 'ball drop' experiment.

How does the motion of an object change within a gravitational field? (D.1)

If you jump out of a plane (with a parachute on), you will feel the push of the air as it rushes past you. As you fall faster and faster, the air will push upward more and more until you cannot go any faster. At this point, you have reached terminal velocity. We will come back to this after introducing forces.



Apparatus for measuring g .

A.1 Table 3

Height(h)/m ± 0.001 m	Time(t)/s ± 0.001 s					Mean t/s	t ² /s ²	Δ(t ²)/s ²
0.118	0.155	0.153	0.156	0.156	0.152	0.154	0.024	0.001
0.168	0.183	0.182	0.183	0.182	0.184	0.183	0.0334	0.0004
0.218	0.208	0.205	0.210	0.211	0.210	0.209	0.044	0.001
0.268	0.236	0.235	0.237	0.239	0.231	0.236	0.056	0.002
0.318	0.250	0.254	0.255	0.250	0.256	0.253	0.064	0.002
0.368	0.276	0.277	0.276	0.278	0.276	0.277	0.077	0.001
0.418	0.292	0.293	0.294	0.291	0.292	0.292	0.085	0.001
0.468	0.310	0.310	0.303	0.300	0.311	0.307	0.094	0.003
0.518	0.322	0.328	0.330	0.328	0.324	0.326	0.107	0.003
0.568	0.342	0.341	0.343	0.343	0.352	0.344	0.118	0.004

If a parachutist kept accelerating at a constant rate, they would break the sound barrier after about 30s of flight. By understanding the forces involved, scientists have been able to design wing suits so that base jumpers can achieve forward velocities greater than their rate of falling.



A worksheet with full details of how to carry out this experiment is available in the eBook.

SKILLS



Notice that the uncertainty in t^2 is calculated from: $\frac{(t_{\max}^2 - t_{\min}^2)}{2}$

Notice how the line in Figure 16 is very close to the points and that the uncertainties reflect the actual random variation in the data. The gradient of the line is equal to $\frac{1}{2}g$ so $g = 2 \times \text{gradient}$.

$$g = 2 \times 4.814 = 9.624 \text{ m s}^{-2}$$

The uncertainty in this value can be estimated from the steepest and least steep lines:

$$g_{\max} = 2 \times 5.112 = 10.224 \text{ m s}^{-2}$$

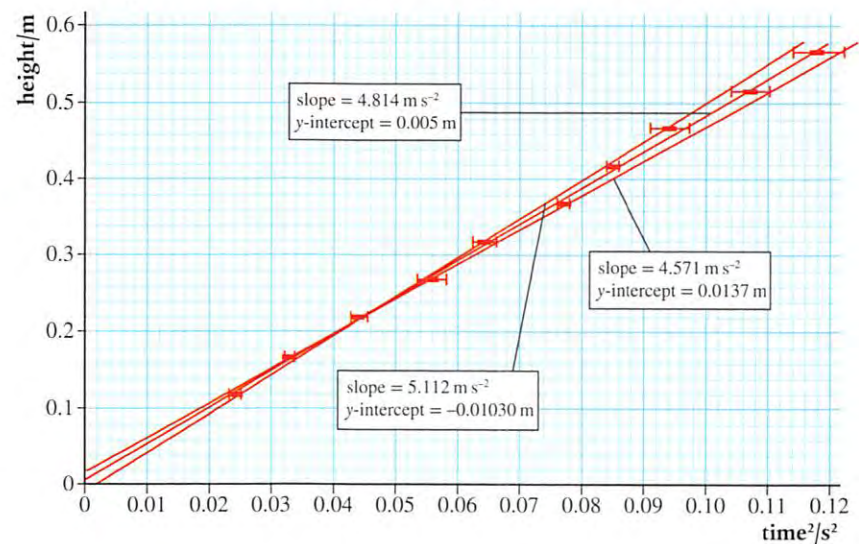
$$g_{\min} = 2 \times 4.571 = 9.142 \text{ m s}^{-2}$$

$$\Delta g = \frac{(g_{\max} - g_{\min})}{2} = \frac{(10.224 - 9.142)}{2} = 0.541 \text{ m s}^{-2}$$

So, the final value including uncertainty is $9.6 \pm 0.5 \text{ m s}^{-2}$.

This is in agreement with the accepted average value which is 9.81 m s^{-2} .

A.1 Figure 16 Height vs time² for a falling object.



Why would it not be appropriate to apply the suvat equations to the motion of a body falling freely from a distance of 2 times the Earth's radius to the surface of the Earth? (D.1)

Graphical representation of motion

Graphs are used in physics to give a visual representation of relationships. In kinematics, they can be used to show how displacement, velocity and acceleration change with time. Figure 17 shows the graphs for four different examples of motion.

The best way to sketch graphs is to split the motion into sections then plot where the body is at different times. Joining these points will give the displacement–time graph. Once you have done that, you can work out the v - t and a - t graphs by looking at the s - t graph rather than the motion.

Gradient of displacement–time graph

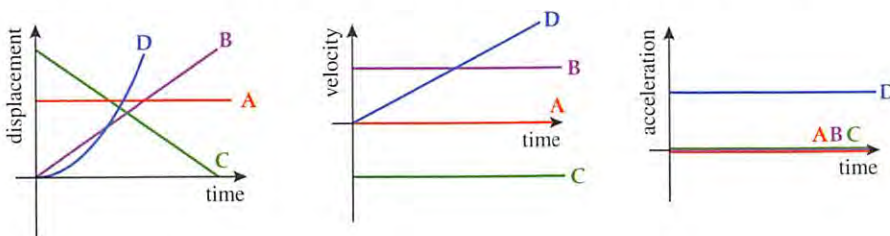
The gradient of a graph is: $\frac{\text{change in } y}{\text{change in } x} = \frac{\Delta y}{\Delta x}$

In the case of the displacement–time graph, this will give:

$$\text{gradient} = \frac{\Delta s}{\Delta t}$$

This is the same as velocity.

We can represent the motion of a body on displacement–time graphs, velocity–time graphs and acceleration–time graphs. The three graphs of these types shown in Figure 17 display the motion of four bodies, which are labeled A, B, C and D.



Body A

A body that is not moving.
Displacement is always the same.
Velocity is zero.
Acceleration is zero.

Body C

A body that has a constant negative velocity.
Displacement is decreasing linearly with time.
Velocity is a constant negative value.
Acceleration is zero.

Body B

A body that is traveling with a constant positive velocity.
Displacement increases linearly with time.
Velocity is a constant positive value.
Acceleration is zero.

Body D

A body that is accelerating with constant acceleration.
Displacement is increasing at a non-linear rate. The shape of this line is a parabola since displacement is proportional to t^2 ($s = ut + \frac{1}{2}at^2$).
Velocity is increasing linearly with time.
Acceleration is a constant positive value.

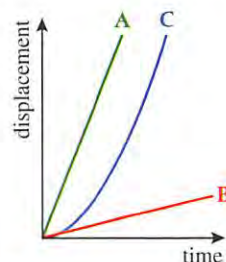
So, the gradient of the displacement–time graph equals the velocity. Using this information, we can see that line A in Figure 18 represents a body with a greater velocity than line B, and that since the gradient of line C is increasing, this must be the graph for an accelerating body.



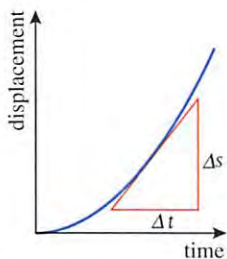
You need to be able to:

- work out what kind of motion a body has by looking at the graphs
- sketch graphs for a given motion.

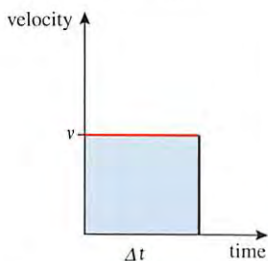
A.1 Figure 17 Graphical representation of motion.



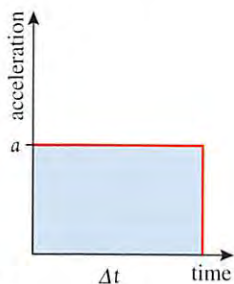
A.1 Figure 18 Three new bodies to compare.



A.1 Figure 19 Finding the gradient of the tangent.



A.1 Figure 20 The area is displacement.



A.1 Figure 21 The area is change in velocity.

How does analyzing graphs allow us to determine other physical quantities? (NOS)

A GeoGebra worksheet linked to this topic is available in the eBook.



SKILLS



Instantaneous velocity

When a body accelerates, its velocity is constantly changing. The displacement–time graph for this motion is therefore a curve. To find the instantaneous velocity from the graph, we can draw a tangent to the curve and find the gradient of the tangent as shown in Figure 19.

Area under velocity–time graph

The area under the velocity–time graph for the body traveling at constant velocity v shown in Figure 20 is given by:

$$\text{area} = v\Delta t$$

But we know from the definition of velocity that: $v = \frac{\Delta s}{\Delta t}$

Rearranging gives $\Delta s = v\Delta t$ so the area under a velocity–time graph gives the displacement.

This is true, not only for simple cases such as this, but for all examples.

Gradient of velocity–time graph

The gradient of the velocity–time graph is given by $\frac{\Delta v}{\Delta t}$. This is the same as acceleration.

Area under acceleration–time graph

The area under the acceleration–time graph in Figure 21 is given by $a\Delta t$. But we know from the definition of acceleration that: $a = \frac{(v - u)}{t}$

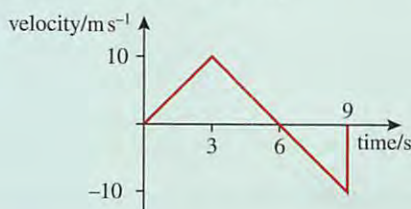
Rearranging this gives $v - u = a\Delta t$ so the area under the graph gives the change in velocity.

If you have covered calculus in your mathematics course, you may recognize these equations:

$$v = \frac{ds}{dt}, a = \frac{dv}{dt} = \frac{d^2s}{dt^2} \text{ and } s = \int v dt, v = \int a dt$$

Exercise

- Q11.** Sketch a velocity–time graph for a body starting from rest and accelerating at a constant rate to a final velocity of 25 m s^{-1} in 10 seconds. Use the graph to find the distance traveled and the acceleration of the body.
- Q12.** Describe the motion of the body whose velocity–time graph is shown. What is the final displacement of the body?



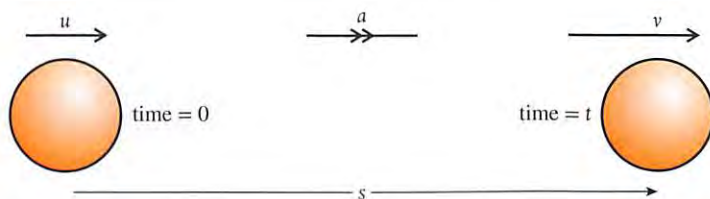
Q13. A ball is released from rest on the hill in the figure below. Sketch the $s-t$, $v-t$, and $a-t$ graphs for its horizontal motion.



Q14. A ball rolls along a table then falls off the edge, landing on soft sand. Sketch the $s-t$, $v-t$, and $a-t$ graphs for its vertical motion.

Example 1: The *suvat* example

As an example, let us consider the motion we looked at when deriving the *suvat* equations.



Displacement–time

The body starts with velocity u and travels to the right with constant acceleration a for a time t . If we take the starting point to be zero displacement, then the displacement–time graph starts from zero and rises to s in t seconds. We can therefore plot the two points shown in Figure 23. The body is accelerating so the line joining these points is a parabola. The whole parabola has been drawn to show what it would look like – the reason it is offset is because the body is not starting from rest. The part of the curve to the left of the origin tells us what the particle was doing before we started the clock.

Velocity–time

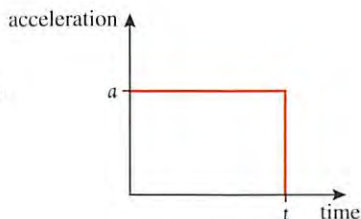
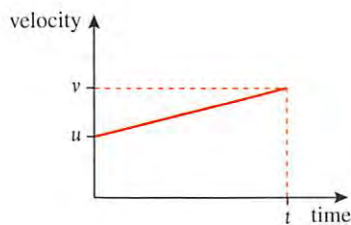
Figure 24 is a straight line with a positive gradient showing that the acceleration is constant. The line does not start from the origin since the initial velocity is u .

The gradient of this line is $\frac{(v-u)}{t}$, which we know from the *suvat* equations is acceleration.

The area under the line makes the shape of a trapezium. The area of this trapezium is $\frac{1}{2}(v+u)t$. This is the *suvat* equation for s .

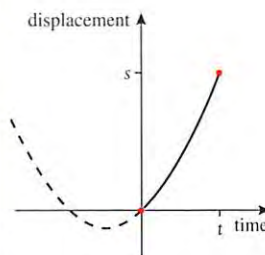
Acceleration–time

The acceleration is constant so the acceleration–time graph is a horizontal line as shown in Figure 25. The area under this line is $a \times t$, which we know from the *suvat* equations equals $(v-u)$.



A.1 Figure 22 A body with constant acceleration.

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



A.1 Figure 23 Constant acceleration.

A.1 Figure 24 Constant acceleration.

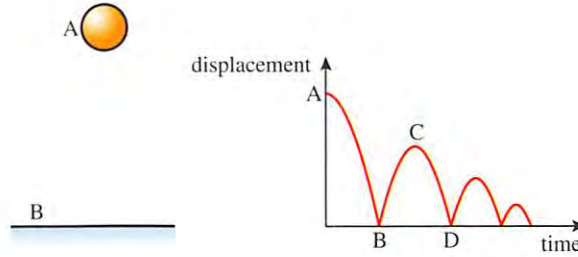
A.1 Figure 25 Constant acceleration.

Example 2: The bouncing ball

Consider a rubber ball dropped from position A above the ground onto hard surface B. The ball bounces up and down several times. Figure 26 shows the displacement–time graph for four bounces. From the graph, we see that the ball starts above the ground then falls with increasing velocity (as shown by the increasing negative gradient). When the ball bounces at B, the velocity suddenly changes from negative to positive as the ball begins to travel back up. As the ball goes up, its velocity decreases until it stops at C and begins to fall again.

A.1 Figure 26 Vertical displacement vs time.

Why is the height reached by a bouncing ball less than the height of release? (A.3)



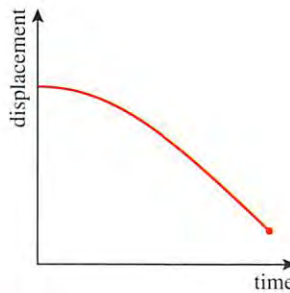
Exercise

Q15. By considering the gradient of the displacement–time graph in Figure 26, plot the velocity–time graph for the motion of the bouncing ball.

Example 3: A ball falling with air resistance

Figure 27 shows the motion of a ball that is dropped several hundred meters through the air. It starts from rest and accelerates for some time. As the ball accelerates, the air resistance increases, which stops the ball from getting any faster. At this point, the ball continues with constant velocity.

A.1 Figure 27 Vertical displacement vs time.



Exercise

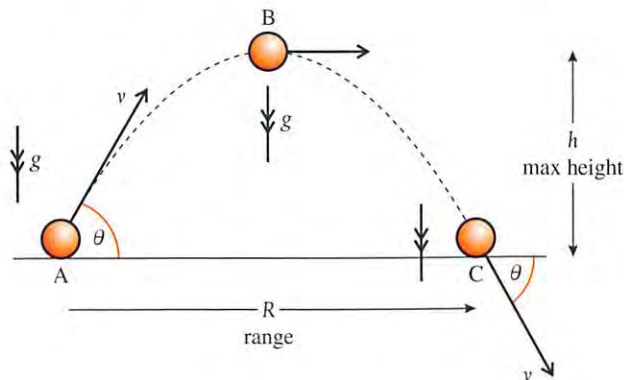
Q16. By considering the gradient of the displacement–time graph, plot the velocity–time graph for the motion of the falling ball in Figure 27.

Projectile motion

We all know what happens when a ball is thrown. It follows a curved path like the one in the photo. We can see from this photo that the path is parabolic and later we will show why that is the case.

Modeling projectile motion

All examples of motion up to this point have been in one dimension but projectile motion is two-dimensional. However, if we take components of all the vectors vertically and horizontally, we can simplify this into two simultaneous one-dimensional problems. The important thing to realize is that the vertical and horizontal components are independent of each other. You can test this by dropping an eraser off your desk and flicking one forward at the same time – they both hit the floor together. The downward motion is not changed by the fact that one stone is also moving forward.



Consider a ball that is projected at an angle θ to the horizontal, as shown in Figure 28. We can split the motion into three parts, beginning, middle and end, and analyze the vectors representing displacement, velocity and time at each stage. Notice that the path is symmetrical, so the motion on the way down is the same as on the way up.

Horizontal components

At A (time = 0)	At B (time = $\frac{t}{2}$)	At C (time = t)
displacement = zero	displacement = $\frac{R}{2}$	displacement = R
velocity = $v \cos \theta$	velocity = $v \cos \theta$	velocity = $v \cos \theta$
acceleration = 0	acceleration = 0	acceleration = 0

Vertical components

At A	At B	At C
displacement = zero	displacement = h	displacement = zero
velocity = $v \sin \theta$	velocity = zero	velocity = $-v \sin \theta$
acceleration = $-g$	acceleration = $-g$	acceleration = $-g$

We can see that the vertical motion is constant acceleration and the horizontal motion is constant velocity. We can therefore use the *suvat* equations.



▲ A stroboscopic photograph of a projected ball.



When can problems on projectile motion be solved by applying conservation of energy instead of kinematic equations? (A.3)

◀ **A.1 Figure 28** A projectile launched at an angle θ .



Note that, at C, we are using the magnitude of θ (which is unchanged from position A). Therefore the negative sign is in place to provide the correct velocity direction; the projectile is moving downward.

Since the horizontal displacement is proportional to t , the path has the same shape as a graph of vertical displacement plotted against time. This is parabolic since the vertical displacement is proportional to t^2 .



suvat for horizontal motion

Since acceleration is zero, there is only one equation needed to define the motion.

<i>suvat</i>	A to C
$v = \frac{s}{t}$	$R = v \cos \theta t$

suvat for vertical motion

When considering the vertical motion, it is worth splitting the motion into two parts.

A.1 Table 4



A GeoGebra worksheet linked to this topic is available in the eBook.



<i>suvat</i>	At B	At C
$s = \frac{1}{2}(u + v)t$	$h = \frac{1}{2}(v \sin \theta) \frac{t}{2}$	$0 = \frac{1}{2}(v \sin \theta - v \sin \theta)t$
$v^2 = u^2 + 2as$	$0 = v^2 \sin^2 \theta - 2gh$	$(-v \sin \theta)^2 = (v \sin \theta)^2 - 0$
$s = ut + \frac{1}{2}at^2$	$h = v \sin \theta t - \frac{1}{2}g\left(\frac{t}{2}\right)^2$	$0 = v \sin \theta t - \frac{1}{2}gt^2$
$a = \frac{v - u}{t}$	$g = \frac{v \sin \theta - 0}{\frac{t}{2}}$	$g = \frac{v \sin \theta - (-v \sin \theta)}{t}$

For a given value of v , the maximum range is when $v \cos \theta t$ is a maximum value.

$$t = \frac{2v \sin \theta}{g}$$

If we substitute this for t we get:

$$R = \frac{2v^2 \cos \theta \sin \theta}{g}$$

Now, $2 \sin \theta \cos \theta = \sin^2 \theta$ (a trigonometric identity)

$$\text{So, } R = \frac{v^2 \sin^2 \theta}{g}$$

This is maximum when $\sin^2 \theta$ is a maximum ($\sin^2 \theta = 1$), which is when $\theta = 45^\circ$.



Some of these equations are not very useful since they simply state that $0 = 0$. However, we do end up with three useful ones (highlighted):

$$R = v \cos \theta t \tag{7}$$

$$0 = v^2 \sin^2 \theta - 2gh \quad \text{or} \quad h = \frac{v^2 \sin^2 \theta}{2g} \tag{8}$$

$$0 = v \sin \theta t - \frac{1}{2}gt^2 \quad \text{or} \quad t = \frac{2v \sin \theta}{g} \tag{9}$$

Solving problems

In a typical problem, you will be given the magnitude and direction of the initial velocity and asked to find either the maximum height or range. To calculate h , you can use equation (8), but to calculate R , you need to find the time of flight so must use (9) first. (You could also substitute for t into equation (6) to give another equation but we have enough equations already.)

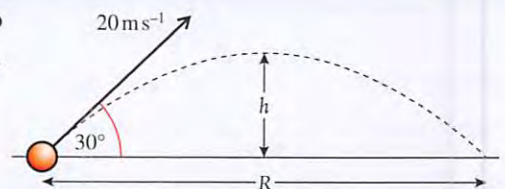
You do not have to remember a lot of equations to solve a projectile problem. If you understand how to apply the *suvat* equations to the two components of the projectile motion, you only have to remember the *suvat* equations (and they are in the data booklet).



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

Worked example

A ball is thrown at an angle of 30° to the horizontal at a speed of 20 m s^{-1} . Calculate its range and the maximum height reached.



Solution

First, draw a diagram, including labels defining all the quantities known and unknown.

Now we need to find the time of flight. If we apply $s = ut + \frac{1}{2}at^2$ to the whole flight we get:

$$t = \frac{2v \sin \theta}{g} = \frac{(2 \times 20 \times \sin 30^\circ)}{10} = 2 \text{ s}$$

We can now apply $s = vt$ to the whole flight to find the range:

$$R = v \cos \theta t = 20 \times \cos 30^\circ \times 2 = 34.6 \text{ m}$$

Finally, to find the height, we apply $s = ut + \frac{1}{2}at^2$ to the vertical motion, but remember that this is only half the complete flight so the time is 1 s.

$$h = v \sin \theta t - \frac{1}{2}gt^2 = 20 \times \sin 30^\circ \times 1 - \frac{1}{2} \times 10 \times 1^2 = 10 - 5 = 5 \text{ m}$$



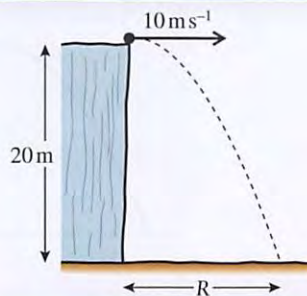
When a bullet is fired at a distant target, it will travel in a curved path due to the action of gravity. Precision marksmen adjust their sights to compensate for this. The angle of this adjustment could be based on calculation or experiment (trial and error).

If you have ever played golf, you will know that it is not true that the maximum range is achieved with an angle of 45° . The angle is actually much less. This is because the ball is held up by the air like a plane is. In this photo, Alan Shepard is playing golf on the Moon. Here, the maximum range will be at 45° .

Worked example

A ball is thrown horizontally from a cliff top with a horizontal speed of 10 m s^{-1} .

If the cliff is 20 m high, what is the range of the ball?



Solution

This is an easy one since there are no angles to deal with. The initial vertical component of the velocity is zero and the horizontal component is 10 m s^{-1} . To calculate the time of flight, we apply $s = ut + \frac{1}{2}at^2$ to the vertical component. Knowing that the final displacement is -20 m , this gives:

$$-20 \text{ m} = 0 - \frac{1}{2}gt^2 \text{ so } t = \sqrt{\frac{(2 \times 20)}{10}} = 2 \text{ s}$$

We can now use this value to find the range by applying the equation $s = vt$ to the horizontal component: $R = 10 \times 2 = 20 \text{ m}$

Exercise

- Q17.** Calculate the range of a projectile thrown at an angle of 60° to the horizontal with a velocity of 30 m s^{-1} .
- Q18.** You throw a ball at a speed of 20 m s^{-1} .
- At what angle must you throw the ball so that it will just get over a wall that is 5 m high?
 - How far away from the wall must you be standing?
- Q19.** A gun is aimed so that it points directly at the center of a target 200 m away. If the bullet travels at 200 m s^{-1} , how far below the center of the target will the bullet hit?
- Q20.** If you can throw a ball at 20 m s^{-1} , what is the maximum distance you can throw it?

Challenge yourself

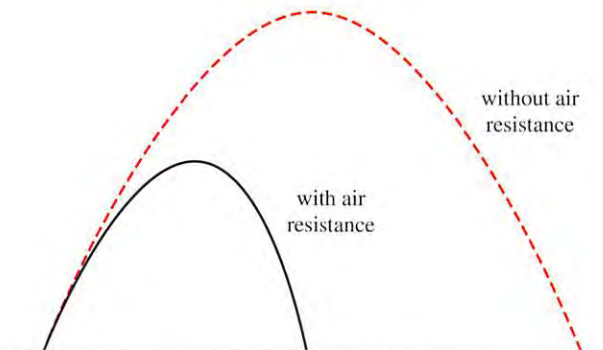
- A projectile is launched perpendicular to a 30° slope at 20 m s^{-1} . Calculate the distance between the launching position and landing position.

How does gravitational force allow for orbital motion? (A.2)

**Projectile motion with air resistance**

In all the examples above, we have ignored the fact that the air will resist the motion of the ball. Air resistance opposes motion and increases with the speed of the moving object. The actual path of a ball including air resistance is likely to be as shown in Figure 29.

A.1 Figure 29 When air resistance is present, the projectile's motion is asymmetric.

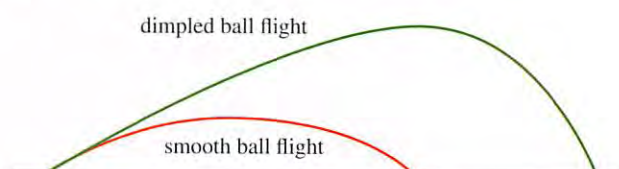


Notice that both the maximum height and the range are less. The path is also no longer a parabola – the way down is steeper than the way up.

The equation for this motion is complex. Horizontally, there is negative acceleration and so the horizontal component of velocity decreases. Vertically, there is increased magnitude of acceleration on the way up and a decreased magnitude of acceleration on the way down. None of these accelerations are constant so the *suvat* equations cannot be used. Luckily, all you need to know is the shape of the trajectory and the qualitative effects on range and time of flight.

Alternative air effects

The air does not always reduce the range of a projectile. A golf ball travels further than a ball projected in a vacuum. This is because the air holds the ball up, in the same way that it holds up a plane, due to the dimples in the ball and its spin.



A.1 Figure 30 The path of a smooth ball and a dimpled golf ball.

Guiding Questions revisited

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?

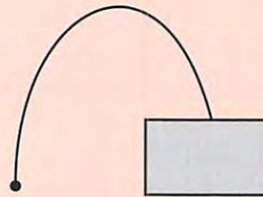
How can the analysis of motion in one and two dimensions be used to solve real-life problems?

In this chapter, we have considered real-life examples to show that:

- Displacement is the straight-line distance between the start and end points of a body's motion and it has a direction.
- Velocity is the rate of change of displacement (and the vector equivalent of speed).
- Acceleration is the rate of change of velocity (and can therefore be treated as a vector).
- Motion graphs of displacement and velocity (or acceleration) against time enable qualitative changes in these quantities to be described and calculations of other quantities to be performed.
- The *suvat* equations of uniformly accelerated motion can be used to predict how position and velocity change with time (or one another) when a body experiences a constant acceleration.
- Vector quantities can be split into perpendicular components that can be treated independently, making it possible to solve problems in two dimensions using the *suvat* equations twice, for example, vertically and then horizontally for a projectile.
- Air resistance changes the acceleration in both perpendicular components, which means that the *suvat* equations cannot be used.

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 m s^{-1} . Car P sets off to catch car S just as car S passes car P. Car P accelerates at 4.5 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)
 - (c) Calculate the speed of car P after it has completed its acceleration. (1)
 - (d) State an expression, in terms of t , for the distance traveled by car P during the time that it is traveling at constant speed. (1)
 - (e) Using your answers to (a) to (d), determine the total time t taken by car P to draw level with car S. (2)
- (Total 6 marks)*
2. A ball is kicked with a speed of 14 m s^{-1} at 60° to the horizontal and lands on the roof of a 4 m high building.



- (a) (i) State the final vertical displacement of the ball. (1)
- (ii) Calculate the time of flight. (3)
- (iii) Calculate the horizontal displacement between the start point and the landing point on the roof. (2)
- (b) The ball is kicked vertically upward. Explain the difference between the time to reach the highest point and the time from the highest point back to the ground. (3)

(Total 9 marks)

3. Two boys kick a football up and down a hill that is at an angle of 30° to the horizontal. One boy stands at the top of the hill and one boy stands at the bottom of the hill.

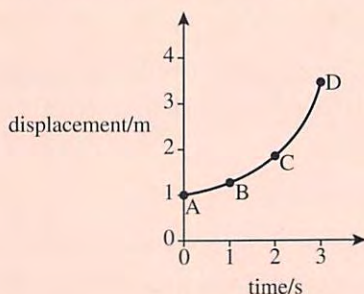


(a) Assuming that each boy kicks the ball perfectly to the other boy (without spin or bouncing), sketch a single path that the ball could take in either direction. (2)

(b) Compare the velocities with which each boy must strike the ball to achieve this path. (2)

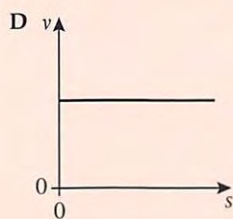
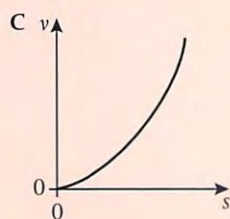
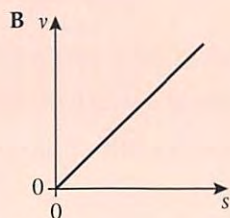
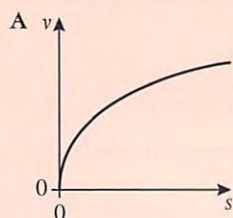
(Total 4 marks)

4. The graph shows how the displacement of an object varies with time. At which point (A, B, C or D) does the instantaneous speed of the object equal its average speed over the interval from 0 to 3 s?



(Total 1 mark)

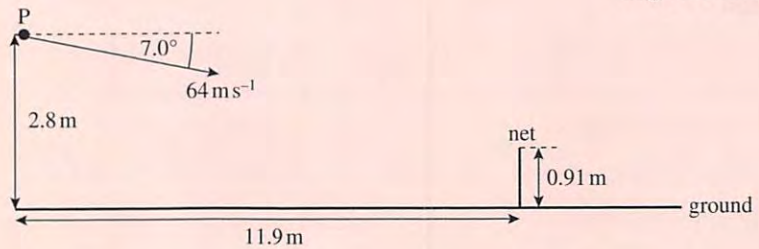
5. A runner starts from rest and accelerates at a constant rate. Which graph (A, B, C or D) shows the variation of the speed v of the runner with the distance traveled s ?



(Total 1 mark)

6. A student hits a tennis ball at point P, which is 2.8 m above the ground. The tennis ball travels at an initial speed of 64 m s^{-1} at an angle of 7.0° to the horizontal. The student is 11.9 m from the net and the net has a height of 0.91 m.

diagram not to scale



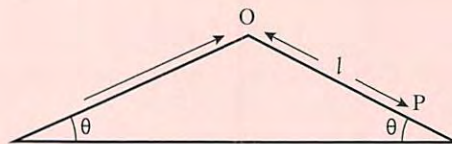
- (a) Calculate the time it takes the tennis ball to reach the net. (2)
 (b) Show that the tennis ball passes over the net. (3)
 (c) Determine the speed of the tennis ball as it hits the ground. (2)

(Total 7 marks)

7. Estimate from what height, under free-fall conditions, a heavy stone would need to be dropped if it were to reach the surface of the Earth at the speed of sound (330 m s^{-1}).

(Total 2 marks)

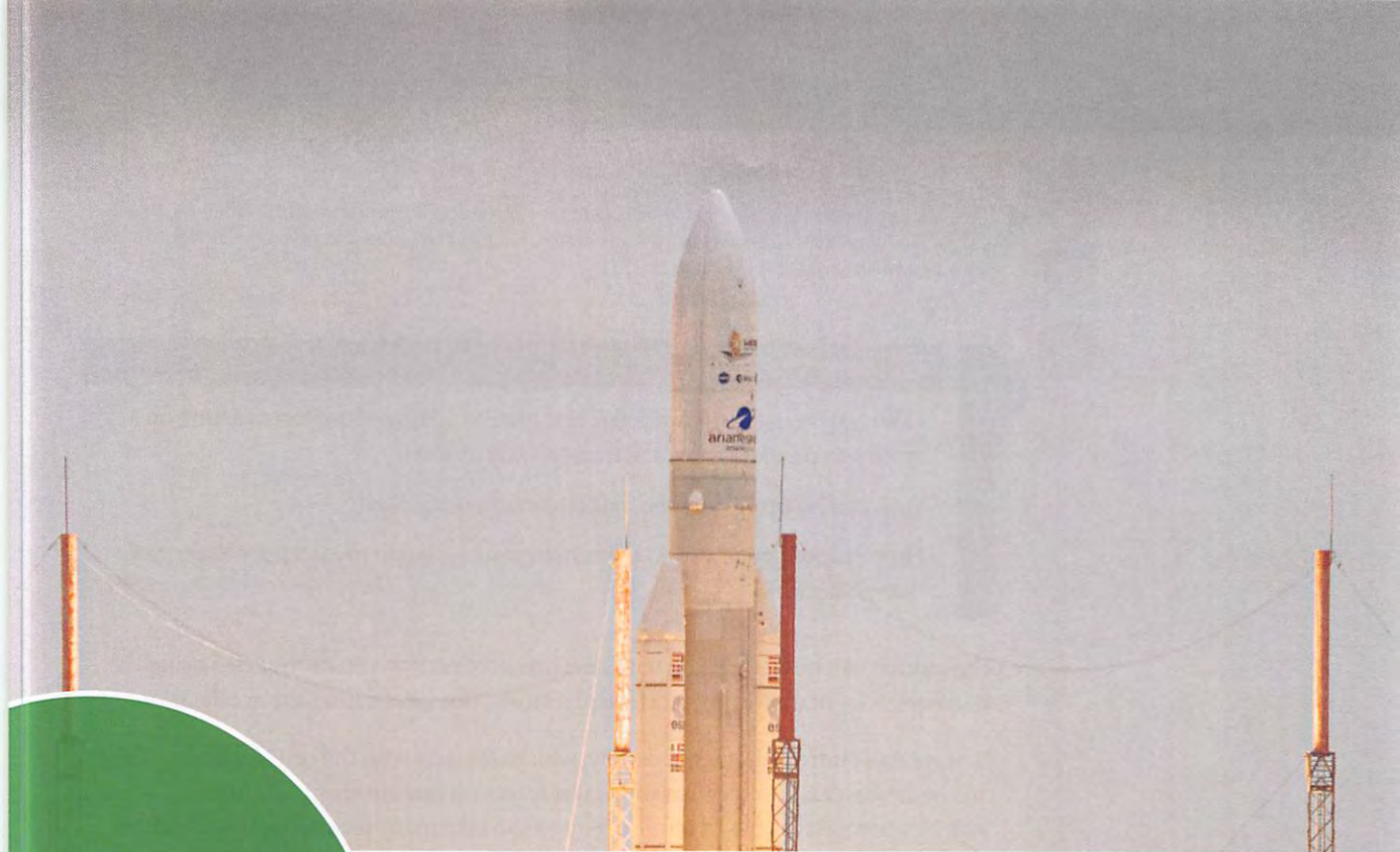
8. A motorbike is ridden up the left side of a symmetrical ramp. The bike reaches the top of the ramp at speed u , becomes airborne and falls to a point P on the other side of the ramp.



In terms of u , l and g , obtain expressions for:

- (a) the time t for which the motorbike is in the air (2)
 (b) the distance OP ($= l$) along the right side of the ramp. (3)

(Total 5 marks)



A.2

Forces and momentum





◀ The launch of the James Webb Space Telescope took place on 25 December 2021. When an object ejects a gas in a downward direction, the gas exerts an equal and upward force on the object. This is an example of a Newton's third law pair.



Guiding Questions

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

How can Newton's laws be modeled mathematically?

How can the conservation of momentum be used to predict the behavior of interacting objects?

The motion of a body traveling with constant acceleration can be modeled using the *suvat* equations of uniformly accelerated motion. But what causes the acceleration?

First we must introduce a second body, which interacts with the original body. When two bodies interact, we say that they exert forces on one another in accordance with Newton's three laws of motion. Forces can take many forms, but the presence of a force is required for one body to change the speed or course of another (an acceleration).

The effect of the force depends upon its direction, so we use an arrow to represent the size and direction of a given force. By adding all the arrows together as vectors, we can calculate the overall size and direction of the resultant force. Using this direction of force and, therefore, acceleration in combination with the *suvat* equations, we can predict the new position and velocity of the original body.

Momentum is the product of mass and velocity, two quantities that we met in the previous chapter. What makes it worth defining in its own right? Momentum is always conserved in any collision provided there are no external forces. This conservation is a direct consequence of Newton's three laws and can be used as a quick way to apply them.



Nature of Science

Newton's three laws of motion are a set of statements, based on observation and experiment, that can be used to predict the motion of a point object from the forces acting on it.

Students should understand:

Newton's three laws of motion
forces as interactions between bodies
forces acting on a body can be represented in a free-body diagram
free-body diagrams can be analyzed to find the resultant force on a system

the nature and use of the following contact forces:

- normal force F_N is the component of the contact force acting perpendicular to the surface that counteracts the body
- surface frictional force F_f acting in a direction parallel to the plane of contact between a body and a surface, on a stationary body as given by $F_f \leq \mu_s F_N$ or a body in motion as given by
 $F_f = \mu_d F_N$ where μ_s and μ_d are the coefficients of static and dynamic friction respectively
- elastic restoring force F_H following Hooke's law as given by $F_H = -kx$ where k is the spring constant
- viscous drag force F_d acting on a small sphere opposing its motion through a fluid as given by $F_d = 6\pi\eta r v$ where η is the fluid viscosity, r is the radius of the sphere, and v is the velocity of the sphere through the fluid
- buoyancy F_b acting on a body due to the displacement of the fluid as given by $F_b = \rho V g$ where V is the volume of fluid displaced

the nature and use of the following field forces:

- gravitational force F_g as the weight of the body and calculated as given by $F_g = mg$
- electric force F_e
- magnetic force F_m

linear momentum as given by $p = mv$ remains constant unless the system is acted upon by a resultant external force

a resultant external force applied to a system constitutes an impulse J as given by $J = F\Delta t$ where F is the average resultant force and Δt is the time of contact

the applied external impulse equals the change in momentum of the system

Newton's second law in the form $F = ma$ assumes mass is constant whereas $F = \frac{\Delta p}{\Delta t}$ allows for situations where mass is changing

the elastic and inelastic collisions of two bodies

explosions

energy considerations in elastic collisions, inelastic collisions, and explosions

bodies moving along a circular trajectory at a constant speed experience an acceleration that is directed radially toward the center of the circle – known as a centripetal acceleration as given

$$by a = \frac{v^2}{r} = \omega^2 r = \frac{4\pi^2 r}{T^2}$$

circular motion is caused by a centripetal force acting perpendicular to the velocity

a centripetal force causes the body to change direction even if its magnitude of velocity may remain constant

the motion along a circular trajectory can be described in terms of the angular velocity ω which is related to the linear speed v by the equation as given by $v = \frac{2\pi r}{T} = \omega r$.

Hooke's law and the elastic restoring force is discussed in A.3. The definitions of elastic and inelastic collisions can also be found in A.3. Information about electric and magnetic forces can be found in D.2.

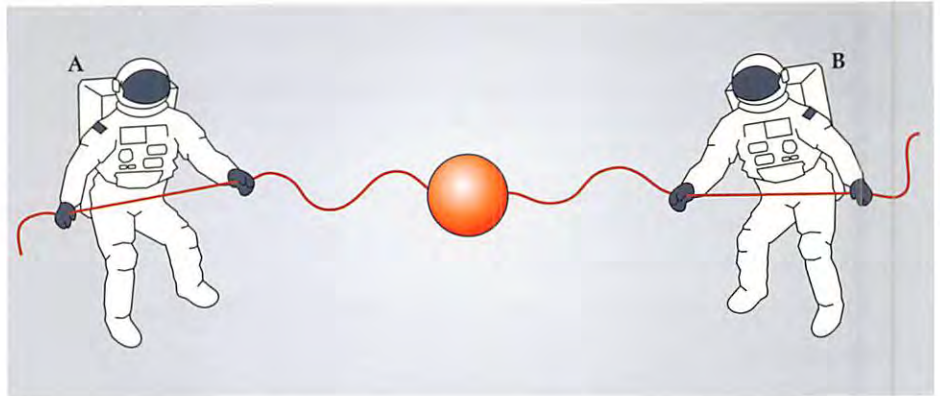
A force is a push or a pull. The unit of force is the newton.



A.2 Figure 1 Two astronauts and a red ball.

Force

We can now model the motion of a constantly accelerating body but what makes it accelerate? From experience, we know that to make something move we must push or pull it. We call this **applying a force**. One simple way of applying a force to a body is to attach a string and pull it. Imagine a sphere floating in space with two strings attached. The sphere will not start to move unless one of the astronauts pulls the string as in Figure 1.



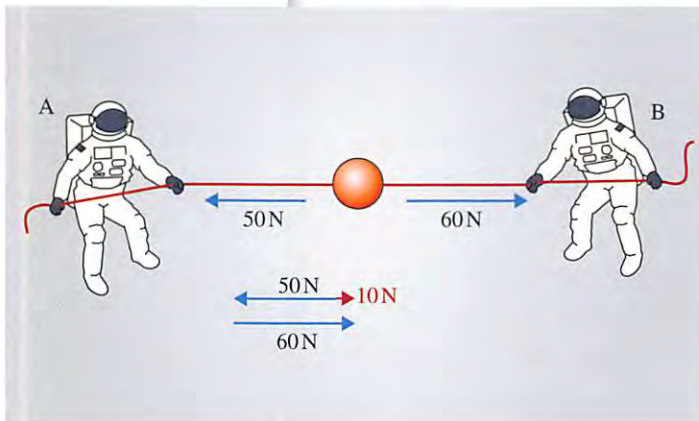
If you hold an object of mass 100 g in your hand, then you will be exerting an upward force of about one newton (1 N).



If A pulls the string, then the body will move to the left, and if B pulls the string, it will move to the right. We can see that force is a **vector** quantity since it has **direction**.

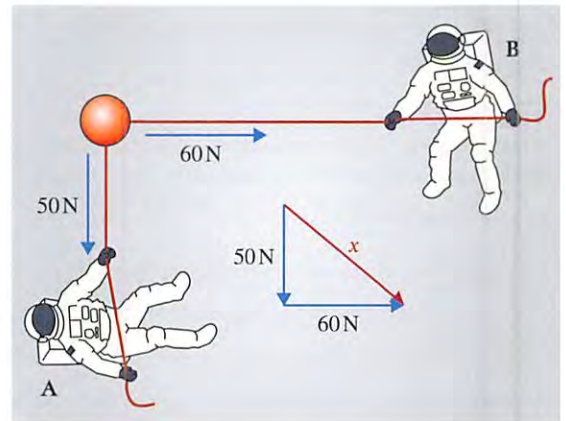
Addition of forces

Since force is a vector, we must add forces vectorially, so if A applies a force of 50 N and B applies a force of 60 N, the resultant force will be 10 N toward B, as can be seen in Figure 2.



A.2 Figure 2 Astronaut B pulls harder than A.

Astronauts in space are considered here so that no other forces (except for very low gravity) are present. This makes things simpler.



A.2 Figure 3 Astronauts pulling at right angles.

Or, in two dimensions, we can use trigonometry as in Figure 3.

In this case, because the addition of forces forms a right-angled triangle, we can use Pythagoras to find x :

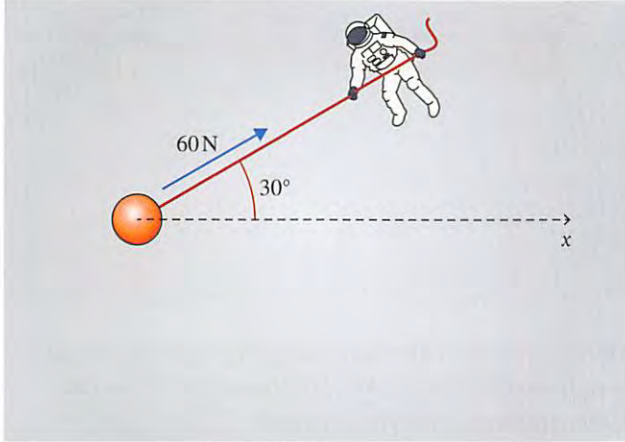
$$x = \sqrt{50^2 + 60^2} = 78 \text{ N}$$

Taking components

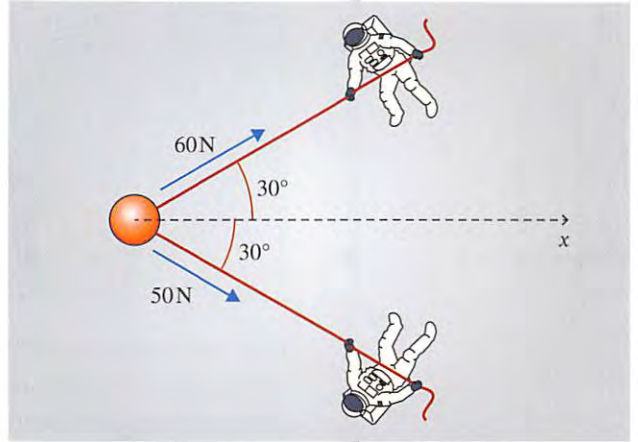
As with other vector quantities, we can calculate components of forces. For example, we might want to know the resultant force in a particular direction.

In Figure 4, the component of the force in the x -direction is: $F_x = 60 \times \cos 30^\circ = 52 \text{ N}$

This is particularly useful when we have several forces.



A.2 Figure 4 Pulling at an angle.

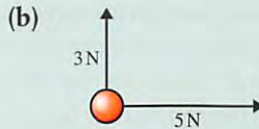
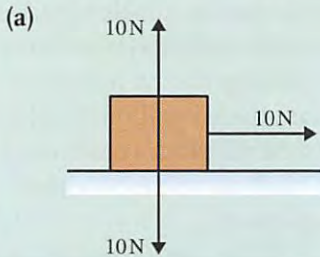


A.2 Figure 5 Astronauts not pulling in line.

In the example shown in Figure 5, we can use components to calculate the resultant force in the x -direction: $60 \times \cos 30^\circ + 50 \times \cos 30^\circ = 52 + 43 = 95 \text{ N}$

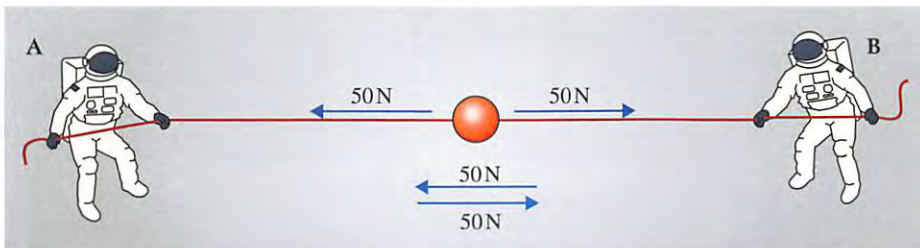
Exercise

Q1. Find the resultant force in the following examples:



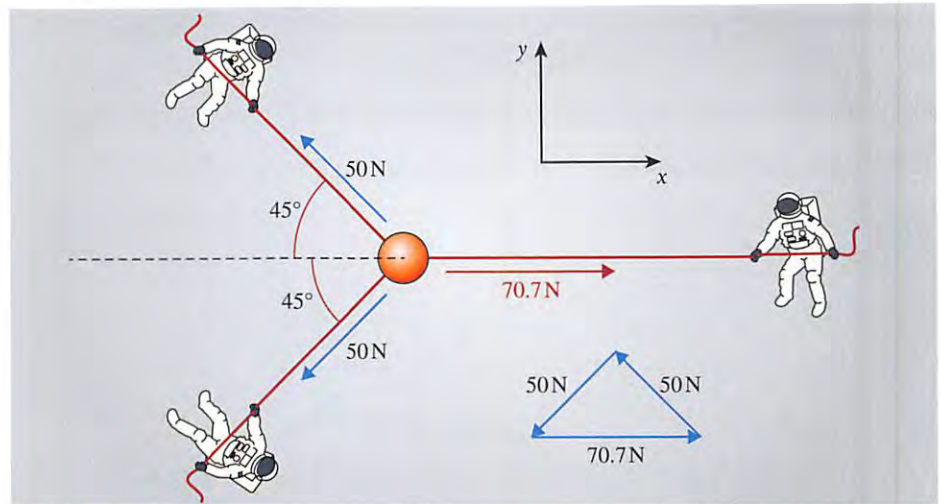
Equilibrium

If the resultant force on a body is zero, as in Figure 6, then we say the forces are **balanced** or the body is in **equilibrium**.



A.2 Figure 6 Balanced forces.

Or with three forces as in Figure 7.



A.2 Figure 7 Three balanced forces.

In this example, the two blue forces are perpendicular, making the trigonometry easy. Adding all three forces gives a right-angled triangle. We can also see that if we take components in any direction, then the forces must be balanced.

Taking components in the x-direction:

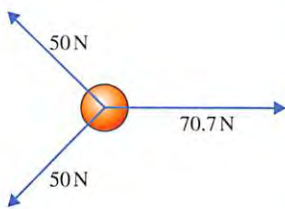
$$-50 \times \cos 45^\circ - 50 \times \cos 45^\circ + 70.7 = -35.35 - 35.35 + 70.7 = 0$$

Taking components in the y-direction:

$$50 \times \sin 45^\circ - 50 \times \sin 45^\circ = 0$$

Free-body diagrams

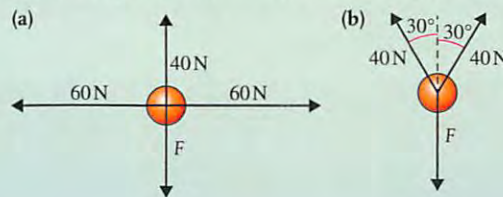
Problems often involve more than one body. For example, the previous problem involved four bodies, three astronauts, and one red ball. All of these bodies will experience forces, but if we draw them all on the diagram, it would be very confusing. For that reason, we only draw forces on the body we are interested in; in this case, the red ball. This is called a free-body diagram, as shown in Figure 8. Note that we treat the red ball as a point object by drawing the forces acting on the center. Not all forces actually act on the center, but when adding forces, it can be convenient to draw them as if they do.



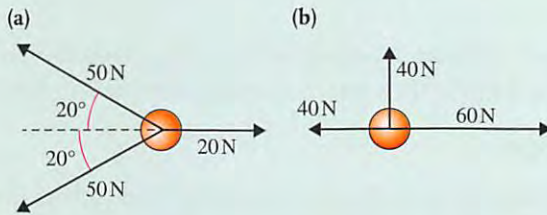
A.2 Figure 8 A free-body diagram of the forces in Figure 7.

Exercise

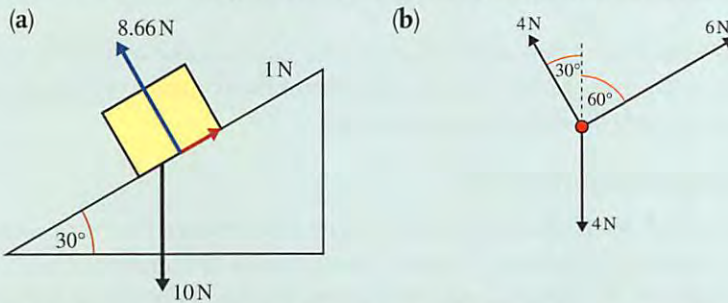
Q2. In the following examples, calculate the force F required to balance the forces.



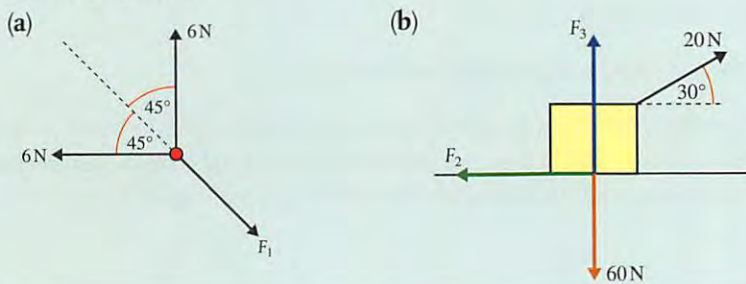
Q3. Calculate the resultant force for the following.



Q4. By resolving the vectors into components, calculate if the following bodies are in translational equilibrium or not. If not, calculate the resultant force.



Q5. If the following two examples are in equilibrium, calculate the unknown forces F_1 , F_2 and F_3 .



Newton's first law of motion

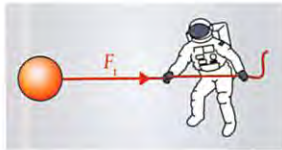
From observation, we can conclude that to make a body move we need to apply an unbalanced force to it. What is not so obvious is that once moving it will continue to move with a constant velocity unless acted upon by another unbalanced force. Newton's first law of motion is a formal statement of this:

A body will remain at rest or moving with constant velocity unless acted upon by an unbalanced force.

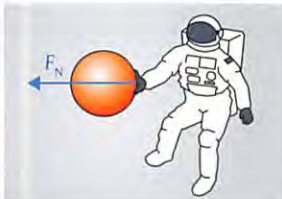
The reason that this is not obvious to us on Earth is that we do not tend to observe bodies traveling with constant velocity with no forces acting on them; in space, it would be more obvious. Newton's first law can be used in two ways. If the forces on a body are balanced, then we can use Newton's first law to predict that it will be at rest or moving with constant velocity. If the forces are unbalanced, then the body will not be at rest or moving with constant velocity. This means its velocity changes – in other words, it accelerates. Using the law the other way round, if a body accelerates, then Newton's first law predicts that the forces acting on the body are unbalanced. To apply this law in real situations, we need to know a bit more about the different types of force.

TOK

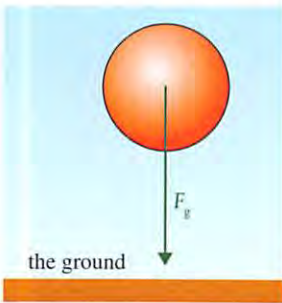
A law in physics is a very useful tool. If applied properly, it enables us to make a very strong argument that what we say is true. If asked 'will a box move?' you can say that you think it will and someone else could say it will not. You both have your opinions and you would then argue as to who is right. However, if you say that Newton's law says it will move, then you have a much stronger argument (assuming you have applied the law correctly).



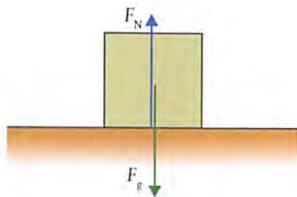
A.2 Figure 9 Exerting tension with a string.



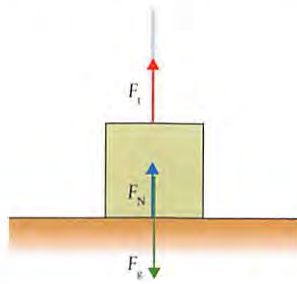
A.2 Figure 10 A normal reaction force is exerted when a hand is in contact with a ball.



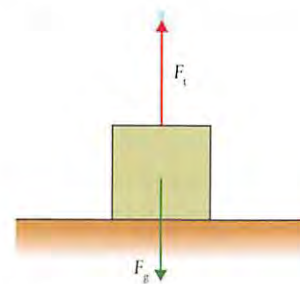
A.2 Figure 11 A ball in free fall.



A.2 Figure 12 A free-body diagram of a box resting on the ground.



A.2 Figure 13 A string applies an upward force on the box.



A.2 Figure 14 The block is lifted as the tension is bigger than its weight.

Types of force

Tension

Tension is the name of the force exerted by the astronauts on the red ball. If you attach a string to a body and pull it, then you are exerting tension, as in Figure 9.

Normal reaction

Whenever two surfaces are in contact with (touching) each other, there will be a force between them. This force is perpendicular to the surface so it is called the **normal reaction force**. If the astronaut pushes the ball with his hand as in Figure 10, then there will be a normal reaction between the hand and the ball.

Note that the force acts on both surfaces so the astronaut will also experience a normal force. However, since we are interested in the ball, not the astronaut, we take the ball as our 'free body' so only draw the forces acting on it.

Gravitational force (weight)

Back on Earth, if a body is released above the ground as in Figure 11, it accelerates downward. According to Newton's first law, there must be an unbalanced force causing this motion. This force is called the **weight**. The weight of a body is directly proportional to its mass: $F_g = mg$ where gravitational field strength, $g = 9.81 \text{ N kg}^{-1}$ close to the surface of the Earth. Note that this is the same as the acceleration of free fall. You will find out why later on.

Note that the weight acts at the **center** of the body.

If a block is at rest on the floor, then Newton's first law implies that the forces are balanced. The forces involved are weight (because the block has mass and is on the Earth) and normal force (because the block is in contact with the ground). Figure 12 shows the forces.

These forces are balanced so: $-F_g + F_N = 0$ or $F_g = F_N$

If the mass of the block is increased, then the normal reaction will also increase.

If a string is added to the block, then we can exert tension on the block as in Figure 13.

The forces are still balanced since $F_t + F_N = F_g$. Notice how F_g has remained the same but F_N has got smaller. If we pull with more force, we can lift the block as in Figure 14. At this point, the normal reaction F_N will be zero. The block is no longer in contact with the ground; now $F_t = F_g$.

The block in Figure 15 is on an inclined plane (slope) so the weight still acts downward. In this case, it might be convenient to split the weight into components, one acting parallel to the slope and one acting perpendicular to the slope.

The component of weight perpendicular to the slope is $F_g \cos \theta$. Since there is no movement in this direction, the force is balanced by F_N . The component of weight parallel to the slope is $F_g \sin \theta$. This force is unbalanced, causing the block to accelerate parallel to the slope. If the angle of the slope is increased, then $\sin \theta$ will also increase, resulting in a greater force down the slope.

Electric and magnetic forces

Electric forces act on charged particles. Magnetic forces act on moving charged particles and magnetic materials.

Like weight (i.e. gravitational forces), electric and magnetic forces act at a distance. Unlike weight, they can be attractive and repulsive.

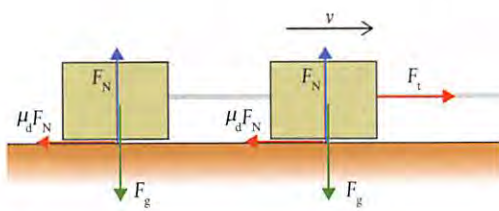
Friction

There are two types of friction: **static friction**, which is the force that stops the relative motion between two touching surfaces, and **dynamic friction**, which opposes the relative motion between two touching surfaces. In both cases, the force is related to both the normal force and the nature of the surfaces, so pushing two surfaces together increases the friction between them.

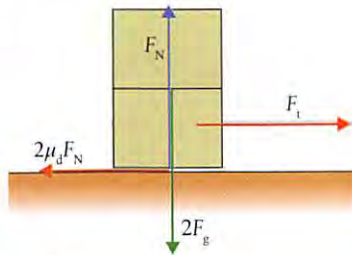
$F_f = \mu F_N$ where μ is the coefficient of friction (static or dynamic).

Dynamic friction

In Figure 16, a block is being pulled along a table at a constant velocity.



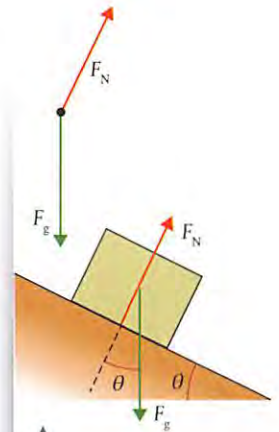
A.2 Figure 17 Two blocks joined with a rope.



A.2 Figure 18 Two blocks on top of each other.

Since the velocity is constant, Newton's first law implies that the forces are balanced so $F_t = F_f$ and $F_g = F_N$. Notice that friction does not depend on the area of contact. We can show this by considering two identical blocks sliding at constant velocity across a table top joined together by a rope as in Figure 17. The friction under each cube is $\mu_d F_N$ so the total friction would be $2\mu_d F_N$.

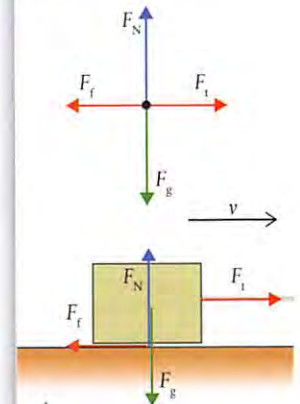
If one cube is now placed on top of the other as in Figure 18, the normal force under the bottom cube will be twice as much so the friction is now $2\mu_d F_N$. It does not matter if the blocks are side by side (large area of contact) or on top of each other (small area of contact); the friction is the same.



A.2 Figure 15 Free-body diagram for a block on a slope.



What assumptions (NOS) about the forces between molecules of gas allow for ideal gas behavior? (B.3)



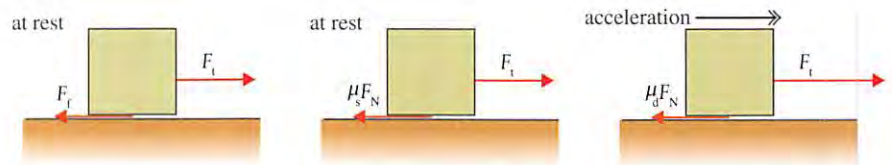
A.2 Figure 16 The force experienced by a block pulled along a table.

If this is the case, then why do racing cars have wide tires with no tread pattern (slicks)? There are several reasons for this, but one is to increase the friction between the tires and the road. This is strange because friction is not supposed to depend on area of contact. In practice, friction is not so simple. When one of the surfaces is sticky like the tires of a racing car, the force *does* depend upon the surface area. The type of surfaces we are concerned with here are quite smooth, non-sticky surfaces like wood and metal.

Static friction

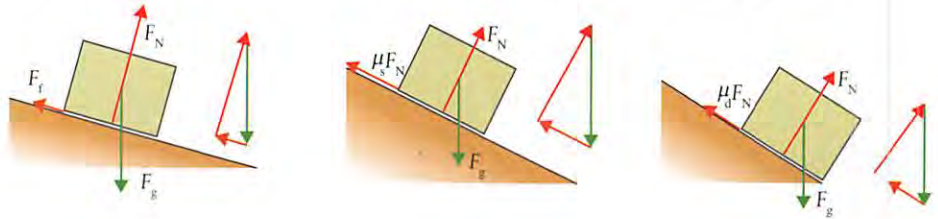
If a very small force is applied to a block at rest on the ground, it will not move. This means that the forces on the block are **balanced** (Newton's first law): the applied force is balanced by the static friction.

A.2 Figure 19 μF_N is the maximum size of friction.



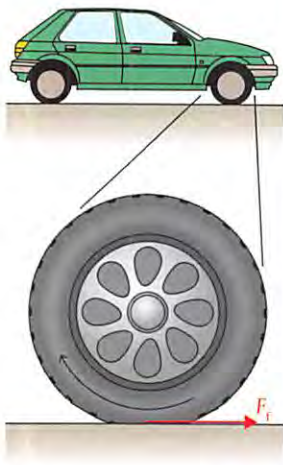
In this case, the friction simply equals the applied force: $F_f = F_t$. As the applied force is increased, the friction will also increase. However, there will be a point when the friction cannot be any bigger. If the applied force is increased past that point, the block will start to move; the forces have become **unbalanced** as illustrated in Figure 19. The maximum value that friction can have is $\mu_s F_N$ where μ_s is the coefficient of static friction. The value of static friction is always *greater* than dynamic friction. This can easily be demonstrated with a block on an inclined plane as shown in Figure 20.

A.2 Figure 20 A block rests on a slope until the forces become unbalanced.



In the first example, the friction is balancing the component of weight down the plane, which equals $F_g \sin \theta$, where θ is the angle of the slope. As the angle of the slope is increased, the point is reached where the static friction $= \mu_s F_N$. The forces are still balanced but the friction cannot get any bigger, so if the angle is increased further, the forces become unbalanced and the block will start to move. Once the block moves, the friction becomes dynamic friction. Dynamic friction is less than static friction, so this results in a bigger resultant force down the slope, causing the block to accelerate.

Friction does not just slow things down; it is also the force that makes things move. Consider the tire of a car as it starts to drive away from the traffic lights. The rubber of the tire is trying to move relative to the road. In fact, if there was no friction, the wheel would spin as the tire slipped backward on the road. The force of friction that opposes the motion of the tire slipping backward on the road is therefore in the **forward** direction.

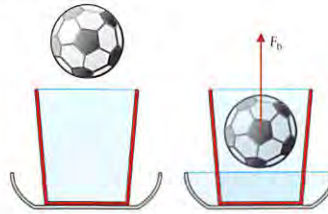


A.2 Figure 21 Friction pushes the car forwards.

If the static friction between the tire and the road is not big enough, the tire will slip. Once this happens, the friction becomes dynamic friction, which is less than static friction, so once tires start to slip, they tend to continue slipping.

Buoyancy

Buoyancy is the name of the force experienced by a body totally or partially immersed in a fluid (a fluid is a liquid or gas). The size of this force is equal to the weight of fluid displaced. It is this force that enables a boat to float and a helium balloon to rise in the air. Let us consider a football and a bucket full of water.



▲ **A.2 Figure 22** A football immersed in a bucket of water

If you take the football and push it under the water, then water will flow out of the bucket (luckily a big bowl was placed there to catch it). The weight of this displaced water is equal to the upward force on the ball. To keep the ball under water, you would therefore have to balance that force by pushing the ball down.

The forces on a floating object are balanced so the weight must equal the buoyant force. This means that the ball must have displaced its own weight of water as in Figure 23.

$$F_g = \rho V g$$

where V is the volume of fluid displaced and ρ is the density of the fluid.

Air resistance

Air resistance is the force that opposes the motion of a body through the air. More broadly, this is known as fluid resistance or **drag**. The size of this force depends on the speed, size, and shape of the body. At low speeds, the drag force experienced by a sphere is given by Stokes' law:

$$F_d = 6\pi\eta vr$$

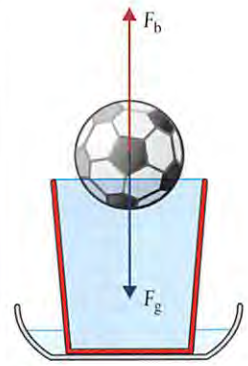
where η = viscosity (a constant)

v = velocity

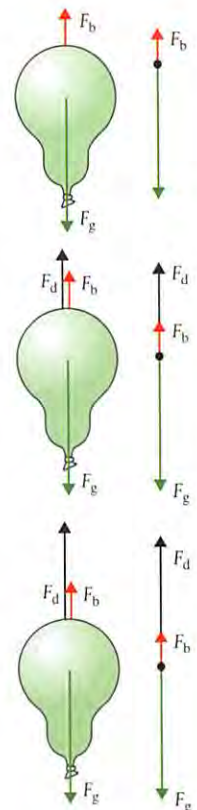
r = radius

When a balloon is dropped, it accelerates downward due to the force of gravity. As it falls through the air, it experiences a drag force opposing its motion. As the balloon's velocity gets bigger so does the drag force, until the drag force balances its weight, at which point its velocity will remain constant (Figure 24). This maximum velocity is called its **terminal velocity**.

The same thing happens when a parachutist jumps out of a plane. The terminal velocity in this case is around 54 m s^{-1} (195 km h^{-1}). Opening the parachute increases the drag force, which slows the parachutist down to a safer 10 m s^{-1} for landing.



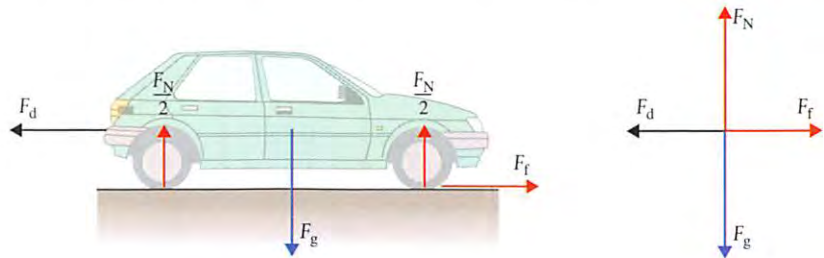
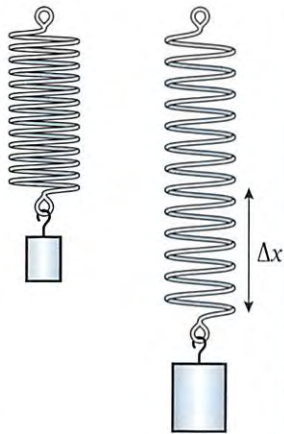
▲ **A.2 Figure 23** A football floats in a bucket of water.



▲ **A.2 Figure 24** A balloon reaches terminal velocity as the forces become balanced. Notice the buoyant force is also present.

As it is mainly the air resistance that limits the top speed of a car, a lot of time and money is spent by car designers to try to reduce this force. This is particularly important at high speeds when the drag force is related to the square of the speed.

A.2 Figure 25 The forces acting on a car traveling at constant velocity.



Elastic restoring force

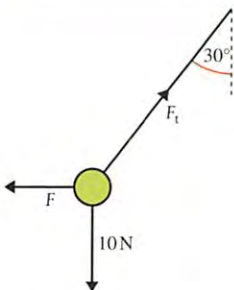
An elastic restoring force, F_{Hr} , acts when the shape of an object is changed. An object is stretched when in tension and squashed when in compression. The size of the elastic restoring force increases with the extension (or compression) from the original length.



A.2 Figure 26 Stretching a spring.

Speed skiers wear special clothes and squat down like this to reduce air resistance.

How does the application of a restoring force acting on a particle result in simple harmonic motion? (C.1)

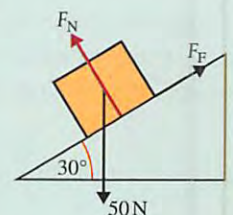


A.2 Figure 27 A ball on a string that is pulled to the side.

Exercise

- Q6.** A ball of weight 10 N is suspended on a string and pulled to one side by another horizontal string as shown in Figure 27. If the forces are balanced:
 - (a) write an equation for the horizontal components of the forces acting on the ball
 - (b) write an equation for the vertical components of the forces acting on the ball
 - (c) use the second equation to calculate the tension in the upper string, F_t
 - (d) use your answer to (c) plus the first equation to find the horizontal force F .

- Q7.** The condition for the forces to be balanced is that the sum of components of the forces in any two perpendicular components is zero. In the 'box on a ramp' example, the vertical and horizontal components were taken. However, it is sometimes more convenient to consider components parallel and perpendicular to the ramp.



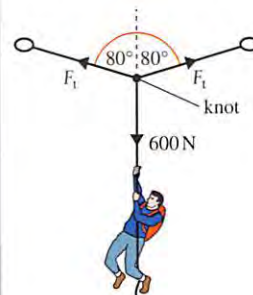
Consider the situation in the figure. If the forces on this box are balanced:

- write an equation for the components of the forces parallel to the ramp
- write an equation for the forces perpendicular to the ramp
- use your answers to find the friction (F_f) and normal force (F_N).

Q8. A rock climber is hanging from a rope attached to the cliff by two bolts as shown in Figure 28. If the forces are balanced:

- write an equation for the vertical component of the forces on the knot
- write an equation for the horizontal forces exerted on the knot
- calculate the tension F_t in the ropes joined to the bolts.

The result of this calculation shows why ropes should not be connected in this way.



A.2 Figure 28 The rope is attached at two bolts.

The relationship between force and acceleration

Newton's first law states that a body will accelerate if an unbalanced force is applied to it. Newton's second law tells us how big the acceleration will be and in which direction. Before we look in detail at Newton's second law, we should look at the factors that affect the acceleration of a body when an unbalanced force is applied. Let us consider the example of catching a ball. When we catch the ball, we change its velocity, Newton's first law tells us that we must therefore apply an unbalanced force to the ball. The size of that force depends upon two things: the mass and the velocity. A heavy ball is more difficult to stop than a light one traveling at the same speed, and a fast one is harder to stop than a slow one. Rather than having to concern ourselves with two quantities, we will introduce a new quantity that incorporates both mass and velocity: **momentum**.



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.

Momentum (p)

Momentum is defined as the product of mass and velocity: $p = mv$

The unit of momentum is kg m s^{-1} . Momentum is a vector quantity.

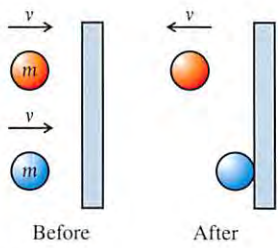
Impulse

When you get hit by a ball, the effect it has on you is greater if the ball bounces off you than if you catch it. This is because the change of momentum, Δp , is greater when the ball bounces, as shown in Figure 29.

The unit of impulse is kg m s^{-1} .

Impulse, J , is the change in momentum and is equal to the product of force and the time over which the force is acting. It is a vector.

$$J = \Delta p = F\Delta t$$



A.2 Figure 29 The change of momentum of the red ball is greater.

Red ball

momentum before = mv

momentum after = $-mv$ (remember momentum is a vector)

change in momentum, $J = -mv - mv = -2mv$

Blue ball

momentum before = mv

momentum after = 0

change in momentum, $J = 0 - mv = -mv$

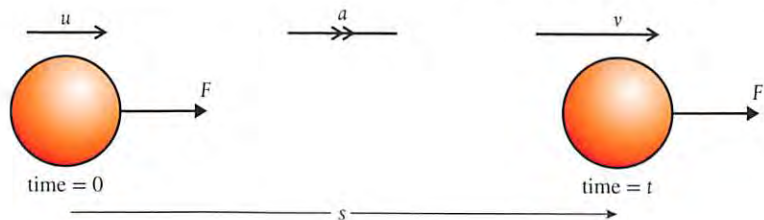
Exercise

- Q9.** A ball of mass 200 g traveling at 10 m s^{-1} bounces off a wall as in Figure 29. If after hitting the wall it travels at 5 m s^{-1} , what is the impulse?
- Q10.** Calculate the impulse on a tennis racket that hits a ball of mass 67 g traveling at 10 m s^{-1} so that it comes off the racket at a velocity of 50 m s^{-1} .

Newton's second law of motion

The rate of change of momentum of a body is directly proportional to the unbalanced force acting on that body and takes place in same direction.

Let us once again consider a ball with a constant force acting on it as in Figure 30.



A.2 Figure 30 A ball gains momentum.

If force = $\frac{\text{change in momentum}}{\text{time}}$
 then change in momentum = force \times time.
 So the unit of momentum is N s.
 This is the same as kg m s^{-1} .



Newton's first law tells us that there must be an unbalanced force acting on the ball since it is accelerating.

Newton's second law tells us that the size of the unbalanced force is directly proportional to the rate of change of momentum. We know that the force is constant so the rate of change of momentum is also constant, which, since the mass is also constant, implies that the acceleration is uniform so the *suvat* equations apply.

If the ball has mass, m we can calculate the change of momentum of the ball.

initial momentum = mu

final momentum = mv

change in momentum = $mv - mu$

The time taken is t so the rate of change of momentum = $\frac{mv - mu}{t}$

This is the same as $\frac{m(v - u)}{t} = ma$

Newton's second law states that the rate of change of momentum is proportional to the force, so $F \propto ma$.

To make things simple, the newton is defined so that the constant of proportionality is equal to 1 so:

$$F = ma$$

So when a force is applied to a body in this way, Newton's second law can be simplified to:

The acceleration of a body is proportional to the force applied and inversely proportional to its mass.

Not all examples are so simple. Consider a jet of water hitting a wall as in Figure 31. The water hits the wall and loses its momentum, ending up in a puddle on the floor.

Newton's first law tells us that since the velocity of the water is changing, there must be a force on the water,

Newton's second law tells us that the size of the force is equal to the rate of change of momentum. The rate of change of momentum in this case is equal to the amount of water hitting the wall per second multiplied by the change in velocity. This is not the same as ma . For this reason, it is best to use the first, more general, statement of Newton's second law, since this can always be applied.

However, in this course, most of the examples will be of the $F = ma$ type.

Example 1: Elevator accelerating upward

An elevator has an upward acceleration of 1 m s^{-2} . If the mass of the elevator is 500 kg , what is the tension in the cables pulling it up?

First draw a free-body diagram as in Figure 32. Now we can see what forces are acting. Newton's first law tells us that the forces must be unbalanced. Newton's second law tells us that the unbalanced force must be in the direction of the acceleration (upward). This means that F_t is bigger than mg .

Newton's second law also tells us that the size of the unbalanced force equals ma so we get the equation:

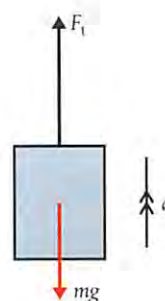
$$F_t - mg = ma$$

Rearranging gives:

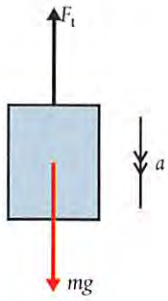
$$\begin{aligned} F_t &= mg + ma \\ &= 500 \times 10 + 500 \times 1 \\ &= 5500 \text{ N} \end{aligned}$$



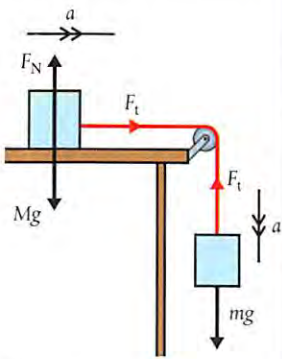
A.2 Figure 31 A jet becomes a puddle.



A.2 Figure 32 An elevator accelerating upward. This could either be going up getting *faster* or going down getting *slower*.



A.2 Figure 33 The elevator with downward acceleration.



A.2 Figure 34 Two masses are joined by a rope.



A.2 Figure 35 The parachutist just after opening the parachute.

Example 2: Elevator accelerating downward

The same elevator as in Example 1 now has a downward acceleration of 1 m s^{-2} as in Figure 33.

This time, Newton's laws tell us that the weight is bigger than the tension so:

$$mg - F_t = ma$$

Rearranging gives:

$$\begin{aligned} F_t &= mg - ma \\ &= 500 \times 10 - 500 \times 1 \\ &= 4500 \text{ N} \end{aligned}$$

Example 3: Joined masses

Two masses are joined by a rope. One of the masses sits on a frictionless table, while the other hangs off the edge as in Figure 34.

M is being dragged to the edge of the table by m .

Both are connected to the same rope so F_t is the same for both masses. This also means that the acceleration a is the same.

We do not need to consider F_N and mg for the mass on the table because these forces are balanced. However, the horizontally unbalanced force is F_t .

Applying Newton's laws to the mass on the table gives:

$$F_t = ma$$

The hanging mass is accelerating down so mg is bigger than F_t . Newton's second law implies that: $mg - F_t = ma$

$$\text{Substituting for } F_t \text{ gives: } mg - ma = ma \text{ so } a = \frac{mg}{M + m}$$

Example 4: The free fall parachutist

After falling freely for some time, a free fall parachutist, whose weight is 60 kg , opens his parachute. Suddenly, the force due to air resistance increases to 1200 N . What happens?

Looking at the free-body diagram in Figure 35, we can see that the forces are unbalanced and that, according to Newton's second law, the acceleration, a , will be upward.

The size of the acceleration is given by:

$$ma = 1200 - 600 = 60 \times a$$

So:

$$a = 10 \text{ m s}^{-2}$$

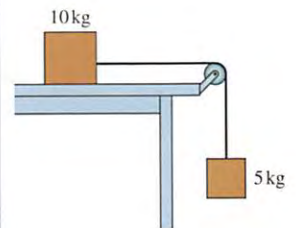
The acceleration is in the opposite direction to the motion. This will cause the parachutist to slow down. As he slows down, the air resistance gets less until the forces are balanced. He will then continue down with a constant velocity.

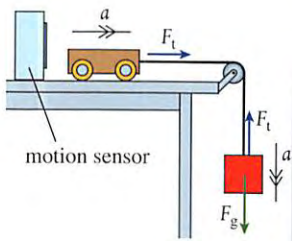


◀ Even before opening their parachutes, base jumpers reach terminal velocity.

Exercise

- Q11.** The helium in a balloon causes an upthrust of 0.1 N . If the mass of the balloon and helium is 6 g , calculate the acceleration of the balloon.
- Q12.** A rope is used to pull a felled tree (mass 50 kg) along the ground. A tension of 1000 N causes the tree to move from rest to a velocity of 0.1 m s^{-1} in 2 s . Calculate the force due to friction acting on the tree.
- Q13.** Two masses are arranged on a frictionless table as shown in the figure on the right. Calculate:
- the acceleration of the masses
 - the tension in the string.
- Q14.** A helicopter is lifting a load of mass 1000 kg with a rope. The rope is strong enough to hold a force of 12 kN . What is the maximum upward acceleration of the helicopter?
- Q15.** A person of mass 65 kg is standing in an elevator that is accelerating upwards at 0.5 m s^{-2} .
What is the normal force between the floor and the person?
- Q16.** A plastic ball is held under the water by a child in a swimming pool. The volume of the ball is 4000 cm^3 .
- If the density of water is 1000 kg m^{-3} , calculate the buoyant force on the ball (buoyant force = weight of fluid displaced).
 - If the mass of the ball is 250 g , calculate the theoretical acceleration of the ball when it is released. Why will the ball not accelerate this quickly in a real situation?





A.2 Figure 36 Apparatus for finding the relationship between force and acceleration.

SKILLS

It is not easy to apply a constant known force to a moving body: just try pulling a cart along the table with a force meter and you will see. One way this is often done in the laboratory is by hanging a mass over the edge of the table as shown in Figure 36.

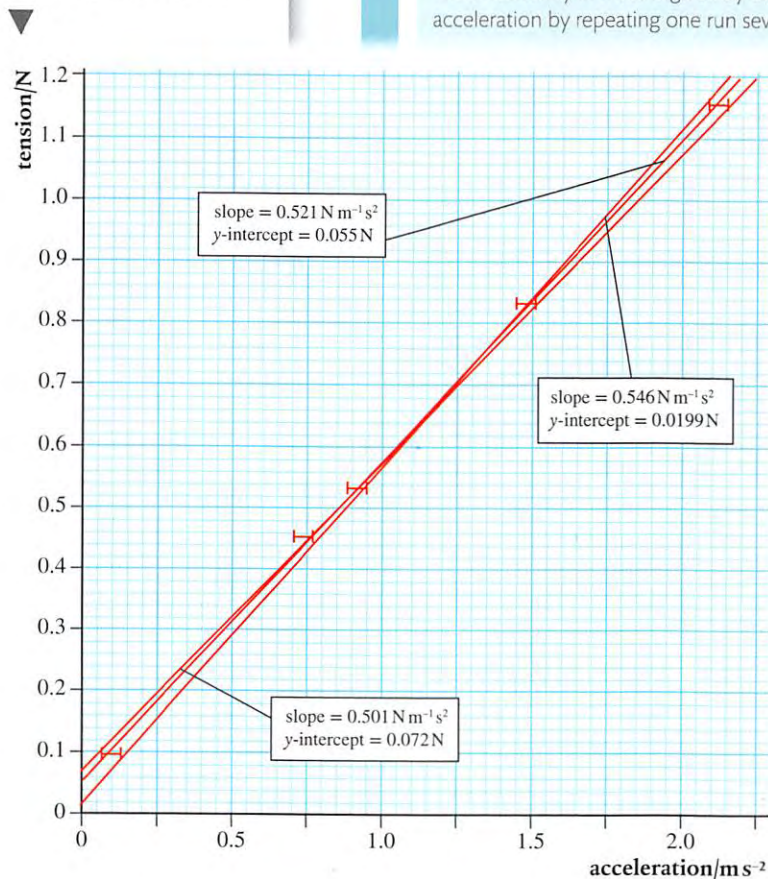
If we ignore any friction in the pulley or in the wheels of the trolley, then the unbalanced force on the trolley = F_t . Since the mass is accelerating down, then the weight is bigger than F_t so $F_g - F_t = ma$ where m is the mass hanging on the string. The tension is therefore given by: $F_t = mg - ma = m(g - a)$

There are several ways to measure the acceleration of the trolley; one is to use a motion sensor. This senses the position of the trolley by reflecting an ultrasonic pulse off it. Knowing the speed of the pulse, the software can calculate the distance between the trolley and sensor. As the trolley moves away from the sensor, the time taken for the pulse to return increases; the software calculates the velocity from these changing times. Using this apparatus, the acceleration of the trolley for different masses was measured, and the results are given in the Table 1.

A.2 Table 1

Mass/kg ± 0.0001	Acceleration/ m s^{-2} ± 0.03	Tension ($F_t = mg - ma$)/N	Max F_t /N	Min F_t /N	ΔF_t /N
0.0100	0.10	0.097	0.098	0.096	0.001
0.0500	0.74	0.454	0.453	0.451	0.001
0.0600	0.92	0.533	0.532	0.531	0.001
0.1000	1.49	0.832	0.830	0.828	0.001
0.1500	2.12	1.154	1.150	1.148	0.001

A.2 Figure 37 Graph of tension against acceleration.



The uncertainty in mass is given by the last decimal place in the scale, and the uncertainty in acceleration by repeating one run several times. To calculate the uncertainty in tension, the maximum and minimum values have been calculated by adding and subtracting the uncertainties.

These results are shown in Figure 37.

Applying Newton's second law to the trolley, the relationship between F_t and a should be $F_t = ma$ where m is the mass of the trolley. This implies that the gradient of the line should be m . From the graph, we can see that the gradient is $0.52 \pm 0.02 \text{ kg}$, which is quite close to the 0.5 kg mass of the trolley.

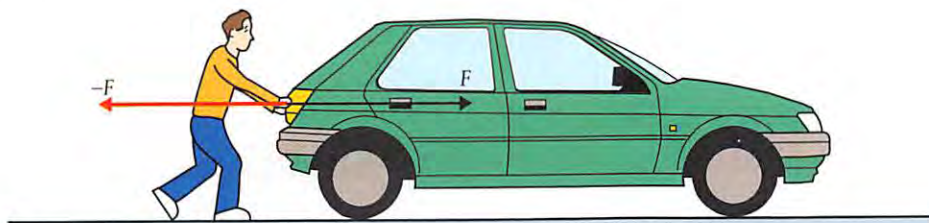
According to theory, the intercept should be $(0, 0)$ but we can see that there is a positive intercept of 0.05 N . It appears that each value is 0.05 N too big. The reason for this could be friction. If there was friction, then the actual unbalanced force acting on the trolley would be tension - friction. If this is the case, then the results would imply that friction is about 0.05 N .

Newton's third law of motion

When dealing with Newton's first and second laws, we are careful to consider only the body that is *experiencing* the forces, not the body that is *exerting* the forces. Newton's third law relates these forces.

If body A exerts a force on body B, then body B will exert an equal and opposite force on body A.

So if someone is pushing a car with a force F as shown in Figure 38, the car will push back on the person with a force $-F$. In this case, both of these forces are normal to the car's surface.



If experimental measurements contain uncertainties, how can laws be developed based on experimental evidence? (NOS)



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.

A.2 Figure 38 The man pushes the car and the car pushes the man.

You might think that, since these forces are equal and opposite, they will be balanced, and, in that case, how does the person get the car moving? This is wrong. The forces act on different bodies so cannot balance each other.

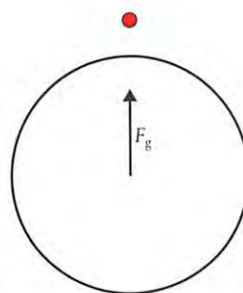
In summary, a Newton's third law pair is made up of two forces of the same type and magnitude acting in opposite directions on different bodies.

Example 1: A falling body

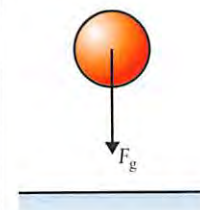
A body falls freely toward the ground as in Figure 39. If we ignore air resistance, there is only one force acting on the body – the force due to the gravitational attraction of the Earth, which we call weight.

Applying Newton's third law

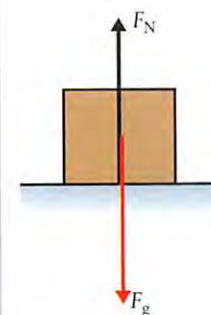
If the Earth pulls the body down, then the body must pull the Earth up with an equal and opposite force. We have seen that the gravitational force always acts on the center of the body, so Newton's third law implies that there must be a force equal to F_g acting upward on the center of the Earth as in Figure 40.



A.2 Figure 40 The Earth pulled up by gravity.



A.2 Figure 39 A falling body pulled down by gravity.



A.2 Figure 41 Forces acting on a box resting on the floor.

Example 2: A box rests on the floor

A box sits on the floor as shown in Figure 41. Let us apply Newton's third law to this situation.

There are two forces acting on the box.

Normal force: The floor is pushing up on the box with a force F_N . According to Newton's third law, the box must therefore push down on the floor with a force of magnitude F_N .

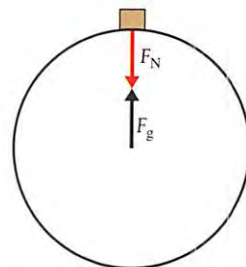
Students often think that Newton's third law implies that the normal force = -weight, but both of these forces act on the box. If the box is at rest, these forces are indeed equal and opposite but this is due to Newton's first law.



Weight: The Earth is pulling the box down with a force F_g . According to Newton's third law, the box must be pulling the Earth up with a force of magnitude F_g as shown in Figure 42.

Example 3: Recoil of a gun

When a gun is fired, the velocity of the bullet changes. Newton's first law implies that there must be an unbalanced force on the bullet. This force must come from the gun. Newton's third law says that if the gun exerts a force on the bullet, the bullet must exert an equal and opposite force on the gun. This is the force that makes the gun recoil or 'kick back'.



A.2 Figure 42 Forces acting on the Earth according to Newton's third law.

Example 4: The water cannon

When water is sprayed at a wall from a hosepipe, it hits the wall and stops. Newton's first law says that if the velocity of the water changes, there must be an unbalanced force on the water. This force comes from the wall. Newton's third law says that if the wall exerts a force on the water, then the water will exert a force on the wall. This is the force that makes a water cannon so effective at dispersing demonstrators.

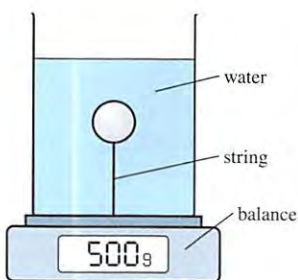
A boat tests its water cannons,



Exercise

Q17. Use Newton's first and third laws to explain the following:

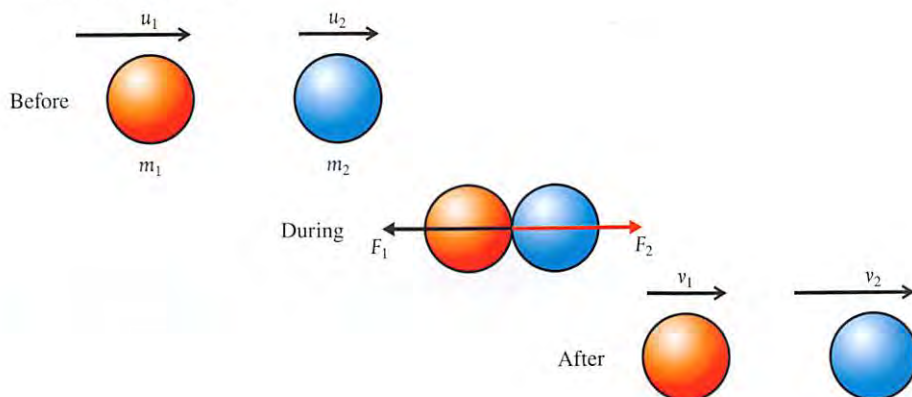
- When burning gas is forced downward out of a rocket motor, the rocket accelerates up.
- When the water cannons on the boat in the photo are operating, the boat accelerates forward.
- When you step forwards off a skateboard, the skateboard accelerates backward.
- A table tennis ball is immersed in a fluid and held down by a string as shown in Figure 43. The container is placed on a balance. What will happen to the reading of the balance if the string breaks?



A.2 Figure 43 A table tennis ball attached to a mass balance.

Collisions

In this section, we have been dealing with the interaction between two bodies (gun–bullet, skater–skateboard, hose–water). To develop our understanding of the interaction between bodies, let us consider a simple collision between two balls as illustrated in Figure 44.



A.2 Figure 44 Collision between two balls.

Let us apply Newton's three laws to this problem.

Newton's first law

In the collision, the red ball slows down and the blue ball speeds up. Newton's first law tells us that this means there is a force acting to the left on the red ball (F_1) and to the right on the blue ball (F_2).

Newton's second law

This law tells us that the force will be equal to the rate of change of momentum of the balls so if the balls are touching each other for a time Δt :

$$F_1 = \frac{m_1 v_1 - m_1 u_1}{\Delta t}$$

$$F_2 = \frac{m_2 v_2 - m_2 u_2}{\Delta t}$$

Newton's third law

According to the third law, if the red ball exerts a force on the blue ball, then the blue ball will exert an equal and opposite force on the red ball.

$$F_1 = -F_2$$

$$\frac{m_1 v_1 - m_1 u_1}{\Delta t} = \frac{-(m_2 v_2 - m_2 u_2)}{\Delta t}$$

Rearranging gives: $m_1 u_1 + m_2 u_2 = m_1 v_1 + m_2 v_2$

In other words, the momentum at the start equals the momentum at the end. We find that this applies not only to this example but to all interactions.



An isolated system is one in which no external forces are acting. When a ball hits a wall, the momentum of the ball is not conserved because the ball and wall is not an isolated system, since the wall is attached to the ground. If the ball and wall were floating in space, then momentum would be conserved.

The law of the conservation of momentum

For a system of isolated bodies, the total momentum is always the same.

This is not a new law since it is really just a combination of Newton's laws. However, it provides a useful short cut when solving problems.

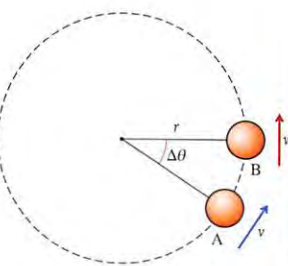
In many examples, we will have to pretend everything is in space isolated from the rest of the Universe, otherwise they are not isolated and the law of conservation of momentum will not apply.

You may have noticed that some collisions enable the bodies to bounce off one another, while there are other collisions where the bodies stick together. This is discussed further in A.3 Work, energy and power.

How are concepts of equilibrium and conservation applied to understand matter and motion from the smallest atom to the whole Universe? (B.3, D.1)

In which way is conservation of momentum relevant to the workings of a nuclear power station? (E.4)

When dealing with circular motion in physics, we always measure the angle in radians.



A.2 Figure 45 Although speed is constant, velocity is changing because direction is changing.

Nature of Science

By applying what we know about motion in a straight line, we can develop a model for motion in a circle. This is a common way that models are developed in physics: start simple and add complexity later.

Circular motion

If a car travels around a bend at 30 km h^{-1} , it is obviously traveling at a constant speed, since the speedometer registers 30 km h^{-1} all the way round. However, it is not traveling at constant velocity. This is because velocity is a vector quantity, and for a vector quantity to be constant, both magnitude and direction must remain the same. Bends in a road can be many different shapes, but, to simplify things, we will only consider circular bends taken at constant speed.

Quantities of circular motion

Consider the body in Figure 45 traveling in a circle radius r , with constant speed v . In time Δt , the body moves from A to B. As it does this, the radius sweeps out an angle $\Delta\theta$.

When describing motion in a circle, we often use quantities referring to the angular motion rather than the linear motion. These quantities are:

Time period (T)

The time period is the time taken to complete one circle.

The unit of the time period is the second.

Angular displacement (θ)

The angular displacement is the angle swept out by a line joining the body to the center.

The unit of angular displacement is the radian.

Angular velocity (ω)

The angular velocity is the angle swept out by per unit time.

The unit of angular displacement is the radian s^{-1} .

$$\omega = \frac{\Delta\theta}{\Delta t}$$

The angle swept out when the body completes a circle is 2π and the time taken is by definition the time period T so this equation can also be written:

$$\omega = \frac{2\pi}{T}$$

Frequency (f)

The frequency is the number of complete revolutions per unit time.

$$f = \frac{1}{T}$$

So:

$$\omega = 2\pi f$$

Angular velocity and speed

In a time T , the body in Figure 46 completes one full circle so it travels a distance $2\pi r$, the circumference of the circle. Speed is defined as the $\frac{\text{distance traveled}}{\text{time taken}}$ so $v = \frac{2\pi r}{T}$. In this time, a line joining the body to the center will sweep out an angle of 2π radians so the angular velocity, $\omega = \frac{2\pi}{T}$. Substituting into the equation for v we get:

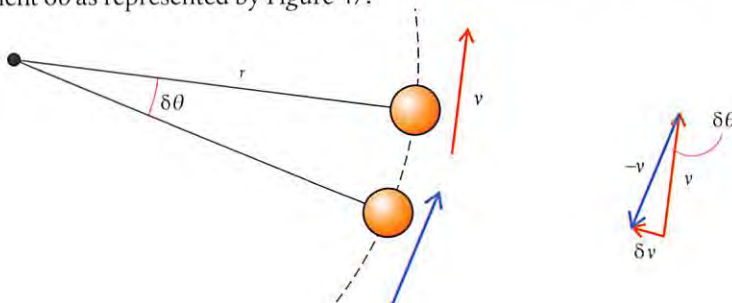
$$v = \omega r$$

Although the speed is constant, when a body moves in a circle, its direction and velocity are always changing. At any moment in time, the magnitude of the instantaneous velocity is equal to the speed and the direction is perpendicular to the radius of the circle.

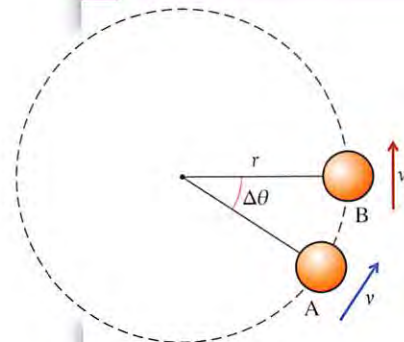
Centripetal acceleration

From the definition of acceleration, we know that if the velocity of a body changes, it must be accelerating, and that the direction of acceleration is in the direction of the change in velocity. Let us consider a body moving in a circle with a constant speed v . Figure 46 shows two positions of the body separated by a short time.

To derive the equation for this acceleration, let us consider a very small angular displacement $\delta\theta$ as represented by Figure 47.

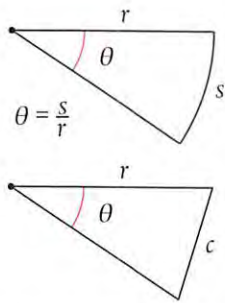


Why is no work done on a body moving along a circular trajectory at constant speed? (A.3)



A.2 Figure 46 A body travels at constant speed along a circular trajectory around a circle of radius r .

A.2 Figure 47 Angular displacement.



if θ is small then $\theta = \frac{c}{r}$

A.2 Figure 48 A small angle approximation.

You will not be asked to reproduce this derivation in the exam.



If this small angular displacement has taken place in a short time δt , then the angular velocity, $\omega = \frac{\delta\theta}{\delta t}$.

From the definition of acceleration: $a = \frac{\text{change of velocity}}{\text{time}}$

If we took only the magnitude of velocity, then the change of velocity would be zero. However, velocity is a vector so change in velocity is found by taking the final velocity vector – initial velocity vector as in the vector addition in Figure 48. This triangle is not a right-angled triangle so cannot be solved using Pythagoras. However, since the angle $\delta\theta$ is small, we can say that the angle $\delta\theta$ in radians is approximately equal to $\frac{\delta v}{v}$.

Rearranging gives:

$$\delta v = v\delta\theta$$

$$\text{acceleration} = \frac{\delta v}{\delta t} = \frac{v\delta\theta}{\delta t}$$

$$a = v\omega$$

But we know that $v = \omega r$ so we can substitute for v and get $a = \omega^2 r$

Or substituting for:

$$\omega = \frac{v}{r}$$

$$a = \frac{v^2}{r}$$

The direction of this acceleration is in the direction of δv . Now, as the angle $\delta\theta$ is small, the angle between δv and v is approximately 90° , which implies that the acceleration is perpendicular to the velocity. This makes it directed *toward* the center of the circle; hence the name **centripetal acceleration**.

Exercise

Q18. A body travels with constant speed of 2 m s^{-1} around a circle of radius 5 m. Calculate:

- the distance moved in one revolution
- the displacement in one revolution
- the time taken for one revolution
- the frequency of the motion
- the angular velocity
- the centripetal acceleration.

Centripetal force

From Newton's first law, we know that if a body accelerates, there must be an unbalanced force acting on it. The second law tells us that this force is in the direction of the acceleration. This implies that there must be a resultant force acting toward the center. This force is called the **centripetal force**.

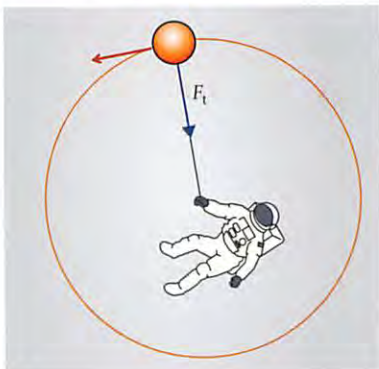
From Newton's second law, we can also deduce that $F = ma$ so $F = \frac{mv^2}{r} = m\omega^2 r$.

$$F = m\omega^2 r$$

Examples of circular motion

All bodies moving in a circle must be acted upon by a force toward the center of the circle. However, this can be provided by many different forces.

Mass on a string in space

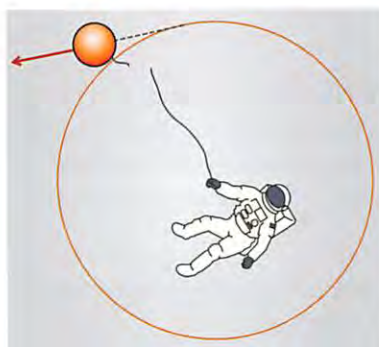


If you take a mass on the end of a string, you can easily make it move in a circle, but the presence of gravity makes the motion difficult to analyze. It will be simpler if we start by considering what this would be like if performed by an astronaut in deep space: much more difficult to do but easier to analyze. Figure 49 shows an astronaut making a mass move in a circle on the end of a string. The only force acting on the mass is the tension in the string.

In this case, it is obvious that the centripetal force is provided by the tension so:

$$F_t = \frac{mv^2}{r}$$

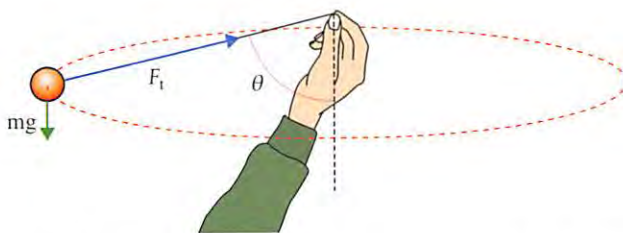
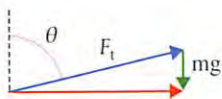
From this, we can predict that the force required to keep the mass in its circular motion will increase if the speed increases. This will be felt by the astronaut who, according to Newton's third law, must be experiencing an equal and opposite force on the other end of the string. If the string were to break, the ball would have no forces acting on it so would travel at a constant velocity in the same direction as it was moving when the break occurred. This would be at some tangent to the circle as in Figure 50.



A.2 Figure 50 The string breaks.

Mass on a string on the Earth (horizontal)

When playing with a mass on a string on the Earth, there will be gravity acting as well as tension. We will first consider how this changes the motion when the mass is made to travel in a horizontal circle as in Figure 51.



For the motion to be horizontal, there will be no vertical acceleration so the weight must be balanced by the vertical component of tension ($F_t \cos \theta = mg$). This means that the string cannot be horizontal but will always be at an angle, as shown in Figure 51. The centripetal force is provided by the horizontal component of tension ($F_t \sin \theta = \frac{mv^2}{r}$), which is equal to the vector sum of the two forces.

How can knowledge of electric and magnetic forces allow the prediction of changes to the motion of charged particles? (D.2)

In this example, the astronaut has a much larger mass than the ball. If this was not the case, the astronaut would be pulled out of position by the equal and opposite force acting on the other end of the string.

People often think that the mass will fly outward if the string breaks. This is because they feel themselves being forced outward so think that if the string breaks, the mass will move in this direction. Applying Newton's laws, we know that this is not the case. This is an example of a case where intuition gives the wrong answer.

A.2 Figure 51 A mass swung in a horizontal circle.

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