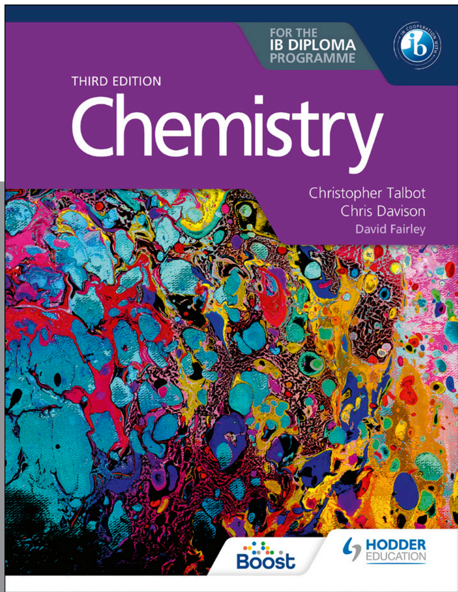
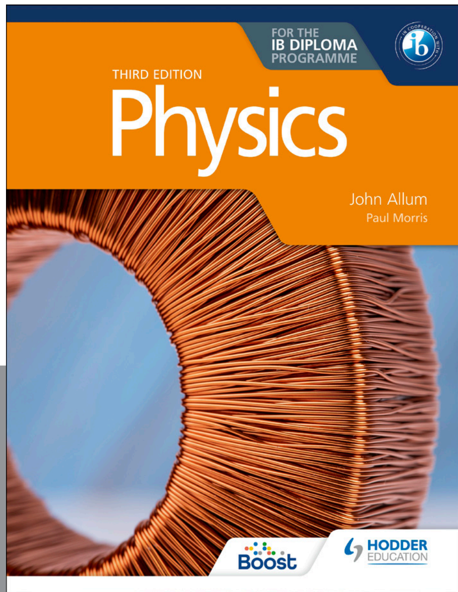
NEW 3RD EDITIONS

FOR THE
IB DIPLOMA
PROGRAMME

Biology, Chemistry and Physics for the IB Diploma

Trust experienced and best-selling authors to navigate the new syllabuses confidently with these co-published coursebooks that encompass inquiry-based, conceptually-focused teaching and learning.





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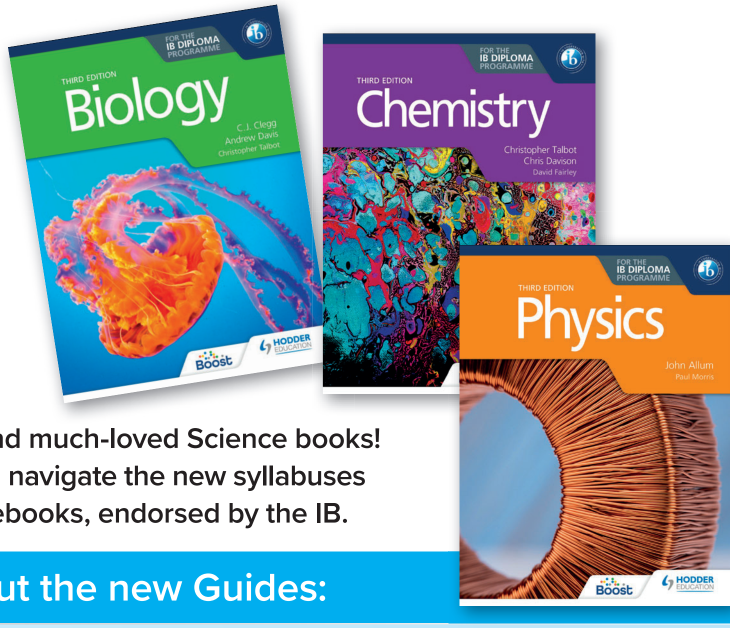

Dear IB Science educator,

We're really excited to be publishing for the new IB Sciences: Biology, Chemistry and Physics Guides for first teaching 2023, and first assessment 2025.

We are now going into third editions of our bestselling and much-loved Science books! Let our trusted, experienced, and expert authors help you navigate the new syllabuses confidently with Hodder Education's co-published coursebooks, endorsed by the IB.

We asked our authors what they like about the new Guides:

Andrew Davis has taught biology for over 20 years. He is the author of several IB textbooks and digital teaching and learning resources for Diploma and MYP, including *Biology for the MYP 4&5: By Concept*.

"This new IB Biology syllabus has many exciting changes, with greater integration of concepts, content, and skills. The reorganization of content into Themes, each based around two linked concepts, enables students to gain a greater appreciation of interconnections within the subject.

The new syllabus offers greater flexibility for how the course is delivered. Each Theme follows the same path through four levels of organization: molecules, cells, organisms and ecosystems, giving the course a logical structure, which enables students to scaffold their understanding. The course can be taught by Theme, or by level of organization, or a combination of both."

Chris Talbot has taught chemistry, biology and TOK at schools in Singapore for over 20 years. He is the author of numerous science textbooks, including *Chemistry for the MYP 4&5: By Concept*.

"I like the division into Structure and Reactivity, especially in the context of Organic chemistry.

I particularly like the emphasis on fundamental chemical concepts, principles and facts and their integration and linking across traditional chemistry topics."

Chris Davison graduated with a PhD in Organic chemistry and taught at Oundle School before joining Wellington College where he teaches DP Chemistry and runs practical and theoretical based extension lessons.

"I like that the new Guide has been designed to show the interdependence of the different areas of chemistry, inorganic, organic and physical. The topics fit under two broad titles, Structure, and Reactivity, and new linking questions highlight where subject matter both builds on and leads to other areas of the Guide.

The new Guide includes fossil fuels, biofuels and fuel cells – areas which are appealing and relevant to students and which only appeared in the option module previously."

John Allum taught physics to pre-university level in international schools for more than thirty years (as a head of department). He has now retired from teaching, but lives a busy life in a mountainside village in South East Asia. He has also been an IB examiner for many years.

"It is much more diverse than previously, providing students and teachers with many opportunities for variety, expanding beyond the limitations of just pure physics.

The removal of the Options and some of the more difficult content makes the course more manageable."

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HODDER EDUCATION

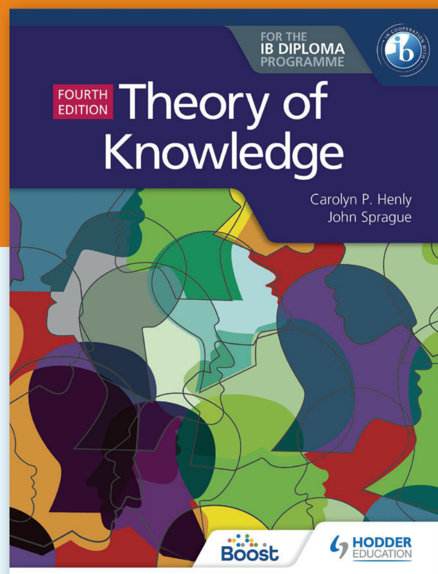
Our new co-published coursebooks support the new Guides by:

- Providing **guiding questions** at the start of each chapter along with a list of learning outcomes, each of which is mapped to the relevant assessment objective.
- Integrating **conceptual understanding** into all units, to ensure that a conceptual thread is woven throughout the course, making the subject more meaningful. This helps students develop clear evidence of synthesis and evaluation in their responses to assessment questions.
- Stimulating **creativity, curiosity, and critical thinking** with 'Inquiry', 'Tools', 'Approaches to Learning (ATL)' and 'Theory of Knowledge (TOK)' features throughout.
- Building the skills and techniques covered in the **Tools** (Experimental techniques, Technology and Mathematics). These skills are directly linked to relevant parts of the syllabus so they can be explored during delivery of the course. These skills also provide the foundation for practical work and internal assessment. They support the application and development of the inquiry process in the delivery of the new course.
- Supporting the **Inquiry** process with the new Inquiry feature, which focuses on aspects of the Inquiry cycle skills: Inquiring and designing, Collecting and processing data, Concluding and evaluating.
- Integrating **Theory of Knowledge** into your lessons and providing opportunities for cross-curriculum study with TOK links and Inquiries that provide real-world examples, case studies and questions. For Biology and Chemistry, the TOK links are written by the author of our bestselling TOK coursebook, John Sprague. For Physics the links are written by Paul Morris, our MYP by Concept series and Physics author, who has taught IB Physics for over 20 years and has also examined TOK.
- Developing **ATL** skills with a range of engaging activities with real-world applications.
- **Creating opportunities** for students to design investigations, collect data, develop manipulative skills, analyse results, collaborate with peers and evaluate and communicate their findings.
- Providing **Top tips** and **Common mistakes** to help ensure students' understanding is accurate and they are able to apply this effectively in their studies.
- **Improving performance** with short and simple knowledge-checking questions, a mixture of questions from past exam sessions and author-written exam-style questions and hints to help avoid common mistakes.
- Developing **International mindedness** by exploring how the exchange of information and ideas across national boundaries has been essential to the progress of science and illustrates the international aspects of science.
- Providing **Nature of science** boxes that encourage thinking, exploring ethical debates and learning how scientists work in the 21st century.
- Guiding students with the **IB Learner Profile** icon to help them develop as Thinkers, Risk-takers and Communicators.
- Creating opportunities for conceptual discussions and comparisons with **linking questions** at the end of each chapter.

We asked two of our expert authors what they are most proud of and what they enjoyed writing.

John Sprague

John Sprague is the author of our bestselling *Theory of Knowledge* coursebook.



> ***"Much like how the IB Diploma is a real "programme" in the sense that all of its moving parts mesh together, Hodder Education is working to incorporate a genuine collaborative and unified vision among its author team. We've brought together writers from the science specialists and DP Core to provide opportunities for students to experience the integrative approach to knowledge that the IBDP captures. We believe that every new publication provides us an opportunity to show our readers how the construction and transfer of knowledge is a collaborative adventure."***

Chris Clegg is an experienced teacher and examiner of Biology and has written many internationally-respected textbooks for pre-university courses. He was encouraged to write by his colleague and mentor at his school, textbook writer and teacher D.G. Mackean in the 1970s, and became his co-author on numerous books. He eventually took over the biology coursebook mantle from Don in the 1980s.

C. J. Clegg

> ***"I'm proudest of the figures and diagrams which I conceived to help students to better understand complex ideas. As a reader said after the first edition of Biology for the IB Diploma, "what rockets this book above others are the brilliant illustrations in the text. They are detailed, well-annotated and ultimately support independent learning."***
>
> ***I gave careful thought to my choice of language and phrasing so as to be clear and precise as a means of helping students in their understanding of the subject."***

To learn more about our IB DP Science series visit **hoddereducation.com/ib-dp-science**

Yours Faithfully,

Hodder Education International Team

Sample pages

FOR THE IB DIPLOMA PROGRAMME

THIRD EDITION

Physics

John Allum

Paul Morris

Boost

HODDER EDUCATION

Contents

E Nuclear and quantum

Free online content

Go to our website www.hoddereducation.com/ib-extras for free access to the following:

- Practice exam-style questions for each chapter
- Glossary
- Answers to self-assessment questions and practice exam-style questions
- Tools and Inquiries reference guide
- Internal Assessment – the scientific investigation

Introduction

Welcome to *Physics for the IB Diploma Third Edition*, updated and designed to meet the criteria of the new International Baccalaureate (IB) Diploma Programme Physics Guide. This coursebook provides complete coverage of the new IB Physics Diploma syllabus, with first teaching from 2023. Differentiated content for SL and HL students is clearly identified throughout.

The aim of this syllabus is to integrate concepts, topic content and the nature of science through inquiry. Approaches to learning in the study of physics are integrated with the topics, along with key scientific inquiry skills. This book comprises five main themes:

- **Theme A**: Space, time and motion
- **Theme B**: The particulate nature of matter
- **Theme C**: Wave behaviour
- **Theme D**: Fields
- **Theme E**: Nuclear and quantum physics

Each theme is divided into syllabus topics.

The book has been written with a sympathetic understanding that English is not the first language of many students.

No prior knowledge of physics by students has been assumed, although many will have taken an earlier course (and they will find some useful reminders in the content).

In keeping with the IB philosophy, a wide variety of approaches to teaching and learning has been included in the book (not just the core physics syllabus). The intention is to stimulate interest and motivate beyond the confines of the basic physics content. However, it is very important students know what is the essential knowledge they have to take into the examination room. This is provided by the Key information boxes. If this information is well understood, and plenty of self-assessment questions have been done (and answers checked), then a student will be well-prepared for their IB Physics examination.

The online Glossary is another useful resource. It's aim is to list and explain basic terminology used in physics, but it is not intended as a list of essential information for students. Many of the terms in the Glossary are highlighted in the book as 'Key terms' and also emphasized in the nearby margins.

The ‘In cooperation with IB’ logo signifies that this coursebook has been rigorously reviewed by the IB to ensure it fully aligns with the current IB curriculum and offers high-quality guidance and support for IB teaching and learning.

How to use this book

The following features will help you consolidate and develop your understanding of physics, through concept-based learning.

Guiding questions

- There are guiding questions at the start of every chapter, as signposts for inquiry.
- These questions will help you to view the content of the syllabus through the conceptual lenses of the themes.

SYLLABUS CONTENT

- This coursebook follows the order of the contents of the IB Physics Diploma syllabus.
- Syllabus understandings are introduced naturally throughout each topic.

Key information

Throughout the book, you will find some content in pink boxes like this one. These highlight the essential Physics knowledge you will need to know when you come to the examination. Included in these boxes are the key equations and constants that are also listed in the IBDP Physics data booklet for the course.

Tools

The Tools features explore the skills and techniques that you require and are integrated into the physics content to be practiced in context. These skills can be assessed through internal and external assessment.

Inquiry process

The application and development of the Inquiry process is supported in close association with the Tools.

Nature of science

Nature of science (NOS) explores conceptual understandings related to the purpose, features and impact of scientific knowledge. It can be examined in Physics papers. NOS explores the scientific process itself, and how science is represented and understood by the general public. NOS covers 11 aspects: Observations, Patterns and trends, Hypotheses, Experiments, Measurements, Models, Evidence, Theories, Falsification, Science as a shared endeavour, and Global impact of science. It also examines the way in which science is the basis for technological developments and how these modern technologies, in turn, drive developments in science.

Key terms

◆ Definitions appear throughout the margins to provide context and help you understand the language of physics. There is also a glossary of all key terms online.

Common mistake

These detail some common misunderstandings and typical errors made by students, so that you can avoid making the same mistakes yourself.

Content from the IBDP Physics data booklet is indicated with this icon and shown in bold. The data booklet contains electrical symbols, equations and constants that you need to familiarize yourself with as you progress through the course. You will have access to a copy of the data booklet during your examination.

ATL ACTIVITY

Approaches to learning (ATL) activities, including learning through inquiry, are integral to IB pedagogy. These activities are contextualized through real-world applications of physics.

Top tip!

This feature includes advice relating to the content being discussed and tips to help you retain the knowledge you need.

WORKED EXAMPLE

These provide a step-by-step guide showing you how to answer the kind of quantitative and other questions that you might encounter in your studies and in the assessment.

International mindedness is indicated with this icon. It explores how the exchange of information and ideas across national boundaries has been essential to the progress of science and illustrates the international aspects of physics.

Self-assessment questions appear throughout the chapters, phrased to assist comprehension and recall, but also to help familiarize you with the assessment implications of the command terms. These command terms are defined in the online glossary. Practice exam-style questions and their answers, together with answers to most self-assessment questions are on the accompanying website, IB Extras: **www.hoddereducation.com/ib-extras**

The IB learner profile icon indicates material that is particularly useful to help you towards developing in the following attributes: to be inquirers, knowledgeable, thinkers, communicators, principled, open-minded, caring, risk-takers, balanced and reflective. When you see the icon, think about what learner profile attribute you might be demonstrating – it could be more than one.

LINKING QUESTIONS

These questions are introduced throughout each topic. They are to strengthen your understanding by making connections across the themes. The linking questions encourage you to apply broad, integrating and discipline-specific concepts from one topic to another, ideally networking your knowledge. Practise answering the linking questions first, on your own or in groups. The links in this coursebook are not exhaustive, you may also encounter other connections between concepts, leading you to create your own linking questions.

TOK

Links to Theory of Knowledge (TOK) allow you to develop critical thinking skills and deepen scientific understanding by bringing discussions about the subject beyond the scope of the content of the curriculum.

About the author

John Allum taught physics to pre-university level in international schools for more than thirty years (as a head of department). He has now retired from teaching, but lives a busy life in a mountainside village in South East Asia. He has also been an IB examiner for many years.

Adviser, writer and reader

Paul Morris is Deputy Principal and IB Diploma Coordinator at the International School of London. He has taught IB Physics and IB Theory of Knowledge for over 20 years, has led teacher workshops internationally and has examined Theory of Knowledge. As an enthusiast for the IB concept-based continuum, Paul designed and developed Hodder Education's 'MYP by Concept' series and was author and co-author of the Physics and Sciences titles in the series. He has also advised on publishing projects for the national sciences education programmes for Singapore and Qatar.

Tools and Inquiry

Skills in the study of physics

The skills and techniques you must experience through the course are encompassed within the tools. These support the application and development of the inquiry process in the delivery of the physics course.

Tools

- **Tool 1:** Experimental techniques
- **Tool 2:** Technology
- **Tool 3:** Mathematics

Inquiry process

- **Inquiry 1:** Exploring and designing
- **Inquiry 2:** Collecting and processing data
- **Inquiry 3:** Concluding and evaluating

Throughout the programme, you will be given opportunities to encounter and practise the skills; and instead of stand-alone topics, they will be integrated into the teaching of the syllabus when they are relevant to the syllabus topics being covered.

You can see what the Tools and Inquiry boxes look like in the *How to use this book* section on page vi.

The skills in the study of physics can be assessed through internal and external assessment. The Approaches to learning provide the framework for the development of these skills.

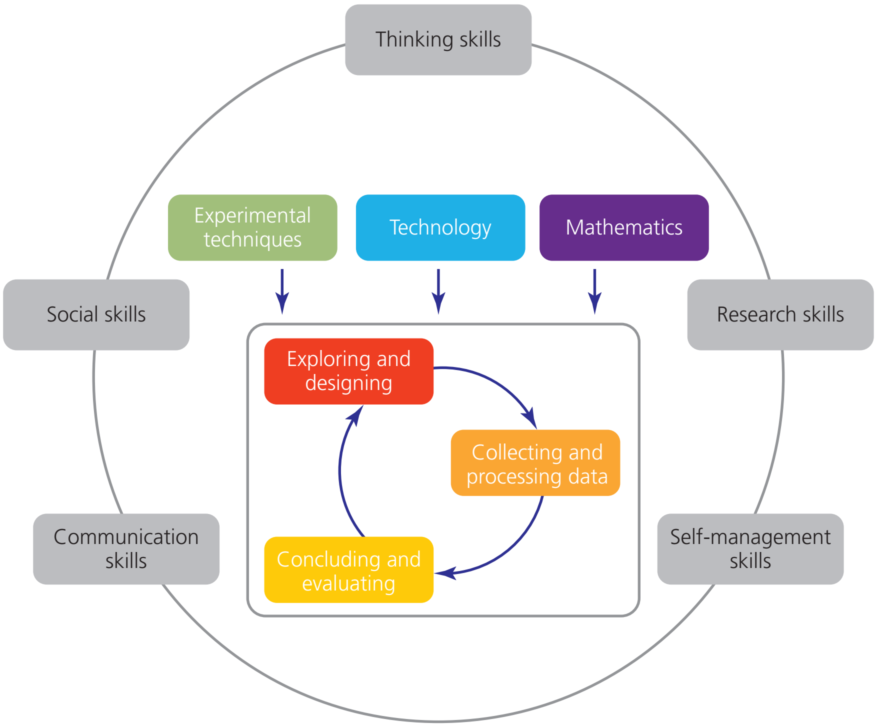


Figure 0.01 Tools for physics

Visit the link in the QR code or this website to view the Tools and Inquiry reference guide: www.hoddereducation.com/ib-extras

Tools

Tool 1: Experimental techniques

Skill	Description
Addressing safety of self, others and the environment	• Recognize and address relevant safety, ethical or environmental issues in an investigation.
Measuring variables	Understand how to accurately measure the following to an appropriate level of precision: • Mass • Time • Length • Volume • Temperature • Force • Electric current • Electric potential difference • Angle • Sound and light intensity

Tool 2: Technology

Skill	Description
Applying technology to collect data	• Use sensors. • Identify and extract data from databases. • Generate data from models and simulations. • Carry out image analysis and video analysis of motion.
Applying technology to process data	• Use spreadsheets to manipulate data. • Represent data in a graphical form. • Use computer modelling.

Tool 3: Mathematics

Skill	Description
Applying general mathematics	• Use basic arithmetic and algebraic calculations to solve problems. • Calculate areas and volumes for simple shapes. • Carry out calculations involving decimals, fractions, percentages, ratios, reciprocals, exponents and trigonometric ratios. • Carry out calculations involving logarithmic and exponential functions. • Determine rates of change. • Calculate mean and range. • Use and interpret scientific notation (for example, 3.5×10^6). • Select and manipulate equations. • Derive relationships algebraically. • Use approximation and estimation. • Appreciate when some effects can be neglected and why this is useful. • Compare and quote ratios, values and approximations to the nearest order of magnitude. • Distinguish between continuous and discrete variables.

Skill	Description
	• Understand direct and inverse proportionality, as well as positive and negative relationships or correlations between variables. • Determine the effect of changes to variables on other variables in a relationship. • Calculate and interpret percentage change and percentage difference. • Calculate and interpret percentage error and percentage uncertainty. • Construct and use scale diagrams. • Identify a quantity as a scalar or vector. • Draw and label vectors including magnitude, point of application and direction. • Draw and interpret free-body diagrams showing forces at point of application or centre of mass as required. • Add and subtract vectors in the same plane (limited to three vectors). • Multiply vectors by a scalar. • Resolve vectors (limited to two perpendicular components).
Using units, symbols and numerical values	• Apply and use SI prefixes and units. • Identify and use symbols stated in the guide and the data booklet. • Work with fundamental units. • Use of units (for example, eV, eVc^{-2}, ly, pc, h, day, year) whenever appropriate. • Express derived units in terms of SI units. • Check an expression using dimensional analysis of units (the formal process of dimensional analysis will not be assessed). • Express quantities and uncertainties to an appropriate number of significant figures or decimal places.
Processing uncertainties	• Understand the significance of uncertainties in raw and processed data. • Record uncertainties in measurements as a range (±) to an appropriate precision. • Propagate uncertainties in processed data in calculations involving addition, subtraction, multiplication, division and raising to a power. • Express measurement and processed uncertainties—absolute, fractional (relative) and percentage—to an appropriate number of significant figures or level of precision.
Graphing	• Sketch graphs, with labelled but unscaled axes, to qualitatively describe trends. • Construct and interpret tables, charts and graphs for raw and processed data including bar charts, histograms, scatter graphs and line and curve graphs. • Construct and interpret graphs using logarithmic scales. • Plot linear and non-linear graphs showing the relationship between two variables with appropriate scales and axes. • Draw lines or curves of best fit. • Draw and interpret uncertainty bars. • Extrapolate and interpolate graphs. • Linearize graphs (only where appropriate). • On a best-fit linear graph, construct lines of maximum and minimum gradients with relative accuracy (by eye) considering all uncertainty bars. • Determining the uncertainty in gradients and intercepts. • Interpret features of graphs including gradient, changes in gradient, intercepts, maxima and minima, and areas under the graph.

Inquiry process

Inquiry 1: Exploring and designing

Skill	Description
Exploring	• Demonstrate independent thinking, initiative and insight. • Consult a variety of sources. • Select sufficient and relevant sources of information. • Formulate research questions and hypotheses. • State and explain predictions using scientific understanding.
Designing	• Demonstrate creativity in the designing, implementation and presentation of the investigation. • Develop investigations that involve hands-on laboratory experiments, databases, simulations and modelling. • Identify and justify the choice of dependent, independent and control variables. • Justify the range and quantity of measurements. • Design and explain a valid methodology. • Pilot methodologies.
Controlling variables	Appreciate when and how to: • calibrate measuring apparatus, including sensors • maintain constant environmental conditions of systems • insulate against heat loss or gain • reduce friction • reduce electrical resistance • take background radiation into account.

Inquiry 2: Collecting and processing data

Skill	Description
Collecting data	• Identify and record relevant qualitative observations. • Collect and record sufficient relevant quantitative data. • Identify and address issues that arise during data collection.
Processing data	• Carry out relevant and accurate data processing.
Interpreting results	• Interpret qualitative and quantitative data. • Interpret diagrams, graphs and charts. • Identify, describe and explain patterns, trends and relationships. • Identify and justify the removal or inclusion of outliers in data (no mathematical processing is required). • Assess accuracy, precision, reliability and validity.

Inquiry 3: Concluding and evaluating

Skill	Description
Concluding	• Interpret processed data and analysis to draw and justify conclusions. • Compare the outcomes of an investigation to the accepted scientific context. • Relate the outcomes of an investigation to the stated research question or hypothesis. • Discuss the impact of uncertainties on the conclusions.
Evaluating	• Evaluate hypotheses. • Identify and discuss sources and impacts of random and systematic errors. • Evaluate the implications of methodological weaknesses, limitations and assumptions on conclusions. • Explain realistic and relevant improvements to an investigation.

A.1 Kinematics

◆ **Kinematics** Study of motion.

◆ **Classical physics** Physics theories that pre-dated the paradigm shifts introduced by quantum physics and relativity.

◆ **Uniform** Unchanging.

◆ **Magnitude** Size.

◆ **Scalars** Quantities that have only magnitude (no direction).

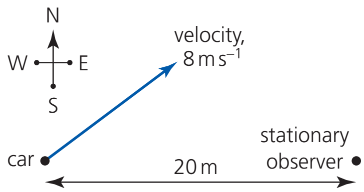
◆ **Vector** A quantity that has both magnitude and direction.

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?

Kinematics is the study of moving objects. In this topic we will describe motion by using graphs and equations, but the causes of motion (forces) will be covered in the next topic, A.2 Forces and Momentum. The ideas of **classical physics** presented in this chapter can be applied to the movement of all masses, from the very small (freely moving atomic particles) to the very large (stars).

To completely describe the motion of an object at any one moment we need to state its position, how fast it is moving, the direction in which it is moving and whether its motion is changing. For example, we might observe that a car is 20 m to the west of an observer and moving northeast with a constant (**uniform**) velocity of 8 m s^{-1}. See Figure A1.1.



■ **Figure A1.1** Describing the position and motion of a car

Of course, any or all, of these quantities might be changing. In real life the movement of many objects can be complicated; they do not often move in straight lines and they might even rotate or have different parts moving in different directions.

In this chapter we will develop an understanding of the basic principles of kinematics by dealing first with objects moving in straight lines, and calculations will be confined to those objects that have a uniform (unchanging) motion.

Tool 3: Mathematics

Identify a quantity as a scalar or a vector

Everything that we measure has a magnitude and a unit. For example, we might measure the mass of a book to be 640 g. Here, 640 g is the **magnitude** (size) of the measurement, but mass has no direction.

Quantities that have only magnitude, and no direction, are called **scalars**.

All physical quantities can be described as scalars or **vectors**.

Quantities that have both magnitude and direction are called vectors.

For example, force is a vector quantity because the direction in which a force acts is important.

Most quantities are scalars. Some common examples of scalars used in physics are mass, length, time, energy, temperature and speed.

However, when using the following quantities, we need to know both the magnitude and the direction in which they are acting, so they are vectors:

- displacement (distance in a specified direction)
- velocity (speed in a given direction)
- force (including weight)
- acceleration
- momentum and impulse
- field strength (gravitational, electric and magnetic).

In diagrams, all vectors are shown with straight arrows, pointing in a certain direction from the correct point of application.

The lengths of the arrows are proportional to the magnitudes of the vectors.

Distance and displacement

SYLLABUS CONTENT

- The motion of bodies through space and time can be described and analysed in terms of position, velocity and acceleration.
- The change in position is the displacement.
- The difference between distance and displacement.

◆ **Distance** Total length travelled, without consideration of directions.

◆ **Displacement, linear** Distance in a straight line from a fixed reference point in a specified direction.

◆ **Metre, m** SI unit of length (fundamental).

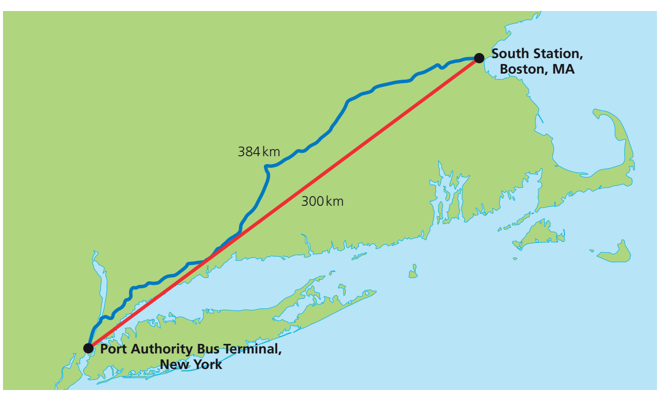
The term **distance** can be used in different ways, for example we might say that the distance between New York City and Boston is 300 km, meaning that a straight line between the two cities has a length of 300 km. Or, we might say that the (travel) distance was 348 km, meaning the length of the road between the cities.

We will define distance as follows:

Distance (of travel) is the total length of a specified path between two points. SI unit: **metre, m**

In physics, **displacement** (change of position) is often more important than distance:

The displacement of an object is the distance in a straight line from a fixed reference point in a specified direction.

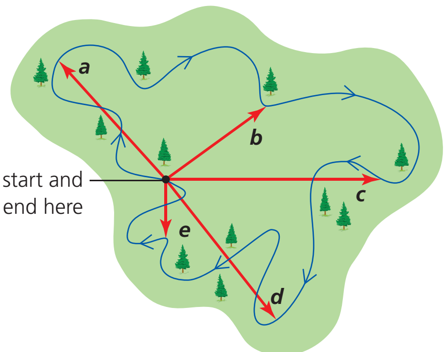


■ **Figure A1.2** Boston is a travel distance of 384 km and a displacement of 300 km northeast from New York City

Continuing the example given above, if a girl travels from New York to Boston, her displacement will be 300 km to the northeast (see Figure A1.2).

Both distance and displacement are given the symbol s and the SI unit metres, m. Kilometres, km, centimetres, cm, and millimetres, mm, are also in widespread use. We often use the symbol h for heights and x for small displacements.

Figure A1.3 shows the route of some people walking around a park. The total distance walked was 4 km, but the displacement from the reference point varied and is shown every few minutes by the vector arrows (***a***–***e***). The final displacement was zero because the walkers returned to their starting place.



■ **Figure A1.3** A walk in the park

Speed and velocity

SYLLABUS CONTENT

- Velocity is the rate of change of position.
- The difference between instantaneous and average values of velocity, speed and acceleration, and how to determine them.

Speed

The displacement of Wellington from Auckland, New Zealand, is 494 km south (Figure A1.4). The road distance is 642 km and it is predicted that a car journey between the two cities will take 9.0 hours.

■ **Figure A1.4** Distance and displacement from Auckland to Wellington

If we divide the total distance by the total time (642 / 9.0) we determine a speed of 71 km h^{-1}. In this example it should be obvious that the speed will have changed during the journey and the calculated result is just an **average speed** for the whole trip. The value seen on the speedometer of the car is the speed at any particular moment, called the **instantaneous speed**.

◆ **Speed, *v*** Average speed = distance travelled/time taken. Instantaneous speed is determined over a very short time interval, during which it is assumed that the speed does not change.

◆ **Reaction time** The time delay between an event occurring and a response. For example, the delay that occurs when using a stopwatch.

◆ **Sensor** An electrical component that responds to a change in a physical property with a corresponding change in an electrical property (usually resistance). Also called a transducer.

◆ **Light gate** Electronic sensor used to detect motion when an object interrupts a beam of light.

Tool 1: Experimental techniques

Understand how to accurately measure quantities to an appropriate level of precision: time

Accurate time measuring instruments are common, but the problem with obtaining accurate measurements of time is starting and stopping the timers at exactly the right moments.

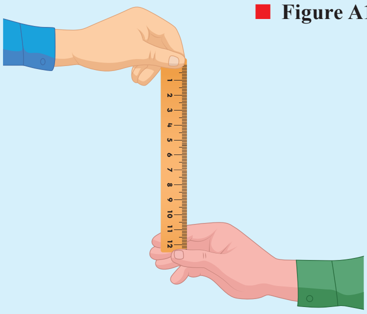
Whenever we use stopwatches or timers operated by hand, the results will have an unavoidable and variable uncertainty because of the delays between seeing an event and pressing a button to start or stop the timer. The delay between seeing something happen and responding with some kind of action is known as **reaction time**. For example, for car drivers it is usually assumed that a driver takes about 0.7 s to press the brake pedal after they have seen a problem. (But some drivers will be able to react quicker than this.) A car will travel about 14 m in this time if it is moving at 50 km h^{-1}. Reaction times will increase if the driver is distracted, tired, or under the influence of any type of drug, such as alcohol.

A simple way of determining a person's reaction time is by measuring how far a metre ruler falls before it can be caught between thumb and finger (see Figure A1.5). The time, t, can then be calculated using the equation for distance, $s = 5t^2$ (explained later in this topic).

If the distance the ruler falls $s = 0.30$

Rearranging for t, $t = \sqrt{\frac{s}{5}} = \sqrt{\frac{0.30}{5}}$

So, reaction time $t = 0.25$ s.



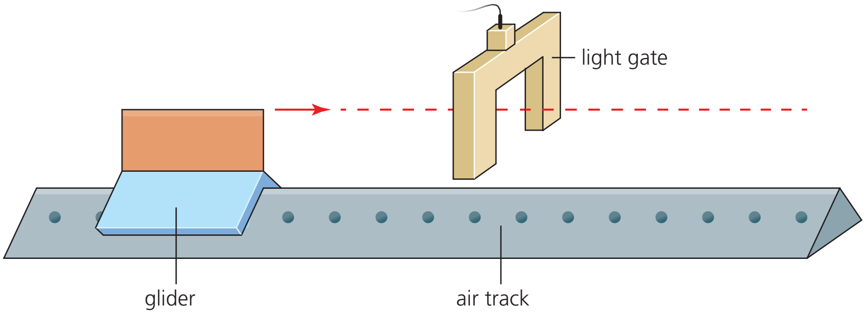
■ **Figure A1.5** Determining reaction time

Under these conditions a typical reaction time is about 0.25 s, but it can vary considerably depending on the conditions involved. The measurement can be repeated with the person tested being blindfolded to see if the reaction time changes if the stimulus (to catch the ruler) is either sound or touch, rather than sight.

In science experiments it is sensible to make time measurements as long as possible to decrease the effect of this problem. (This reduces the percentage uncertainty.) Repeating measurements and calculating an average will also reduce the effect of random uncertainties. If a stopwatch is started late because of the user's reaction time, it may be offset by also stopping the stopwatch late for the same reason.

Electronics **sensors**, such as **light gates**, are very useful in obtaining accurate time measurements. See below.

There are a number of different methods in which speed can be measured in a school or college laboratory. Figure A1.6 shows one possibility, in which a glider is moving on a frictionless air track at a constant velocity. The time taken for a card of known length (on the glider) to pass through the light gate is measured and its speed can be calculated from length of card / time taken.



■ **Figure A1.6** Measuring speed in a laboratory

Tool 2: Technology

Use sensors

An electronic sensor is an electronic device used to convert a physical quantity into an electrical signal. The most common sensors respond to changes in light level, sound level, temperature or pressure.

A light gate contains a source of light that produces a narrow beam of light directed towards a sensor on the other side of a gap. When an object passes across the light beam, the unit behaves as a switch which turns a timer on or off very quickly.

Tool 3: Mathematics

Determine rates of change

The Greek capital letter delta, Δ, is widely used in physics and mathematics to represent a change in the value of a quantity.

For example, $\Delta x = (x_2 - x_1)$, where x_2 and x_1 are two different values of the variable x.

The change involved is often considered to be relatively small.

◆ **Second, s** SI unit of time (fundamental).

Most methods of determining speed involve measuring the small amount of time (Δt) taken to travel a certain distance (Δs). The SI unit for time is the **second**, s.

$$\text{speed} = \frac{\text{distance travelled}}{\text{time taken}} \quad (\text{SI unit m s}^{-1})$$

This calculation determines an average speed during time Δt, but if Δt is small enough, we may assume that the calculated value is a good approximation to an instantaneous speed.

Speed is a scalar quantity. Speed is given the same symbol, (v), as velocity.

■ **Figure A1.7** The peregrine falcon is reported to be the world's fastest animal (speeds measured up to 390 km h^{-1})

◆ **At rest** Stays stationary in the same position.

◆ **Milky Way** The galaxy in which our Solar System is located.

Nature of science: Observations

Objects at rest

It is common in physics for people to refer to an object being **at rest**, meaning that it is not moving. But this is not as simple as it may seem. A stone may be at rest on the ground, meaning that it is not moving when compared with the ground: it appears to us to have no velocity and no acceleration. However, when the same stone is thrown upwards, at the top of its path its instantaneous speed may be zero, but it has an acceleration downwards.

We cannot assume that an object which is at rest has no acceleration; its velocity may be changing – either in magnitude, in direction, or both.

We may prefer to refer to an object being *stationary*, suggesting that an object is not moving over a period of time.

Of course, the surface of the Earth is moving, the Earth is orbiting the Sun, which orbits the centre of the **Milky Way** galaxy, which itself exists in an expanding universe. So, at a deeper level, we must understand that *all* motion is relative and nowhere is truly stationary. This is the starting point for the study of Relativity (Topic A.5).

Velocity

Velocity, *v*, is the rate of change of position. It may be considered to be speed in a specified direction.

◆ **Velocity, *v*** Rate of change of position.

$$\text{velocity, } v = \frac{\text{displacement}}{\text{time taken}} = \frac{\Delta s}{\Delta t} \quad (\text{SI unit m s}^{-1})$$

The symbol Δs represents a change of position (displacement).

Velocity is a vector quantity. $12\,\text{m s}^{-1}$ is a speed. $12\,\text{m s}^{-1}$ to the south is a velocity. We use positive and negative signs to represent velocities in opposite directions. For example, $+12\,\text{m s}^{-1}$ may represent a velocity upwards, while $-12\,\text{m s}^{-1}$ represents the same speed downwards, but we may choose to reverse the signs used.

Speed and velocity are both represented by the same symbol (v) and their magnitudes are calculated in the same way $\left(v = \frac{\Delta s}{\Delta t}\right)$ with the same units. It is not surprising that these two terms are sometimes used interchangeably and this can cause confusion. For this reason, it may be better to define these two quantities in words, rather than symbols.

As with speed, we may need to distinguish between average velocity over a time interval, or instantaneous velocity at a particular moment. As we shall see, the value of an instantaneous velocity can be determined from the gradient of a displacement–time graph.

Top tip!

When a direction of motion is clearly stated (such as 'up', 'to the north', 'to the right' and so on), it is very clear that a velocity is being discussed. However, we may commonly refer to the 'velocity' of a car, for example, without stating a direction. Although this is casual, it is usually acceptable because an unchanging direction is implied, even if it is not specified. For example, we may assume that the direction of the car is along a straight road.

WORKED EXAMPLE A1.1

A satellite moves in circles along the same path around the Earth at a constant distance of 6.7×10^3 km from the Earth's centre. Each **orbit** takes a time of 90 minutes.

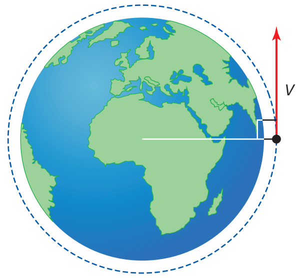
a Calculate the average speed of the satellite.

b Describe the instantaneous velocity of the satellite.

c Determine its displacement from the centre of the Earth after

i 360 minutes

ii 405 minutes.



■ **Figure A1.8** Satellite's instantaneous velocity

◆ **Orbit** The curved path (may be circular) of a mass around a larger central mass.

◆ **Tangent** Line which touches a given curve at a single point.

Answer

a $v = \dfrac{\text{circumference}}{\text{time for orbit}} = \dfrac{2\pi r}{\Delta t}$

$= \dfrac{(2 \times \pi \times 6.7 \times 10^6)}{(90 \times 60)}$

$= 7.8 \times 10^3\,\text{m}\,\text{s}^{-1}$

b The velocity also has a constant magnitude of $7.8 \times 10^3\,\text{m}\,\text{s}^{-1}$, but its direction is continuously changing. Its instantaneous velocity is always directed along a **tangent** to its circular orbit. See Figure A1.8.

c i 360 minutes is the time for four complete orbits. The satellite will have returned to the same place. Its displacement from the centre of the Earth compared to 360 minutes earlier will be the same. (But the Earth will have rotated.)

ii In the extra 45 minutes the satellite will have travelled half of its orbit. It will be on the opposite side of the Earth's centre, but at the same distance. We could represent this as -6.7×10^3 km from the Earth's centre.

1 Calculate the average speed ($\text{m}\,\text{s}^{-1}$) of an athlete who can run a marathon (42.2 km) in 2 hours, 1 minute and 9 seconds. (The men's world record at the time of writing.)

■ **Figure A1.9** Eliud Kipchoge, world record holder for the men's marathon

2 A small ball dropped from a height of 2.0 m takes 0.72 s to reach the ground.

a Calculate $\dfrac{2.0}{0.72}$

b What does your answer represent?

c The speed of the ball just before it hits the ground is $5.3\,\text{m}\,\text{s}^{-1}$. This is an instantaneous speed. Distinguish between an instantaneous value and an average value.

d State the instantaneous velocity of the ball just before it hits the ground.

e After bouncing, the ball only rises to a lower height. Give a rough estimate of the instantaneous velocity of the ball as it leaves the ground.

3 A magnetic field surrounds the Earth and it can be detected by a compass. State whether it is a scalar or a vector quantity. Explain your answer.

4 On a flight from Rome to London, a figure of $900\,\text{km}\,\text{h}^{-1}$ is displayed on the screen.

a State whether this is a speed or a velocity.

b Is it an average or instantaneous value?

c Convert the value to $\text{m}\,\text{s}^{-1}$.

d Calculate how long it will take the aircraft to travel a distance of 100 m.

Acceleration

SYLLABUS CONTENT

- Acceleration is the rate of change of velocity.
- Motion with uniform and non-uniform acceleration.

◆ **Acceleration, *a*** Rate of change of velocity with time. Acceleration is a vector quantity.

◆ **Deceleration** Term commonly used to describe a decreasing speed.

Any variation from moving at a constant speed in a straight line is described as an **acceleration**.

Going faster, going slower and/or changing direction are all different kinds of acceleration (changing velocities).

When the velocity (or speed) of an object changes during a certain time, the symbol u is used for the initial velocity and the symbol v is used for the final velocity. These velocities are not necessarily the beginning and end of the entire motion, just the velocities at the start and end of the period of time that is being considered.

Acceleration, a, is defined as the rate of change of velocity with time:

$$a = \frac{\Delta v}{\Delta t} = \frac{(v - u)}{t} \quad \text{(SI unit m s}^{-2}\text{)}$$

One way to determine an acceleration is to measure two velocities and the time between the measurements. Figure A1.10 shows an example.

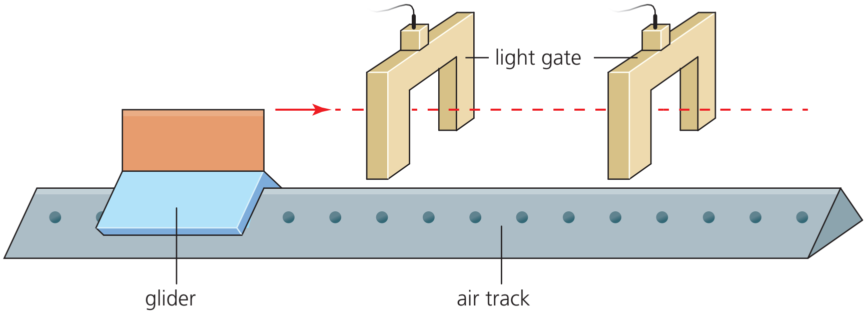


Figure A1.10 Measuring two velocities to determine an acceleration

Acceleration is a vector quantity. For a typical motion in which displacement and velocity are both given positive values, a positive acceleration means increasing speed in the same direction ($+\Delta v$), while a negative acceleration means decreasing speed in the same direction ($-\Delta v$). In everyday speech, a reducing speed is often called a **deceleration**.

For a motion in which displacement and velocity are given negative values, a positive acceleration means a decreasing speed. For example, a velocity change from $-6\,\text{m s}^{-1}$ to $-4\,\text{m s}^{-1}$ in 0.5 s corresponds to an acceleration:

$$a = \frac{\Delta v}{\Delta t} = \frac{([-4]-[-6])}{0.5} = +\,4\,\text{ms}^{-2}$$

As with speed and velocity, we may need to distinguish between average acceleration over a time interval, or instantaneous acceleration at a particular moment.

WORKED EXAMPLE A1.2

A high-speed train travelling with a velocity of $84\,\mathrm{m\,s^{-1}}$ needs to slow down and stop in a time of one minute.

a Determine the necessary average acceleration.

b Calculate the distance that the train will travel in this time assuming that the acceleration is uniform.

Answer

a $a = \dfrac{\Delta v}{\Delta t} = \dfrac{(0 - 84)}{60} = -1.4\,\mathrm{m\,s^{-2}}$

The acceleration is negative. The negative sign shows that the velocity is decreasing.

b average speed $= \dfrac{(84 - 0)}{2} = 42\,\mathrm{m\,s^{-1}}$

distance = average speed × time = $42 \times 60 = 2.5 \times 10^3\,\mathrm{m}$

5 A car moving at $12.5\,\mathrm{m\,s^{-1}}$ accelerates uniformly on a straight road at a rate of $0.850\,\mathrm{m\,s^{-2}}$.

a Calculate its velocity after 4.60 s.

b What uniform rate of acceleration will reduce the speed to $5.0\,\mathrm{m\,s^{-1}}$ in a further 12 s?

6 An athlete accelerates uniformly from rest at the start of a race at a rate of $4.3\,\mathrm{m\,s^{-2}}$. How much time is needed before her speed has reached $8.0\,\mathrm{m\,s^{-1}}$?

7 A trolley takes 3.62 s to accelerate from rest uniformly down a slope at a rate of $0.16\,\mathrm{m\,s^{-2}}$. A light gate at the bottom of the slope records a velocity of $0.58\,\mathrm{m\,s^{-1}}$. What was the speed about halfway down the slope, 1.2 s earlier?

Inquiry 1: Exploring and designing

Designing

Suppose that the Principal of your school or college is worried about safety from traffic on the nearby road. He has asked your physics class to collect evidence that he can take to the police. He is concerned that the traffic travels too fast and that the vehicles do not slow down as they approach the school.

1 Using a team of students, working over a period of one week, with tape measures and stop watches, develop an investigation which will produce sufficient and accurate data that can be given in a report to the Principal. Explain how you would ensure that the investigation was carried out safely.

2 What is the best way of presenting a summary of this data?

Tool 3: Mathematics

Interpret features of graphs

In order to analyse and predict motions we have two methods: graphical and algebraic. Firstly, we will look at how motion can be represented graphically.

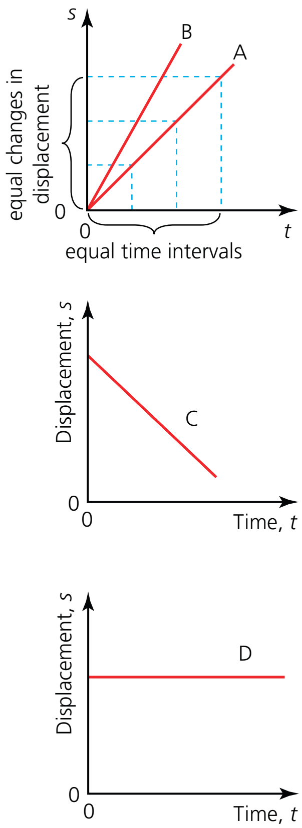
Graphs can be drawn to represent any motion and they provide extra understanding and insight (at a glance) that very few of us can get from written descriptions or equations. Furthermore, the gradients of graphs and the areas under graphs often provide additional useful information.

Displacement–time graphs and distance–time graphs

◆ **Linear relationship** One which produces a straight line graph.

Displacement–time graphs, similar to those shown in Figure A1.11, show how the displacements of objects from a known reference point vary with time. All the examples shown in Figure A1.11 are straight lines and are representing **linear relationships** and constant velocities.

- Line A represents an object moving away from the reference point (zero displacement) such that equal displacements occur in equal times. That is, the object has a constant velocity.



■ **Figure A1.11** Constant velocities on displacement–time graphs

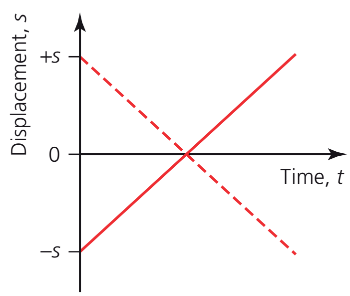
Any linear displacement–time graph represents a constant velocity (it does not need to start or end at the origin).

- Line B represents an object moving with a greater velocity than A.
- Line C represents an object that is moving back towards the reference point.
- Line D represents an object that is stationary (at rest). It has zero velocity and stays at the same distance from the reference point.

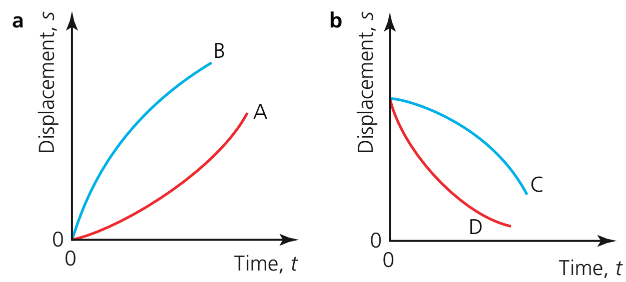
Figure A1.12 shows how we can represent displacements in opposite directions from the same reference point.

The solid line represents the motion of an object moving with a constant (positive) velocity. The object moves towards a reference point (where the displacement is zero), passes it, and then moves away from the reference point with the same velocity. The dotted line represents an identical speed in the opposite direction (or it could also represent the original motion if the directions chosen to be positive and negative were reversed).

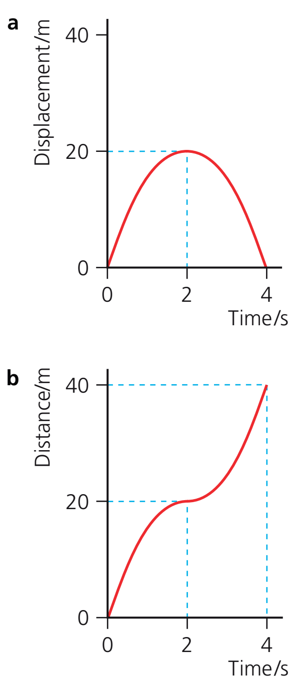
Any curved (non-linear) line on a displacement–time graph represents a changing velocity, in other words, an acceleration. This is illustrated in Figure A1.13.



■ **Figure A1.12** Motion in opposite directions represented on a displacement–time graph



■ **Figure A1.13** Accelerations on displacement–time graphs



■ **Figure A1.14** **a** Displacement–time and **b** distance–time graphs for an object moving up and then down

Figure A1.13a shows motion away from a reference point. Line A represents an object accelerating. Line B represents an object decelerating. Figure A1.13b shows motion towards a reference point. Line C represents an object accelerating. Line D represents an object decelerating. The values of the accelerations represented by these graphs may, or may not, be constant. (This cannot be determined without a more detailed analysis.)

In physics, we are usually more concerned with displacement–time graphs than distance–time graphs. In order to explain the difference, consider Figure A1.14.

Figure A1.14a shows a displacement–time graph for an object thrown vertically upwards with an initial speed of $20\,\mathrm{m\,s^{-1}}$ (without air resistance). It takes 2 s to reach a maximum height of 20 m. At that point it has an instantaneous velocity of zero, before returning to where it began after 4 s and regaining its initial speed. Figure A1.14b is a less commonly used graph showing how the same motion would appear on an overall distance–time graph.

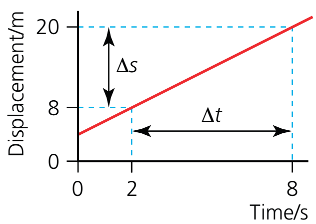
Tool 3: Mathematics

Interpret features of graphs: gradient

In this topic we will need to repeatedly use the following information:

- The gradient of a displacement–time graph equals velocity.
- The gradient of a velocity–time graph equals acceleration.

In the following section we will explore how to measure and interpret gradients.



■ **Figure A1.15** Finding a constant velocity from a displacement–time graph

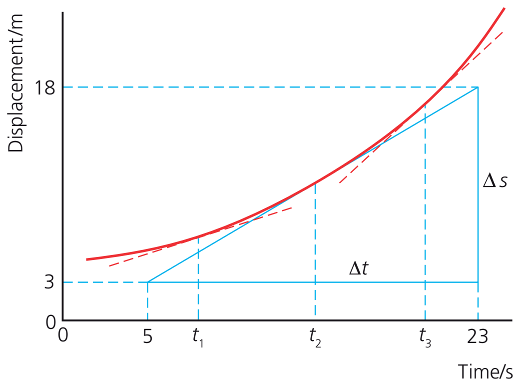
Gradients of displacement–time graphs

Consider the motion at *constant* velocity represented by Figure A1.15.

The **gradient** of the graph $= \frac{\Delta s}{\Delta t}$, which is the velocity of the object. A downwards sloping graph would have a negative gradient (velocity).

In this example,

$$\text{constant velocity, } v = \frac{\Delta s}{\Delta t} = \frac{(20 - 8.0)}{(8.0 - 2.0)} = 2.0\,\text{m s}^{-1}$$



■ **Figure A1.16** Finding an instantaneous velocity from a curved displacement–time graph

Figure A1.16 represents the motion of an object with a *changing* velocity, that is, an accelerating object.

The gradient of this graph varies, but at any point it is still equal to the velocity of the object at that moment, that is, the instantaneous velocity.

The gradient (velocity) can be determined at any time by drawing a tangent to the curve, as shown.

The triangle used to calculate the gradient should be large, in order to make this process as accurate as possible. In this example:

$$\text{velocity at time } t_2 = \frac{(18 - 3.0)}{(23 - 5.0)} = 0.83\,\text{m s}^{-1}$$

A tangent drawn at time t_1 would have a smaller gradient and represent a smaller velocity. A tangent drawn at time t_3 would represent a larger velocity.

◆ **Gradient** The rate at which one physical quantity changes in response to changes in another physical quantity. Commonly, for an y–x graph, gradient $= \frac{\Delta y}{\Delta x}$.

We have been referring to the object's displacement and velocity, although no direction has been stated. This is acceptable because that information would be included when the origin of the graph was explained. If information was presented in the form of a distance–time graph, the gradient would represent the speed.

In summary:

The gradient of a displacement–time graph represents velocity.

The gradient of a distance–time graph represents speed.

WORKED EXAMPLE A1.3

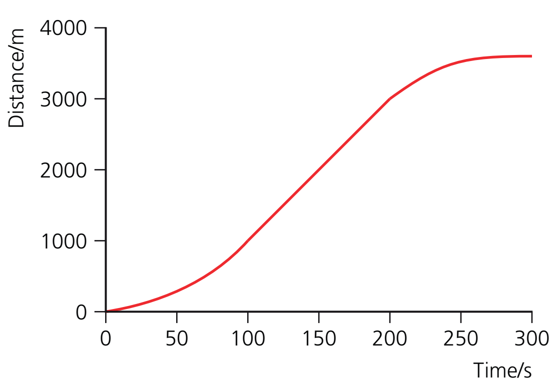
Figure A1.17 represents the motion of a train on a straight track between two stations.

a Describe the motion.

b State the distance between the two stations.

c Calculate the maximum speed of the train.

d Determine the average speed of the train.



■ **Figure A1.17** Distance–time graph for train on a straight track

Answer

a The train started from rest. For the first 90 s the train was accelerating. It then travelled with a constant speed until a time of 200 s. After that, its speed decreased to become zero after 280 s.

b 3500 m

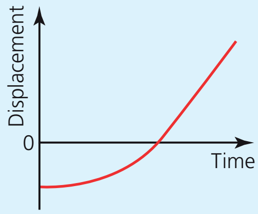
c From the steepest, straight section of the graph:

$$v = \frac{\Delta s}{\Delta t} = \frac{(3000 - 800)}{(200 - 90)} = 20\,\text{m s}^{-1}$$

d $\text{average speed} = \frac{\text{total distance travelled}}{\text{time taken}} = \frac{3500}{300} = 11.7\,\text{m s}^{-1}$

8 Draw a displacement–time graph for a swimmer swimming a total distance of 100 m at a constant speed of 1.0 m s^{-1} in a swimming pool of length 50 m.

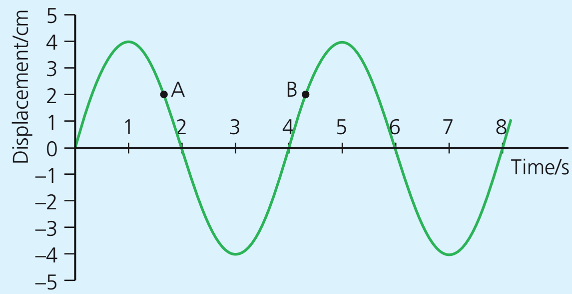
9 Describe the motion of a runner as shown by the graph in Figure A1.18.



■ **Figure A1.18** Displacement–time graph for a runner

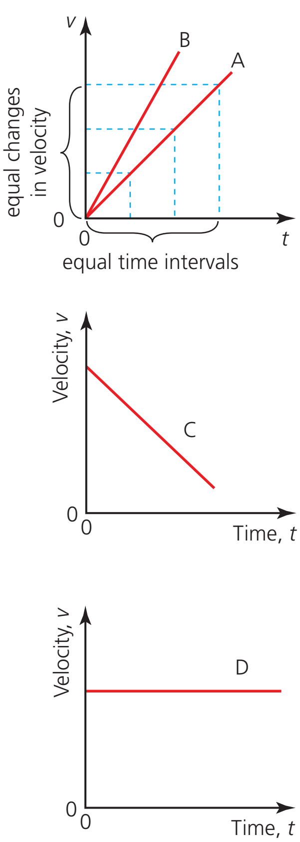
10 Sketch a displacement–time graph for the following motion: a stationary car is 25 m away; 2 s later it starts to move further away in a straight line from you with a constant acceleration of 1.5 m s^{-2} for 4 s; then it continues with a constant velocity for another 8 s.

11 Figure A1.19 is a displacement–time graph for an object.



■ **Figure A1.19** A displacement–time graph for an object

- **a** Describe the motion represented by the graph in Figure A1.19.
- **b** Compare the velocities at points A and B.
- **c** When is the object moving with its maximum and minimum velocities?
- **d** Estimate values for the maximum and minimum velocities.
- **e** Suggest what kind of object could move in this way.



■ **Figure A1.20** Constant accelerations on velocity–time graphs

Velocity–time graphs and speed–time graphs

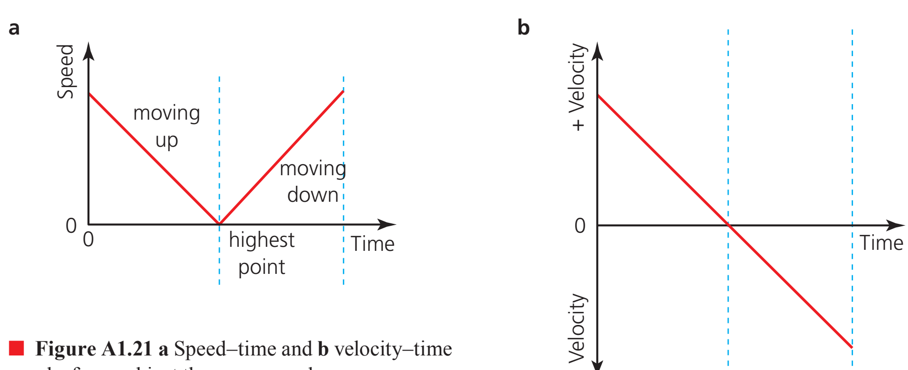
Figure A1.20, shows how the velocity of four objects changed with time. Any straight (linear) line on any velocity–time graph shows that equal changes of velocity occur in equal times – that is, it represents *constant* acceleration.

- Line A shows an object that has a constant positive acceleration.
- Line B represents an object moving with a greater positive acceleration than A.
- Line C represents an object that has a negative acceleration.
- Line D represents an object moving with a constant velocity – that is, it has zero acceleration.

Curved lines on velocity–time graphs represent *changing* accelerations.

Velocities in opposite directions are represented by positive and negative values.

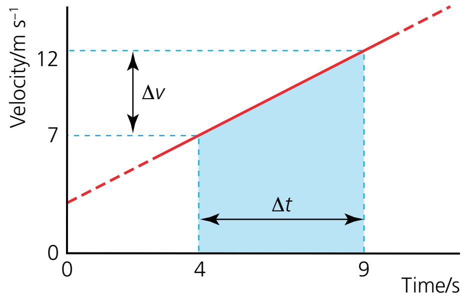
We will return to the example shown in Figure A1.14 to illustrate the difference between velocity–time and speed–time graphs. Figure A1.21a shows how the speed of an object changes as it is thrown up in the air (without air resistance), reaches its highest point, where its speed has reduced to zero, and then returns downwards. Figure A1.21b shows the same information in terms of velocity. Positive velocity represents motion upwards, negative velocity represents motion downwards. In most cases, the velocity graph is preferred to the speed graph.



■ **Figure A1.21** **a** Speed–time and **b** velocity–time graphs for an object thrown upwards.

Gradients of velocity–time graphs

Consider the motion at constant acceleration shown by the straight line in Figure A1.22.



■ **Figure A1.22** Finding the gradient of a velocity–time graph

The gradient of the graph $= \frac{\Delta v}{\Delta t}$, which is equal to the acceleration of the object.

In this example, the constant acceleration:

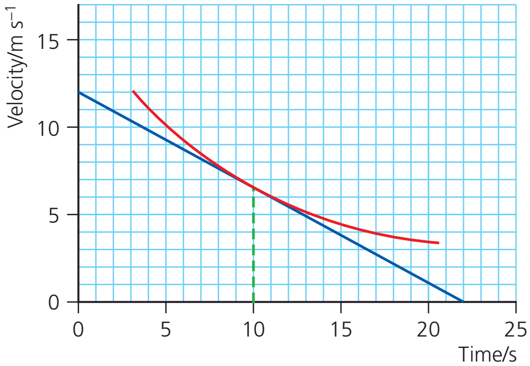
$$a = \frac{\Delta v}{\Delta t} = \frac{(12.0 - 7.0)}{(9.0 - 4.0)} = +\,1.0\,\text{m s}^{-2}$$

The acceleration of an object is equal to the gradient of the velocity–time graph.

A *changing* acceleration will appear as a curved line on a velocity–time graph. A numerical value for the acceleration at any time can be determined from the gradient of the graph at that moment. See Worked example A1.4.

WORKED EXAMPLE A1.4

The red line in Figure A1.23 shows an object decelerating (a decreasing negative acceleration). Use the graph to determine the instantaneous acceleration at a time of 10.0 s.



■ **Figure A1.23** Finding an instantaneous acceleration from a velocity–time graph

Answer

Using a tangent to the curve drawn at t = 10 s.

Acceleration, $a = \frac{\Delta v}{\Delta t} = \frac{(0 - 12)}{(22 - 0)} = -0.55\,\text{m s}^{-2}$

The negative sign indicates a deceleration. In this example the large triangle used to determine the gradient accurately was drawn by extending the tangent to the axes for convenience.

Tool 3: Mathematics

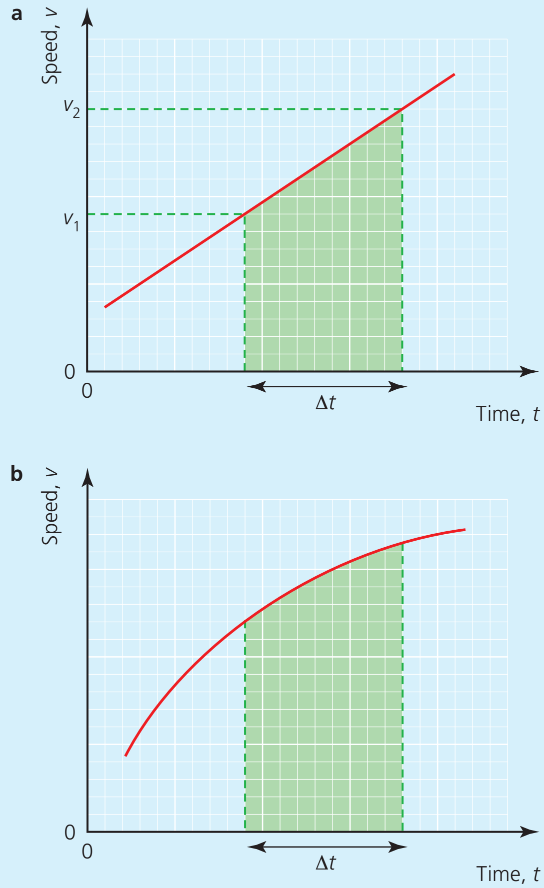
Interpret features of graphs: areas under the graph

The area under many graphs has a physical meaning. As an example, consider Figure A1.24a, which shows part of a speed–time graph for a vehicle moving with constant acceleration. The area under the graph (the shaded area) can be calculated from the average speed, given by $\frac{(v_1 + v_2)}{2}$, multiplied by the time, Δt.

The area under the graph is therefore equal to the distance travelled in time Δt. In Figure A1.24b a vehicle is moving with a changing (decreasing) acceleration, so that the graph is curved, but the same rule applies – the area under the graph (shaded) represents the distance travelled in time Δt.

The area in Figure A1.24b can be estimated in a number of different ways, for example by counting small squares, or by drawing a rectangle that appears (as judged by eye) to have the same area. (If the equation of the line is known, it can be calculated using the process of **integration**, but this is *not* required in the IB course.)

In the following section, we will show how a change in displacement can be calculated from a velocity–time graph.



■ **Figure A1.24** Area under a speed–time graph for **a** constant acceleration and **b** changing acceleration

◆ **Integration** Mathematical process used to determine the area under a graph.

Areas under velocity–time and speed–time graphs

As an example, consider again Figure A1.22. The change of displacement, Δs, between the fourth and ninth seconds can be found from (average velocity) × time.

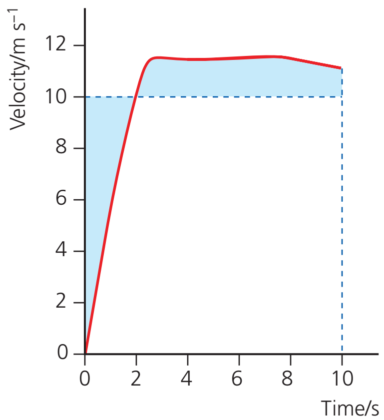
$$\Delta s = \frac{(12.0 + 7.0)}{2} \times (9.0 - 4.0) = 47.5\,\text{m}$$

This is numerically equal to the area under the line between $t = 4.0\,\text{s}$ and $t = 9.0\,\text{s}$ (as shaded in Figure A1.22). This is always true, whatever the shape of the line.

The area under a velocity–time graph is always equal to the change of displacement.

The area under a speed–time graph is always equal to the distance travelled.

As an example, consider Figure A1.21a. The two areas under the speed–time graph are equal and they are both positive. Each area equals the vertical height travelled by the object. The total area = total distance = twice the height. Each area under the velocity graph also represents the height, but the total area is zero because the areas above and below the time axis are equal, indicating that the final displacement is zero – the object has returned to where it started.



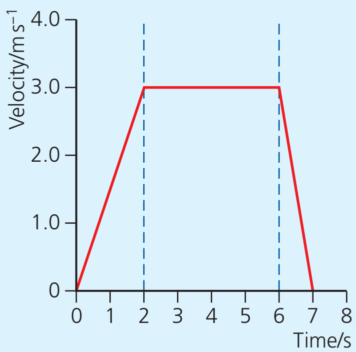
■ **Figure A1.25** Velocity–time graph for an athlete running 100 m

Figure A1.25 shows a velocity–time graph for an athlete running 100 m in 10.0 s. The area under the curve is equal to 100 m and it equals the area under the dotted line. (The two shaded areas are judged by sight to be equal.) The initial acceleration of the athlete is very important, and in this example, it is about 5 m s^{-2}.

■ **Figure A1.26** Elaine Thompson-Herah (Jamaica) won the women's 100 m in the Tokyo Olympics in 2021 in a time of 10.54 s

12 Look at the graph in Figure A1.27.

- **a** Describe the straight-line motion represented by the graph.
- **b** Calculate accelerations for the three parts of the journey.
- **c** What was the total distance travelled?
- **d** What was the average velocity?



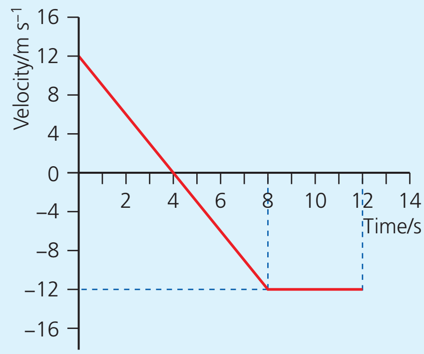
■ **Figure A1.27** Velocity–time graph

13 The velocity of a car was read from its speedometer at the moment it started and every 2 s afterwards. The successive values (converted to m s^{-1}) were: 0, 1.1, 2.4, 6.9, 12.2, 18.0, 19.9, 21.3 and 21.9.

- **a** Draw a graph of these readings.
- **b** Use the graph to estimate
  - **i** the maximum acceleration
  - **ii** the distance covered in 16 s.

14 Look at the graph in Figure A1.28.

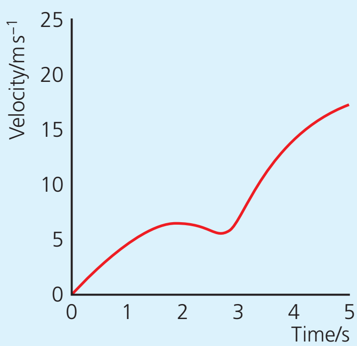
- **a** Describe the straight-line motion of the object represented by the graph.
- **b** Calculate the acceleration during the first 8 s.
- **c** What was the total distance travelled in 12 s?
- **d** What was the total displacement after 12 s?
- **e** What was the average velocity during the 12 s interval?



■ **Figure A1.28** Velocity–time graph

15 Sketch a velocity–time graph of the following motion: a car is 100 m away and travelling along a straight road towards you at a constant velocity of 25 m s^{-1}. Two seconds after passing you, the driver decelerates uniformly and the car stops 62.5 m away from you.

16 Figure A1.29 shows how the velocity of a car, moving in a straight line, changed in the first 5 s after starting. Use the area under the graph to show that the distance travelled was about 40 m.



■ **Figure A1.29** Determining the displacement of a car during acceleration

Tool 2: Technology

Use spreadsheets to manipulate data

Figure A1.30 represents how the velocities of two identical cars changed from the moment that their drivers saw danger in front of them and tried to stop their cars as quickly as possible. It has been assumed that both drivers have the same reaction time (0.7 s) and both cars decelerate at the same rate ($-5.0\,\mathrm{m\,s^{-2}}$).

The distance travelled at constant velocity before the driver reacts and depresses the brake pedal is known as the 'thinking distance'. The distance travelled while decelerating is called the 'braking distance'. The total stopping distance is the sum of these two distances.

Car B, travelling at twice the velocity of car A, has twice the thinking distance. That is, the thinking distance is proportional to the velocity of the car. The distance travelled when braking, however, is proportional to the velocity squared. This can be confirmed from the areas under the *v*–*t* graphs. The area under graph B is four times the area under graph A (during the deceleration). This has important implications for road safety and most countries make sure that people learning to drive must understand how stopping distances change with the vehicle's velocity. Some countries measure the reaction times of people before they are given a driving licence.

Set up a **spreadsheet** that will calculate the total stopping distance for cars travelling at initial speeds, u, between 0 and $40\,\mathrm{m\,s^{-1}}$ with a deceleration of $-6.5\,\mathrm{m\,s^{-2}}$. (Make calculations every $2\,\mathrm{m\,s^{-1}}$.) The thinking distance can be calculated from $s_t = 0.7u$ (reaction time 0.7 s).

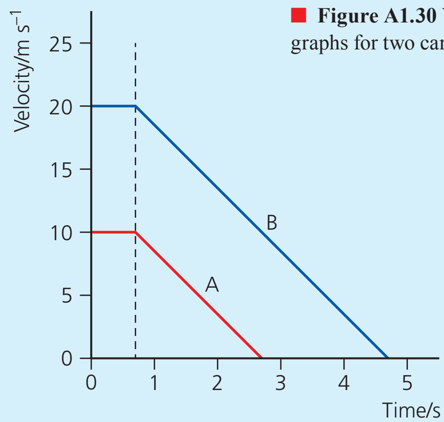
In this example the braking time can be calculated from:

$$t_b = \frac{u}{6.5}$$

and the braking distance can be calculated from:

$$s_b = \left(\frac{u}{2}\right)t_b$$

Use the data produced to plot a computer-generated graph of stopping distance (y-axis) against initial speed (x-axis).

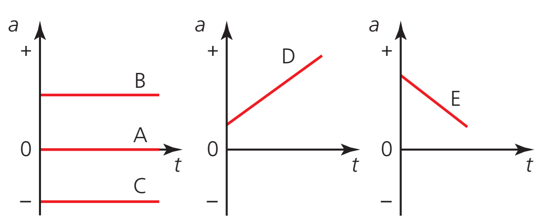


■ **Figure A1.30** Velocity–time graphs for two cars braking

◆ **Spreadsheet (computer)** Electronic document in which data is arranged in the rows and columns of a grid, and can be manipulated and used in calculations.

Acceleration–time graphs

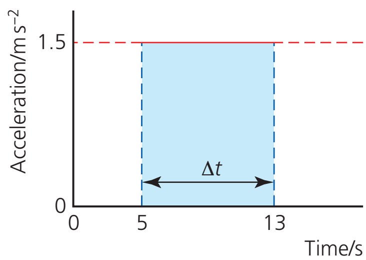
In this topic, we are mostly concerned with constant accelerations. The graphs in Figure A1.31 show five straight lines representing *constant* accelerations. A *changing* acceleration would be represented by a curved line on the graph.



■ **Figure A1.31** Graphs of constant acceleration

- Line A shows zero acceleration, constant velocity.
- Line B shows a constant positive acceleration (uniformly increasing velocity).
- Line C shows the constant negative acceleration (deceleration) of an object that is slowing down at a uniform rate.
- Line D shows a (linearly) increasing positive acceleration.
- Line E shows an object that is accelerating positively, but at a (linearly) decreasing rate.

Areas under acceleration–time graphs



■ **Figure A1.32** Calculating change of velocity from an acceleration–time graph

Figure A1.32 shows the constant acceleration of a moving car.

Using $a = \frac{\Delta v}{\Delta t}$, between the fifth and thirteenth seconds, the velocity of the car increased by:

$$\Delta v = a\Delta t = 1.5 \times (13.0 - 5.0) = 12\,\text{m}\,\text{s}^{-1}$$

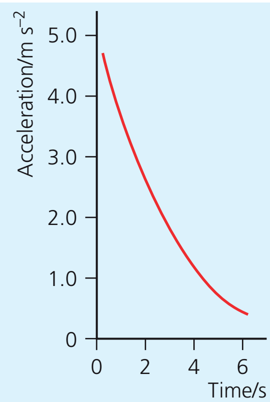
The change in velocity is numerically equal to the area under the line between $t = 5$ s and $t = 13$ s (the shaded area in Figure A1.32). This is always true, whatever the shape of the line.

The area under an acceleration–time graph is equal to the change of velocity.

17 Draw an acceleration–time graph for a car that starts from rest, accelerates at $2\,\text{m}\,\text{s}^{-2}$ for 5 s, then travels at constant velocity for 8 s, before decelerating uniformly to rest again in a further 2 s.

18 Figure A1.33 shows how the acceleration of a car changed during a 6 s interval. If the car was travelling at $2\,\text{m}\,\text{s}^{-1}$ after 1 s, estimate a suitable area under the graph and use it to determine the approximate speed of the car after another 5 s.

19 Sketch displacement–time, velocity–time and acceleration–time graphs for a bouncing ball that was dropped from rest.
Continue the sketches until the third time that the ball contacts the ground.



■ **Figure A1.33** Acceleration–time graph for an accelerating car

◆ **Calculus** Branch of mathematics which deals with continuous change.

◆ **Differentiate** Mathematically determine an equation for a rate of change.

TOK

Mathematics and the arts

- Why is mathematics so important in some areas of knowledge, particularly the natural sciences?

If you study Mathematics: Analysis and Approaches (SL or HL) or Mathematics: Applications and Interpretations (HL) you will explore how **calculus** is used to mathematically describe changing functions. The gradient of a function is found using the process of **differentiation** and the area under a curve is found using the process of integration. The mathematical procedures for calculus were developed by Isaac Newton and he first published his 'method of fluxions' as an appendix to his book *Opticks* in 1704. Newton is usually therefore credited with the 'invention' of calculus – although historians of science point to the earlier work of Gottfried Wilhelm Leibniz, published in 1684. Newton accused Leibniz of plagiarism, even though Leibniz's work was published first! In fact, it is Leibniz's notation that we still use today. So, who invented calculus?

◆ **Equations of motion**
Equations that can be used to make calculations about objects that are moving with uniform acceleration.

Equations of motion for uniformly accelerated motion

SYLLABUS CONTENT

- The **equations of motion** for solving problems with uniformly accelerated motion as given by:

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

$$v = u + at$$

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

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

The five quantities u, v, a, s and t are all that is needed to fully describe the motion of an object that is moving with *uniform* acceleration.

- u = velocity (speed) at the start of time t
- v = velocity (speed) at the end of time t
- a = acceleration (constant)
- s = displacement occurring in time t
- t = time taken for velocity (speed) to change from u to v and to travel a distance s.

If any three of the quantities are known, the other two can be calculated using the first two equations highlighted below.

If we know the initial velocity u and the uniform acceleration a of an object, then we can determine its final velocity v after a time t by rearranging the equation used to define acceleration:

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

This gives:

$$\mathbf{v = u + at}$$

If an object moving with velocity u accelerates uniformly to a velocity v, then its average velocity is:

$$\frac{(u + v)}{2}$$

Then, since distance = average velocity × time:

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

These two equations can be combined mathematically to give two further equations, shown below. These very useful equations do not involve any further physics theory, they just express the same physics principles in a different way.

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

$$\mathbf{v^2 = u^2 + 2as}$$

LINKING QUESTION

- How are the equations for rotational motion related to those for linear motion?

This question links to understandings in Topic A.4.

WORKED EXAMPLE A1.5

A Formula One racing car (see Figure A1.34) accelerates from rest at $18\,\mathrm{m\,s^{-2}}$.

■ **Figure A1.34** Formula One racing cars at the starting grid

a Calculate its speed after 3.0 s.

b Calculate how far it travels in this time.

c If it continues to accelerate at the same rate, determine its velocity after it has travelled 200 m from the start.

Answer

a $v = u + at = 0 + (18 \times 3.0) = 54\,\mathrm{m\,s^{-1}}$

b $s = \frac{(u + v)}{2}t = \frac{(0 + 54)}{2} \times 30 = 81\,\mathrm{m}$

But note that the distance can be calculated directly, without first calculating the final velocity, as follows:

$s = ut + \frac{1}{2}at^2 = (0 \times 3.0) + (0.5 \times 18 \times 3.0^2) = 81\,\mathrm{m}$

c $v^2 = u^2 + 2as = 0^2 + (2 \times 18 \times 200) = 7200$

$v = 85\,\mathrm{m\,s^{-1}}$

WORKED EXAMPLE A1.6

A train travelling at $50\,\mathrm{m\,s^{-1}}$ ($180\,\mathrm{km\,h^{-1}}$) needs to decelerate uniformly so that it stops at a station 2.0 kilometres away.

a Determine the necessary deceleration.

b Calculate the time needed to stop the train.

Answer

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

$0^2 = 50^2 + (2 \times a \times 2000)$

$a = -0.63\,\mathrm{m\,s^{-2}}$

b $v = u + at$

$0 = 50 + (-0.63) \times t$

$t = 80\,\mathrm{s}$

Alternatively, you could use $s = \frac{(u + v)}{2}t$

In the following questions, assume that all accelerations are uniform.

20 A ball rolling down a slope passes a point P with a velocity of $1.2\,\mathrm{m\,s^{-1}}$. A short time later it passes point Q with a velocity of $2.6\,\mathrm{m\,s^{-1}}$.

a What was its average velocity between P and Q?

b If it took 1.4 s to go from P to Q, determine the distance PQ.

c Calculate the acceleration of the ball.

21 An aircraft accelerates from rest along a runway and takes off with a velocity of $86.0\,\mathrm{m\,s^{-1}}$. Its acceleration during this time is $2.40\,\mathrm{m\,s^{-2}}$.

a Calculate the distance along the runway that the aircraft needs to travel before take-off.

b Predict how long after starting its acceleration the aircraft takes off.

22 An ocean-going cruiser can decelerate no quicker than $0.0032\,\mathrm{m\,s^{-2}}$.

■ **Figure A1.35** Ocean-going cruise liner

- **a** Determine the minimum distance needed to stop if the ship is travelling at 10 knots. (1 knot = $0.514\,\mathrm{m\,s^{-1}}$)
- **b** How much time does this deceleration require?

23 An advertisement for a new car states that it can travel 100 m from rest in 8.2 s.

- **a** Discuss why the car manufacturers express the acceleration in this way (or the time needed to reach a certain speed).
- **b** Calculate the average acceleration.
- **c** Calculate the velocity of the car after this time.

24 A car travelling at a constant velocity of $21\,\mathrm{m\,s^{-1}}$ (faster than the speed limit of $50\,\mathrm{km\,h^{-1}}$) passes a stationary police car. The police car accelerates after the other car at $4.0\,\mathrm{m\,s^{-2}}$ for 8.0 s and then continues with the same velocity until it overtakes the other car.

- **a** When did the two cars have the same velocity?
- **b** Determine if the police car has overtaken the other car after 10 s.
- **c** By equating two equations for the same distance at the same time, determine exactly when the police car overtakes the other car.

25 A car brakes suddenly and stops 2.4 s later, after travelling a distance of 38 m.

- **a** Calculate its deceleration.
- **b** What was the velocity of the car before braking?

26 A spacecraft travelling at $8.00\,\mathrm{km\,s^{-1}}$ accelerates at $2.00 \times 10^{-3}\,\mathrm{m\,s^{-2}}$ for 100 hours.

- **a** How far does it travel during this acceleration?
- **b** What is its final velocity?

27 Combine the first two equations of motion (given on page 17) to derive the second two equations:

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

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

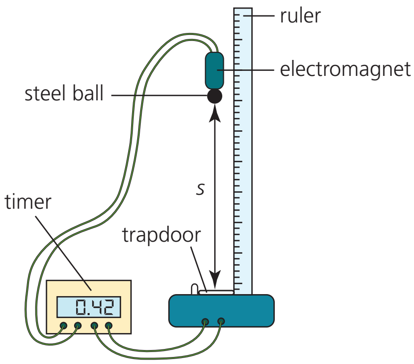
Acceleration due to gravity

The motions of objects through the air are common events and deserve special attention.

At the start, we will consider only objects that are moving vertically up, or down, under the effects of gravity only. That is, we will assume (to begin with) that **air resistance** has no significant effect.

When an object held up in the air is released from rest, it will accelerate downwards because of the force of gravity. Figure A1.36 shows a possible experimental arrangement that could be used to determine a value for this acceleration.

◆ **Air resistance** Resistive force opposing the motion of an object through air. A type of drag force.



■ **Figure A1.36** An experiment to measure the acceleration due to gravity

Inquiry 2: Collecting and processing data

Collecting data

Figure A1.36 shows how the time for a steel ball to fall a certain distance can be determined experimentally.

Describe how this apparatus can be used to collect and record sufficient, relevant quantitative data which will enable an accurate value for the acceleration of free fall to be determined from a suitable graph.

In the absence of air resistance, all objects (close to the Earth's surface) fall towards the Earth with the same acceleration, $g = 9.8\,\mathrm{m\,s^{-2}}$

g is known as the **acceleration of free fall** due to gravity (sometimes called acceleration due to **free fall**).

◆ **Acceleration due to gravity, *g*** Acceleration of a mass falling freely towards Earth. On, or near the Earth's surface, $g = 9.8 \approx 10\,\mathrm{m\,s^{-2}}$. Also called **acceleration of free fall**.

◆ **Free fall** Motion through the air under the effects of gravity but without air resistance.

◆ **Negligible** Too small to be significant.

g is not a true constant. Its value varies very slightly at different locations around the world. Although, to 2 significant figures (9.8) it has the same value everywhere on the Earth's surface. A convenient value of $g = 10\,\mathrm{m\,s^{-2}}$ is commonly used in introductory physics courses.

The acceleration of free fall (*g*) reduces with distance from the Earth. (For example, at a height of 100 km above the Earth's surface the value of *g* is $9.5\,\mathrm{m\,s^{-2}}$.) We will return to this subject in Topic D.1.

WORKED EXAMPLE A1.7

A ball is dropped vertically from a height of 18.3 m. Assuming that the acceleration of free fall is $9.81\,\mathrm{m\,s^{-2}}$ and air resistance is **negligible**, calculate:

- **a** its velocity after 1.70 s
- **b** its height after 1.70 s
- **c** its velocity when it hits the ground
- **d** the time for the ball to reach the ground.

Answer

a $v = u + at = 0 + (9.81 \times 1.70) = 16.7\,\mathrm{m\,s^{-1}}$

b $s = ut + \frac{1}{2}at^2 = 0 + \left(\frac{1}{2} \times 9.81 \times 1.70^2\right) = 14.2\,\mathrm{m}$

So, height above ground = (18.3 – 14.2) = 4.1 m

c $v^2 = u^2 + 2as = 0^2 + (2 \times 9.81 \times 18.3) = 359$

$v = 18.9\,\mathrm{m\,s^{-1}}$

d $v = u + at$

$18.9 = 0 + (9.81 \times t)$

$t = 1.93\,\mathrm{s}$

Tool 3: Mathematics

Appreciate when some effects can be neglected and why this is useful

When studying physics, you may be advised to make assumptions when answering numerical questions. For example: 'assume that air resistance is **negligible** / is insignificant'. It is possible that this is a true statement, for example, air resistance will have no noticeable effect on a solid rubber ball falling 50 cm to the ground. However, the usual reason for advising you to ignore an effect is to make the calculation simpler, and not go beyond what is required in your course.

Calculating the time for a table-tennis ball dropped 50 cm to the ground will result in an underestimate if air resistance is ignored, but the answer can be interpreted as a lower limit to the time taken, and you may be questioned on your understanding of that.

Other examples will be found in all topics. Examples include: assuming friction between surfaces is negligible (Topic A.2); assuming thermal energy losses are negligible (Topic B.1); assuming the internal resistance of a battery is negligible (Topic B.5).

Moving up and down

If gravity is the only force acting, all objects close to the Earth's surface have the same acceleration ($9.8\,m\,s^{-2}$ downwards), whatever their mass and whether they are moving down, moving up or moving sideways.

The velocity of an object moving freely vertically downwards will increase by $9.8\,m\,s^{-1}$ every second. The velocity of an object moving freely vertically upwards will decrease by $9.8\,m\,s^{-1}$ every second.

Top tip!

Displacement, velocity and acceleration are all vector quantities and the signs used for motions up and down can be confusing.

If displacement measured up from the ground is considered to be positive, then the acceleration due to gravity is always negative. Velocity upwards is positive, while velocity downwards is negative.

If displacement measured down from the highest point is considered to be positive, then the acceleration due to gravity is always positive. Velocity upwards is negative, while velocity downwards is positive.

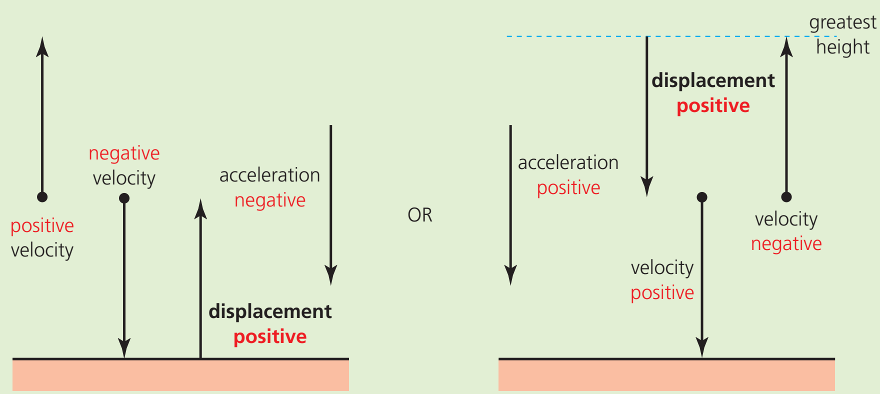


Figure A1.37 Directions of vectors

WORKED EXAMPLE A1.8

A ball is thrown vertically upwards and reaches a maximum height of 21.4 m. For the following questions, assume that $g = 9.81\,m\,s^{-2}$.

a Calculate the speed with which the ball was released.

b State any assumption that you made in answering **a**.

c Determine where the ball will be 3.05 s after it was released.

d Calculate its velocity at this time.

Answer

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

$0^2 = u^2 + (2 \times [-9.81] \times 21.4)$

$u^2 = 419.9$

$u = 20.5\,m\,s^{-1}$

In this example, the vector quantities directed upwards (u, v, s) are considered positive and the quantity directed downwards (a) is negative. The same answer would be obtained by reversing all the signs.

b It was assumed that there was no air resistance.

c $s = ut + \frac{1}{2}at^2 = (20.5 \times 3.05) + \left(\frac{1}{2} \times [-9.81] \times 3.05^2\right)$

$s = +16.9\,m$ (above the ground)

d $v = u + at = 20.5 + (-9.81 \times 3.05)$

$= -9.42\,m\,s^{-1}$ (moving downwards)

In the following questions, ignore the possible effects of air resistance.

Use $g = 9.81\,\mathrm{m\,s^{-2}}$.

28 Discuss possible reasons why the acceleration due to gravity is not exactly the same everywhere on or near the Earth's surface.

29 **a** How long does it take a stone dropped from rest from a height of 2.1 m to reach the ground?

b If the stone was thrown downwards with an initial velocity of $4.4\,\mathrm{m\,s^{-1}}$, calculate the speed with which it hits the ground.

c If the stone was thrown vertically upwards with an initial velocity of $4.4\,\mathrm{m\,s^{-1}}$, with what speed would it hit the ground?

30 A small rock is thrown vertically upwards with an initial velocity of $22\,\mathrm{m\,s^{-1}}$.

a Calculate when its velocity will be $10\,\mathrm{m\,s^{-1}}$.

b Explain why there are two possible answers to **a**.

31 A falling ball has a velocity of $12.7\,\mathrm{m\,s^{-1}}$ as it passes a window 4.81 m above the ground.
Predict when the ball will hit the ground.

32 A ball is thrown vertically upwards with a velocity of $18.5\,\mathrm{m\,s^{-1}}$ from a window that is 12.5 m above the ground.

a Determine when it will pass the same point moving down.

b With what velocity will it hit the ground?

c Calculate how far above the ground the ball was after exactly 2.00 s.

33 Two balls are dropped from rest from the same height. If the second ball is released 0.750 s after the first, and assuming they do not hit the ground, calculate the distance between the balls:

a 3.00 s after the second ball was dropped

b 2.00 s later.

34 A stone is dropped from rest from a height of 34 m. Another stone is thrown downwards 0.5 s later.
If they both hit the ground at the same time, show that the second stone was thrown with a velocity of $5.5\,\mathrm{m\,s^{-1}}$.

Projectile motion

SYLLABUS CONTENT

- The behaviour 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.

◆ **Projectile** An object that has been projected through the air and which then moves only under the action of the forces of gravity and air resistance.

◆ **Resolve (a vector)** To express a single vector as components (usually two components which are perpendicular to each other).

In our discussion of objects moving through the air, we have so far only considered motion vertically up or down. Now we will extend that work to cover objects moving in any direction. A **projectile** is an object that has been projected through the air (for example: fired, launched, thrown, kicked or hit) and which then moves only under the action of the force of gravity (and air resistance, if significant). A projectile has no ability to power or control its own motion.

Tool 3: Mathematics

Resolve vectors

This process occurs in several places during the course, but the most prominent examples are **resolving** velocities (as below) and forces.

Components of a projectile's velocity

The instantaneous velocity of a projectile at any time can conveniently be resolved into vertical and horizontal components, v_V and v_H, as shown in Figure A1.38.

Common mistake

When using these equations make sure that the angle θ is the angle between the velocity and the horizontal.

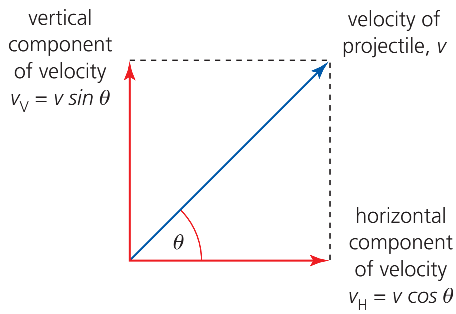


Figure A1.38 Vertical and horizontal components of velocity

Vertical and horizontal components of velocity, v:

$$v_V = v \sin\theta$$

$$v_H = v \cos\theta$$

WORKED EXAMPLE A1.9

A tennis player strikes the ball so that it leaves the racket with a velocity of $64.0\,\mathrm{m\,s^{-1}}$ at an angle of 6.0° below the horizontal. Calculate the vertical and horizontal components of this velocity.

Figure A1.39 A tennis player serving a ball

Answer

$v_H = v\cos\theta = 64.0 \times \cos 6.0 = 64\,\mathrm{m\,s^{-1}}$ (63.649... seen on calculator display)

$v_V = v\sin\theta = 64.0 \times \sin 6.0 = 6.7\,\mathrm{m\,s^{-1}}$ downwards

◆ **Stroboscope** Apparatus used for observing rapid motions. It produces regular flashes of light at an appropriate frequency chosen by the user.

◆ **Trajectory** Path followed by a projectile.

◆ **Parabolic** In the shape of a parabola. The trajectory of a projectile is parabolic in a gravitational field if air resistance is negligible.

◆ **Range (of a projectile)** Horizontal distance travelled before impact with the ground.

Components perpendicular to each other can be analysed separately

The vertical and horizontal components of velocity can be treated separately (independently) in calculations.

- Earlier in this topic, we stated that any object (close to the Earth's surface) which is affected only by gravity (no air resistance) will accelerate towards the Earth with an acceleration of $9.8\,\mathrm{m\,s^{-2}}$. This remains true even if the object is projected sideways (so that its velocity has a horizontal component).
- If there is no air resistance, the horizontal component of a projectile's velocity will remain constant (until it comes into contact with something else).

Figure A1.40 Parabolic trajectory of a bouncing ball

Figure A1.40 shows a **stroboscopic** picture of a bouncing ball. The time intervals between each image of the ball are all the same.

The horizontal separations of successive images of the ball are all the same because the horizontal component of velocity is constant. The vertical separations of successive images of the ball increase as the ball accelerates as it falls, and the separations decrease as the ball decelerates as it moves upwards after bouncing on the ground.

The path followed by a projectile (as seen in Figure A1.40) is called its **trajectory**. The typical shape of a freely moving projectile is **parabolic**. The horizontal distance covered is called the **range** of the projectile.

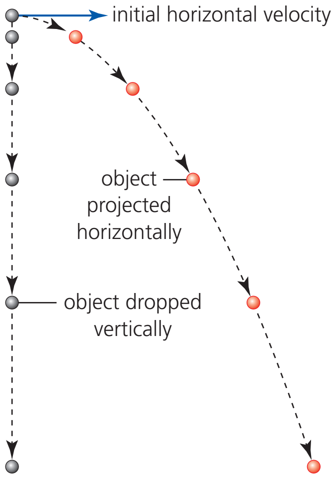


Figure A1.41 The parabolic trajectory of an object projected horizontally compared with an object dropped vertically

Figure A1.41 compares the trajectory of an object dropped vertically to the trajectory of an object projected horizontally at the same time. Note that both objects fall equal distances in the same time. This is true whatever the horizontal component of velocity (assuming negligible air resistance)

WORKED EXAMPLE A1.10

Object projected horizontally

A bullet was fired horizontally with a speed of 524 m s^{-1} from a height of 22.0 m above the ground. Calculate where it hit the ground. Assume that air resistance was negligible.

Answer

First, we need to calculate how long the bullet is in the air. We can do this by finding the time that the same bullet would have taken to fall to the ground if it had been dropped vertically from rest (so $u = 0$):

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

$$22.0 = 0 + (0.5 \times 9.81 \times t^2)$$

$$t = 2.12\,\text{s}$$

Without air resistance the bullet will continue to travel with the same horizontal component of velocity (524 m s^{-1}) until it hits the ground 2.12 s later. Therefore:

horizontal distance travelled = horizontal velocity × time

horizontal distance = 524 × 2.12 = 1.11 × 10^3 m (1.11 km)

ATL A1A: Thinking skills

Providing a reasoned argument to support conclusions

Figure A1.42 shows an experimental arrangement in which a steel ball can be projected horizontally from a table top.

Sketch a graph to show the pattern of results that you would expect to see when the range x was measured for different heights, h. Explain your reasoning.

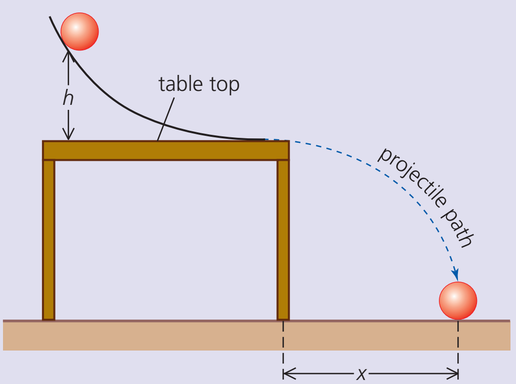


Figure A1.42 Investigating range, x, travelled by a projectile

WORKED EXAMPLE A1.11

Object projected at an angle to the horizontal

A stone was thrown upwards from a height 1.60 m above the ground with a speed of 18.0 m s^{-1} at an angle of 52.0° to the horizontal. Assuming that air resistance is negligible, calculate:

- **a** its maximum height
- **b** the vertical component of velocity when it hits the ground
- **c** the time taken to reach the ground
- **d** the horizontal distance to the point where it hits the ground
- **e** the velocity of **impact**.

◆ **Impact** Collision involving relatively large forces over a short time.

Top tip!

If we know the velocity and position of a projectile, we can always use its vertical component of velocity to determine:

- the time taken before it reaches its maximum height, and the time before it hits the ground
- the maximum height reached (assuming its velocity has an upwards component).

The horizontal component can then be used to determine the range.

Answer

First, we need to know the two components of the initial velocity:

$v_V = v \sin\theta = 18.0 \sin 52.0° = 14.2\,\text{m s}^{-1}$

$v_H = v \cos\theta = 18.0 \cos 52.0° = 11.1\,\text{m s}^{-1}$

a Using $v^2 = u^2 + 2as$ for the upwards vertical motion (with directions upwards considered to be positive), and remembering that at the maximum height $v = 0$, we get:

$0 = 14.2^2 + [2 \times (-9.81) \times s]$

$s = +10.3\,\text{m}$ above the point from which it was released; a total height of 11.9 m.

b Using $v^2 = u^2 + 2as$ for the complete motion gives:

$v^2 = 14.2^2 + [2 \times (-9.81) \times (-1.60)]$

$v = 15.27 = 15.3\,\text{m s}^{-1}$ downwards

c Using $v = u + at$ gives:

$-15.27 = 14.2 + (-9.81)t$

$t = 3.00\,\text{s}$

d Using $s = vt$ with the horizontal component of velocity gives:

$s = 11.1 \times 3.00 = 33.3\,\text{m}$

e Figure A1.43 illustrates the information we have so far, and the unknown angle, θ, and velocity, v_i.

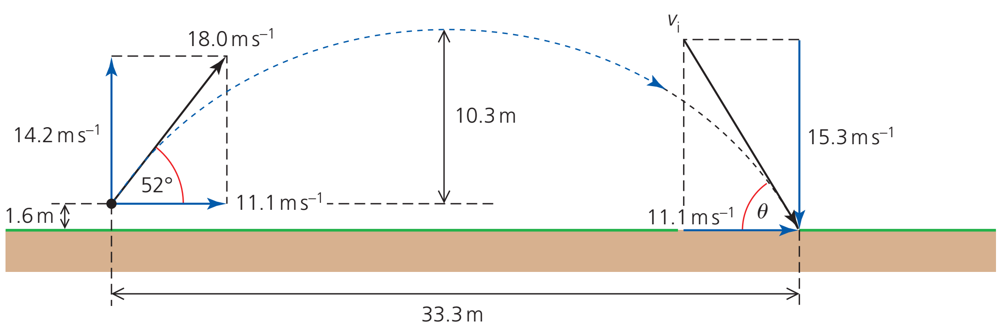


Figure A1.43 Object projected at an angle to the horizontal

From looking at the diagram (Figure A1.43), we can use Pythagoras's theorem to calculate the velocity of impact.

(velocity of impact)^2 = (horizontal component)^2 + (vertical component)^2

$v_i^2 = 11.1^2 + 15.3^2$

$v_i = 18.9\,\text{m s}^{-1}$

The angle of impact with the horizontal, θ, can be found using trigonometry:

$$\tan\theta = \frac{15.3}{11.1}$$

$\theta = 54.0°$

◆ **Imagination** Formation of new ideas that are not related to direct sense perception or experimental results.

◆ **Intuition** Immediate understanding, without reasoning.

◆ **Inspiration** Stimulation (usually to be creative).

TOK

The natural sciences

- What is the role of **imagination** and **intuition** in the creation of hypotheses in the natural sciences?

The independence of horizontal and vertical motion in projectile motion may seem unexpected and counterintuitive. It requires imagination (some would say genius) to propose ideas and theories which are contrary to accepted wisdom and 'common sense'. This is especially true in understanding the worlds of relativity and quantum physics, where relying on everyday experiences for **inspiration** is of little or no use.

It is worth remembering that many of the well-established concepts and theories of classical physics that are taught now in introductory physics lessons would have seemed improbable to many people at the time they were first proposed. For example, many people would say (incorrectly) that a force is needed to keep an object moving at constant speed (see Topic A.2).

Fluid resistance and terminal speed

So far, we have only considered projectile motion in which air resistance is negligible. We will now broaden the discussion.

◆ **Drag** Force(s) opposing motion through a fluid; sometimes called fluid resistance.

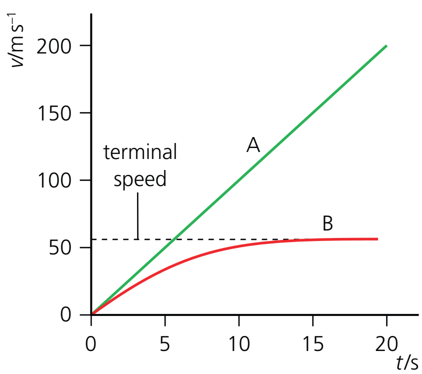
◆ **Fluid** Liquid or gas.

◆ **Fluid resistance (friction)** Force(s) opposing motion through a fluid; sometimes called drag.

As any object moves through air, the air is forced to move out of the path of the object. This causes a force opposing the motion called air resistance, also known as **drag**. Drag forces will oppose the motion of an object moving in any direction through any gas or liquid. (Gases and liquids are both described as **fluids** because they can flow.) Such forces opposing motion are generally described as **fluid resistance**.

Figure A1.44 gives a visual impression of air resistance. It shows the movement of air (marked by streamers) past a model of a car. (The picture was taken in a wind tunnel, in which moving air was directed towards the vehicle.)

Figure A1.44 Air flow over a clay aerodynamic model of a high-performance sports vehicle



■ **Figure A1.45** An example of a graph of velocity against time for an object falling under the effect of gravity, with (B) and without (A) air resistance

Figure A1.45 represents the motion of an object falling towards Earth.

Line A shows the motion without air resistance and with a constant acceleration of $9.8\,\text{m}\,\text{s}^{-2}$ (≈ 10). Line B shows the motion more realistically, with air resistance.

When any object first starts to fall, there is no air resistance. As the object falls faster, the air resistance increases, so that the rate of increase in velocity becomes less. This is shown in the Figure A1.45 by line B becoming less steep. Eventually the object reaches a constant, maximum speed known as the **terminal speed** or **terminal velocity** ('terminal' means final).

Objects falling through fluids (such as air) have a maximum speed, called terminal speed, which occurs when their acceleration has reduced to zero because of increasing fluid resistance (as their velocity increases).

◆ **Terminal speed (velocity)** The greatest downwards speed of a falling object that is experiencing resistive forces (for example, air resistance). It occurs when the object's weight is equal to the sum of resistive forces (+ upthrust).

The value of an object's terminal speed will depend on its cross-sectional area, shape and weight, as discussed in Topic A.2. The terminal speed of skydivers (Figure A1.46) is usually quoted at about $200\,\text{km}\,\text{h}^{-1}$ ($56\,\text{m}\,\text{s}^{-1}$).

Terminal speed also depends on the density of the air. In October 2012 Felix Baumgartner (Figure A1.47), an Austrian skydiver, reached a world record speed of $1358\,\text{km}\,\text{h}^{-1}$ by starting his jump from a height of about 39 km above the Earth's surface, where the density of air is about 250 times less than near the Earth's surface. In 2014 Alan Eustace completed a jump from greater altitude, but at $1323\,\text{km}\,\text{h}^{-1}$ he did not break Baumgartner's speed record.

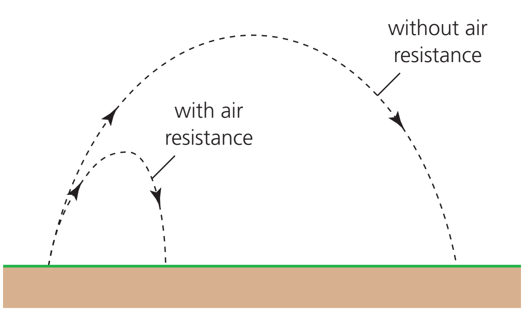
Top tip!

The concept of a top (terminal) speed can also be applied to the horizontal motion of vehicles, like trains, cars and aircraft. As they travel faster, increasing air resistance reduces their acceleration to zero.

■ **Figure A1.46** Skydivers at their terminal speed

■ **Figure A1.47** Felix Baumgartner about to jump from a height of 39 km

Effect of fluid (air) resistance on projectiles



■ **Figure A1.48** Effect of air resistance on the trajectory of a projectile

Without air resistance we assume that the horizontal component of a projectile's velocity is constant, but with air resistance it decreases. Without air resistance the vertical motion always has a downwards acceleration of $9.8\,\text{m}\,\text{s}^{-2}$, but with air resistance the acceleration will be reduced for falling objects and the deceleration increased for objects moving upwards.

Figure A1.48 shows typical trajectories with and without air resistance (for the same initial velocity).

Air resistance reduces the range of a projectile and its trajectory will not be parabolic.

Tool 2: Technology

Carry out image analysis and video analysis of motion

Video-capture technology is used in sports, such as tennis and soccer. Capturing the trajectory of a projectile on video allows us to analyse its motion frame-by-frame. For example, the cameras used in VAR in football usually capture 50 frames per second, so the motion of the projectile (the ball) can be observed at time intervals of 0.02 s.

◆ **Video analysis** Analysis of motion by freeze-frame or slow-motion video replay.

Explain how you could use **video analysis** of motion to investigate the motion of a shuttlecock in a game of badminton.

■ **Figure A1.49** Consider how video analysis could be used to investigate the motion of a badminton shuttlecock.

In the following questions, ignore the possible effects of air resistance. Use $g = 9.81\,\mathrm{m\,s^{-2}}$.

35 At an indoor rifle range, a bullet was fired horizontally at the centre of a target 36 m away. If the speed of the bullet was $310\,\mathrm{m\,s^{-1}}$, predict where the bullet will strike the target.

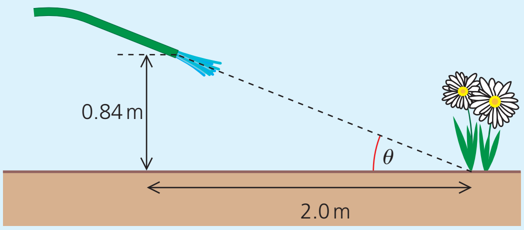
36 Repeat Worked example A1.11 for a stone thrown with a velocity of $26\,\mathrm{m\,s^{-1}}$ at an angle of 38° to the horizontal from a cliff top. The point of release was 33 m vertically above the sea.

37 It can be shown that the maximum theoretical range of a projectile occurs when it is projected at an angle of 45° to the ground (once again, ignoring the effects of air resistance). Calculate the maximum distance a golf ball will travel before hitting the ground if its initial velocity is $72\,\mathrm{m\,s^{-1}}$. (Because you need to assume that there is no air resistance, your answer should be much higher than the actual ranges achieved by top-class golfers. Research to determine the actual ranges achieved in competition golf.)

38 A jet of water from a hose is aimed directly at the base of a flower, as shown in Figure A1.50. The water emerges from the hose with a speed of $3.8\,\mathrm{m\,s^{-1}}$.

a Calculate the vertical and horizontal components of the initial velocity of the water.

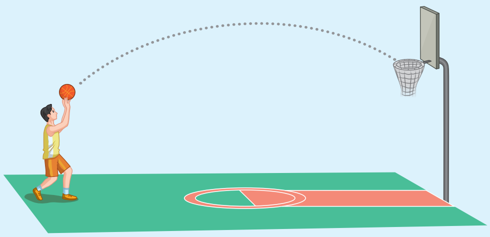
b How far away from the base of the plant does the water hit the ground?



■ **Figure A1.50** Water from a hose aimed at the base of a flower

39 If the maximum distance a man can throw a ball is 78 m, what is the minimum speed of release of the ball? (Assume that the ball lands at the same height from which it was thrown and that the greatest range for a given speed is when the angle is 45°.)

40 Figure A1.51 shows a player making a basketball shot.



■ **Figure A1.51** Basketball player making a shot

a In practice, air resistance can be considered negligible for a basketball. Suggest a reason why.

b Make a copy of the figure and add to it two other possible trajectories which will result in the ball arriving at the basket.

c Suggest which trajectory is best and explain your reasoning.

d Add to your drawing a possible trajectory that would enable a light-weight sponge ball to reach the basket.

Nature of science: Models

The motions of all projectiles are affected – often considerably – by air resistance. But the mathematics we have used to make predictions has assumed that air resistance is negligible. This is a recurring theme in physics: when theories are first developed, or when you are first introduced to a topic, the ideas are simplified. A 'complete' understanding of projectile motion may be expected at university level, but the topic is important enough that you should be introduced to the basic ideas at an earlier age.

In Worked example A1.10, the calculated answer predicts that a bullet will travel 1.1 km before striking the ground, although we should stress that this 'assumes that there is no air resistance'. In reality, it should be well understood that air resistance cannot be ignored, and the bullet will not travel as far as calculated. This should not suggest that the calculation was not useful.

As your knowledge and experience increase, mathematical theories of projectile motion can be expanded to include the effects of air resistance – but this is beyond the limits of the IB Course. Similar comments can be applied to all areas of physics. This simplifying approach to gaining knowledge is not unique to physics but it is, perhaps, most obvious in the sciences.

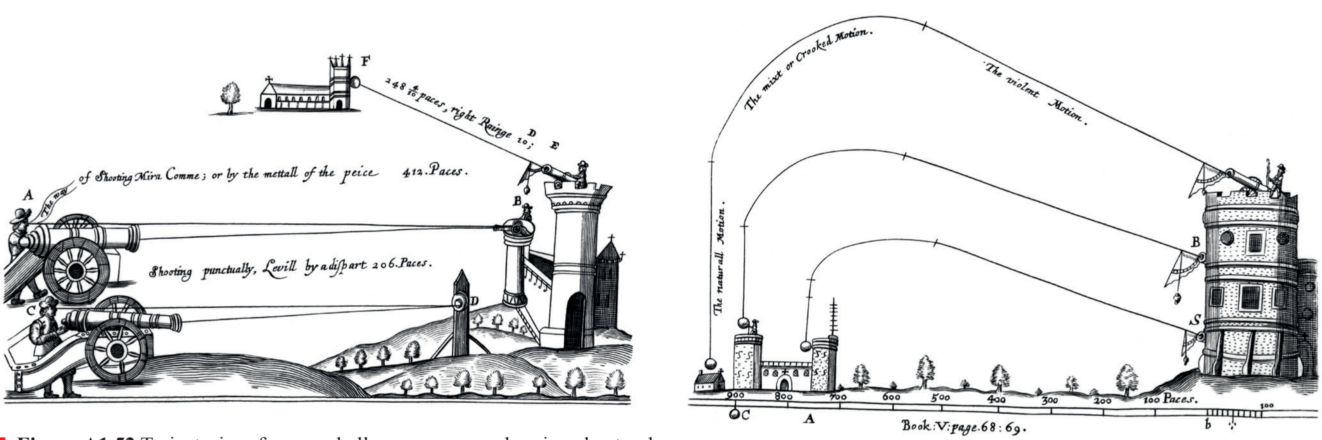
LINKING QUESTION

- How does the motion of an object change within a gravitational field?

This question links to understandings in Topics A.3 and D.1.

Ballistics

The study of the use of projectiles is known as ballistics. Because of its close links to hunting and fighting, this is an area of science with a long history, going all the way back to spears, and bows and arrows. Figure A1.52 shows a common medieval misconception about the motion of cannon balls: they were thought to travel straight until they ran out of energy.

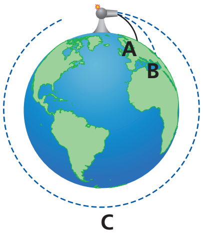


■ **Figure A1.52** Trajectories of cannon balls were commonly misunderstood

Photographs taken in quick succession became useful in analysing many types of motion in the nineteenth century, but the trajectories of very rapidly moving projectiles were difficult to determine until they could be filmed or illuminated by lights flashing very quickly (stroboscopes). The photograph of the bullet from a gun shown in Figure A1.53 required high technology, such as a very high-speed flash and very sensitive image recorders, in order to 'freeze' the projectile (bullet) in its rapid motion (more than 500 m s^{-1}).

◆ **Thought experiment** An experiment that is carried out in the mind, rather than actually being done, normally because it is otherwise impossible.

■ **Figure A1.53** A bullet 'frozen' by high-speed photography



■ **Figure A1.54** Newton's cannonball thought experiment

'Newton's cannonball' is a famous **thought experiment** concerning projectiles, in which Newton imagined what would happen to a cannonball fired (projected) horizontally at various very high speeds from the top of a very high mountain (in the absence of air resistance). See Figure A1.54.

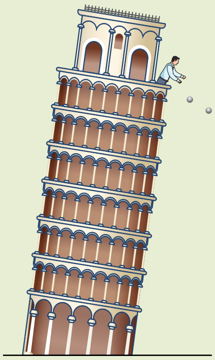
The balls labelled A and B will follow parabolic paths to the Earth's surface. B has a greater range than A because it was fired with greater velocity. Cannonball C has exactly the correct velocity that it never falls back to the Earth's surface and never moves further away from the Earth. (The required velocity would be about 7 km s^{-1}, but remember that we are assuming that there is no air resistance.) These ideas are developed further in Topic D.1.

Nature of science: Models

In a thought experiment, we use our imagination to answer scientific 'what if…?' type questions. Known principles or a possible theory are applied to a precise scenario, and the consequences thought through in detail. Usually, but not always, it would not be possible to actually carry out the experiment.

At the time of 'Newton's cannonball' thought experiment (published in 1728) it would have been impossible to make any object move at 7 km s^{-1} and, even if that had been possible, air resistance would have quickly reduced its speed. Nevertheless, the thought processes involved advanced understanding and led to ideas of satellite motion. The first satellite to orbit the Earth was the Russian Sputnik 1 in 1957, which had a maximum speed of about 8 km s^{-1} and avoided air resistance by being above most of the Earth's atmosphere.

Another (possible) thought experiment connected to this topic, and involving an assumption of no air resistance, is the dropping of two spheres of different masses from the same height on the Tower of Pisa. See Figure A1.55. Most historians doubt if there was an actual experiment at the Tower of Pisa that confirmed Galileo's theory that both masses would fall at the same rate.



■ **Figure A1.55** Galileo's famous experiment to demonstrate acceleration due to gravity

Two further famous thought experiments in physics are *Maxwell's demon* and *Schrödinger's cat*. Research online to find out how these thought experiments prompted new hypotheses and theories in physics.

A.2 Forces and momentum

Guiding questions

- How can we represent the forces acting on a system both visually and algebraically?
- How can Newton's laws be modelled mathematically?
- How can knowledge of forces and momentum be used to predict the behaviour of interacting bodies?

The nature of force

◆ **Interaction** Any event in which two or more objects exert forces on each other.

◆ **Newton, N** Derived SI unit of force. $1\,N = 1\,kg\,m\,s^{-2}$.

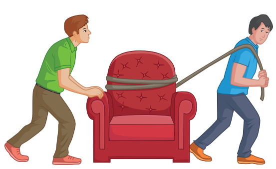
SYLLABUS CONTENT

▶ Forces as interactions between bodies.

In everyday life we may describe a force as a push or a pull but, more generally, a force can be considered to be *any* type of **interaction** / influence on an object which will tend to make it start moving or change its motion if it is already moving (assuming that the force is unopposed). Many forces do not cause changes of motion, simply because the objects on which they are acting are not able to move freely. Forces also change the shapes of objects.

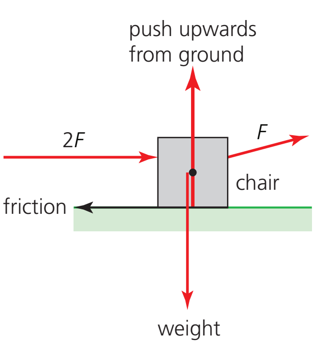
Scientists refer to forces 'acting' on objects, 'exerting' forces on objects and 'applying' forces to objects. If objects 'interact', this means there are forces between them.

The size of a force is measured in the SI unit **newton**, **N**. The direction in which a force acts on an object is important:



■ **Figure A2.1** Pushing and pulling a chair

Forces, F, are vector quantities and are represented in drawings by arrows of scaled length, direction and point of application. All forces should be labelled with commonly accepted symbols, or names.



■ **Figure A2.2** Representing the forces in Figure A2.1

(The vectors displacement, velocity and acceleration were introduced in Topic A.1.)

Most situations, such as the two boys moving a chair in Figure A2.1, involve several forces, not just the obvious forces arising from the boys' actions.

Figure A2.2 shows all the forces acting on the chair. These include the weight of the chair, the friction opposing its movement and the push upwards from the floor which is supporting the chair. The boy on the left is pushing the chair with a force which is twice the size of the force, F, that the boy on the right is using.

We will return to force diagrams later, but first we need to identify and explain different types of force.

Different types of force

In general, we can classify all forces as one of two kinds.

- Forces that involve physical contact. Examples include everyday pushes and pulls, friction and air resistance.

◆ **Mass** A measure of an object's resistance to a change of motion (inertia).

◆ **Kilogramme, kg** SI unit of mass (fundamental).

◆ **Weight, F_g** Gravitational force acting on a mass. $F_g = mg$.

◆ **Gravitational field strength, g** The gravitational force per unit mass (that would be experienced by a small test mass placed at that point). $g = F_g/m$ (SI unit: $N\,kg^{-1}$). Numerically equal to the acceleration due to gravity.

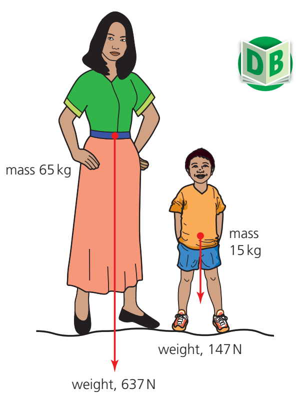


Figure A2.3 Weight acts downwards from the centre of mass

◆ **Centre of mass** Average position of all the mass of an object. The mass of an object is distributed evenly either side of any plane through its centre of mass.

- Forces that act 'at a distance' across empty space. Examples include magnetic forces and the force of gravity. These forces are more difficult to understand and can be described as 'field forces'.

We will now explore some important types of force in greater detail.

Weight

SYLLABUS CONTENT

▶ Gravitational force F_g as the weight of the body and calculated as given by: $F_g = mg$

The **mass** of an object may be considered to be a measure of the quantity of matter it contains. Mass has the SI unit **kilogramme**, kg. Mass does not change with location. This definition may seem rather vague, but this is because mass is such a fundamental concept it is difficult to explain in terms of other things. However, later in this topic we will provide an improved definition.

The **weight**, F_g, of a mass, m, is the gravitational force that pulls it towards the centre of the Earth (or any other planet). Weight and mass are connected by the simple relationship:

weight, $F_g = mg$

Where g is the weight : mass ratio, which is called the **gravitational field strength**. It has the units $N\,kg^{-1}$.

g is numerically equal to the acceleration due to gravity (see Topic A.1). An explanation is given later in this topic.

Clearly, in principle, the weight of an object is not constant, but varies with location (where the value of g changes). The value of g varies with a planet's or a moon's mass and radius, and with distance from the planet's centre of mass. For example, it has a value of $9.8\,N\,kg^{-1}$ on the Earth's surface, $1.6\,N\,kg^{-1}$ on the surface of the Moon and $3.7\,N\,kg^{-1}$ on Mars.

Weight is represented in a diagram by a vector arrow vertically downwards from the **centre of mass** of the object. See Figure A2.3. When an object is subjected to forces, it will behave as if all of its mass was at a single point: its centre of mass. (In a gravitational field, the same point is sometimes called its 'centre of gravity'.)

WORKED EXAMPLE A2.1

An astronaut has a mass of 58.6 kg. Calculate her weight using data from the preceding paragraphs:

a on the Earth's surface
b in a satellite 250 km above the surface ($g = 9.1\,N\,kg^{-1}$)
c on the surface of the Moon
d on the surface of Mars
e in 'deep space', a very long way from any planet or star.

Answer

a $F_g = mg = 58.6 \times 9.8 = 5.7 \times 10^2\,N$
b $F_g = mg = 58.6 \times 9.1 = 5.3 \times 10^2\,N$, which is only 7% lower than on the Earth's surface
c $F_g = mg = 58.6 \times 1.6 = 94\,N$
d $F_g = mg = 58.6 \times 3.7 = 217\,N$
e 0 N, truly weightless

1 Calculate the weight of the following objects on the surface of the Earth:
   a a car of mass 1250 kg
   b a new-born baby of mass 3240 g
   c one pin in a pile of 500 pins that has a total mass of 124 g.

2 It is said that 'an A380 airplane has a maximum take-off weight of 570 tonnes' (Figure A2.4). A tonne is the name given to a mass of 1000 kg.
   a What is the maximum weight of the aircraft (in newtons) during take off?
   b The aircraft can take a maximum of about 850 passengers. Estimate the total mass of all the passengers and crew.
   c What percentage is this of the total mass of the airplane on take off?
   d The maximum landing weight is '390 tonnes'. Suggest a reason why the aircraft needs to be less massive when landing than when taking off.
   e Calculate the difference in mass and explain where the 'missing' mass has gone.

■ **Figure A2.4** The Airbus A380 is the largest passenger airplane in the world

3 A mass of 50 kg would have a weight of 445 N on the planet Venus. What is the strength of the gravitational field there? Compare it with the value of *g* on Earth.

4 Consider two solid spheres made of the same metal. Sphere A has twice the radius of sphere B. Calculate the ratio of the two spheres' circumferences, surface areas, volumes, masses and weights.

◆ **Force meter** Instrument used to measure forces. Also sometimes called a newton meter or a spring balance.

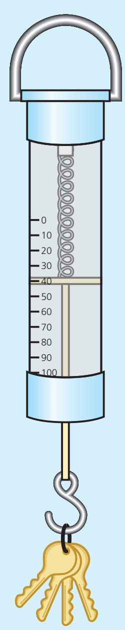
◆ **Calibrate** Put numbered divisions on a scale.

◆ **Weigh** Determine the weight of an object. In everyday use the word 'weighing' usually means quoting the result as the equivalent mass: 'my weight is 60 kg' actually means I have the weight of a 60 kg mass (about 590 N).

Tool 1: Experimental techniques

Understand how to accurately measure quantities to an appropriate level of precision: force, weight and mass

Forces are easily measured by the changes in length they produce when they squash or stretch a spring (or something similar). Such instruments are called **force meters** (also called *newton meters* or *spring balances*) – see Figure A2.5. In this type of instrument, the spring usually has a change of length proportional to the applied force. The length of the spring is shown on a linear scale, which can be **calibrated** (marked in newtons). The spring goes back to its original shape after it has measured the force.



■ **Figure A2.5** A spring balance force meter

Such instruments can be used for measuring forces acting in any direction, but they are also widely used for the measurement of the downwards force of weight. The other common way of measuring weight is with some kind of '*balance*' (scales). In an equal-arm balance, as shown in Figure A2.6, the beam will only balance if the two weights are equal. That is, the unknown weight equals the known weight. (Larger weights can be measured by positioning the pivot closer to the unknown weight and using the 'principle of moments' – mentioned in Topic A.4.)

Either of these methods can be used to determine (**weigh**) an unknown weight (N) and they rely on the force of gravity to do this, but such instruments may be calibrated to indicate mass (in kg or g) rather than weight. This is because we are usually more concerned with the quantity of something, rather than the effects of gravity on it. We usually assume that:

$$\text{mass (kg)} = \frac{\text{weight (N)}}{9.8}$$

anywhere on Earth because any variations in the acceleration due to gravity, *g*, are insignificant for most, but not all, purposes.

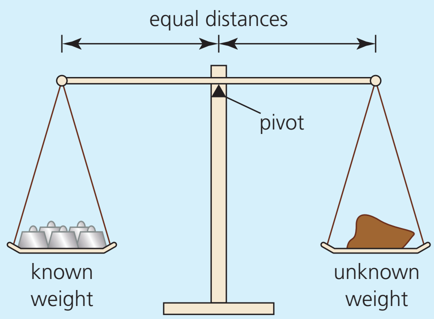


Figure A2.6 An equal-arm balance

Determining a mass without using its weight (gravity) is not so easy. Two ways we can do this are:

- If it is a solid and all the same material, its volume can be measured, then mass = volume × density (assuming that its density is known.)
- As we will see in Topic A.2, resultant force, mass and acceleration are connected by the equation $F = ma$, so that, if the acceleration produced by a known force can be measured, then the mass can be calculated.

Nature of science: Science as a shared endeavour

Science is a collaborative activity – scientists work together across the world to confirm (or dispute) findings by repeating experiments. Scientists review each other's work (**peer review**) to make sure that it is reliable before it is published. Communication is an essential part of science, and precision in communication is very important. Scientists must agree to use specific *terminology*, which is why scientific terminology sometimes differs from everyday use of the same words.

◆ **Peer review** Evaluation of scientific work by experts in the same field of study.

◆ **Tension (force)** Force that tries to stretch an object or material.

◆ **Compression (force)** Force that tries to squash an object or material.

◆ **Deformation** Change of shape.

◆ **Normal** Perpendicular to a surface.

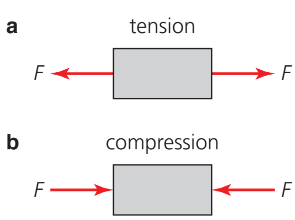


Figure A2.7 Object under **a** tension and **b** compression

Contact forces

Apart from obvious everyday pushes and pulls, the following terms should be understood:

Tension: pulling forces are acting tending to cause stretching.

Compression: forces are pushing inwards on an object (See Figure A2.7).

Both of these types of force will tend to change the shape of an object (**deformation**).

In the following sections we will discuss the following contact forces in more detail: normal forces, buoyancy forces, elastic restoring forces, surface friction and fluid friction.

Normal forces

SYLLABUS CONTENT

- Normal force F_N is the component of the contact force acting perpendicular to the surface that counteracts the body.

When two objects come in contact, they will exert forces on each other. This is because the particles in the surfaces resist getting closer together. A simple example is a book on a table, as shown in Figure A2.8. The book presses down on the table with its weight, and the table pushes up on the book with an equal force (so that the book is stationary). This force from the table is called a **normal** force, F_N. 'Normal' in this sense means that it is perpendicular to the surface.

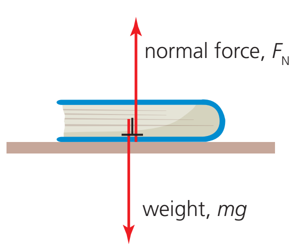


Figure A2.8 Normal force acting upwards on a book

If a force acts on a surface, the surface pushes back. The component of that force which is perpendicular to the surface is called a normal force.

Top tip!

Many students find the idea that solid and hard objects like walls, tables and floors can exert forces, difficult to comprehend, whereas forces from cushions, or trampolines, are easier to visualize and understand. Remember that solid materials will resist any deformation and push back, even if the change of shape is very, very small and not noticeable.

A normal force does not need to be vertical, nor equal to weight, as the two examples in Figure A2.9 illustrate.

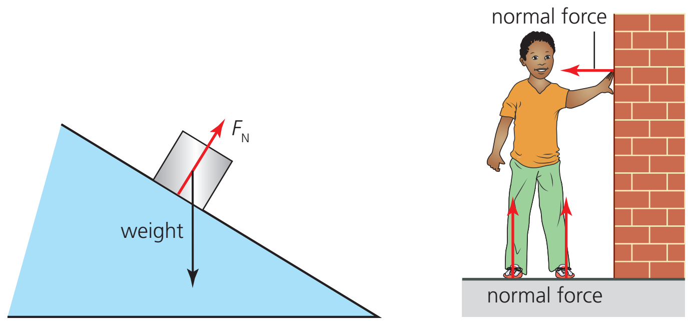


Figure A2.9 Other examples of normal forces

Buoyancy forces

SYLLABUS CONTENT

- Buoyancy force, F_b, acting on a body due to the displacement of the fluid as given by: $F_b = \rho Vg$, where V is the volume of fluid displaced.

We have discussed the normal contact forces which act upwards on objects placed on solid horizontal surfaces. Liquids also provide vertical forces upwards on objects placed in, or on them. Gases, too, provide some support, although it is often insignificant.

◆ **Buoyancy force** Vertical upwards force on an object placed in or on a fluid. Sometimes called **upthrust**.

◆ **Density** $\frac{\text{mass}}{\text{volume}}$.

Buoyancy is the ability of any fluid (liquid or gas) to provide a vertical upwards force on an object placed in, or on it. This force is sometimes called **upthrust**. (Buoyancy can be explained by considering the difference in fluid pressures on the upper and lower surfaces of the object. Pressure is explained in Topic B.3.)

The magnitude of an upthrust will be greater in fluids of greater **density**.

Density is a concept with which you may be familiar, although it is not introduced in this course until Topic B.1.

$$\text{density (SI unit: kg m}^{-3}\text{)} = \frac{\text{mass}}{\text{volume}} \qquad \rho = \frac{m}{V}$$

g cm^{-3} is also widely used as a unit for density. A density of $1000\,\text{kg m}^{-3}$ (the density of pure water at 0 °C) is equivalent to $1.000\,\text{g cm}^{-3}$. It is also useful to know that one litre (1l) of water has a volume of $1000\,\text{cm}^3$ and has a mass of 1.00 kg.

Figure A2.10 shows two forces acting on a rock immersed in water. Its weight is greater than the buoyancy force, so it is sinking.

■ **Figure A2.10** Forces on an object immersed in a fluid

◆ **Archimedes' principle** When an object is wholly or partially immersed in a fluid, it experiences buoyancy force equal to the weight of the fluid displaced.

This area of classical physics was first studied more than 2250 years ago in Syracuse, Italy by **Archimedes** (from Greece, who identified the following principle, which still bears his name):

When an object is wholly or partially immersed in a fluid, it experiences a buoyancy force, F_b, equal to the weight of the fluid displaced. Since weight = mg, and density, $\rho = \frac{m}{V}$:

$$F_b = \rho V g$$

TOK

The natural sciences

- What is the role of imagination in the natural sciences?

Myths, stories and science

The story of Archimedes' discovery of the principle of displacement is well known. The story is that Archimedes was asked by the king of Syracuse, Hiero, to check whether his goldsmith was trying to cheat him by mixing cheaper metals with the gold of a wreath in honour of the gods. Archimedes accepted the challenge, although was uncertain how to establish the true composition of the wreath crown. Reputedly, the idea came to him while sitting in the bath: if the wreath contained other metals, it would be less dense than gold, and as such would need to have a greater volume to achieve the same weight. Archimedes saw that he could test the composition of the wreath by measuring how much water was displaced by it, so measuring its volume and so allowing him to compare its density to that of gold. As the story relates, when Archimedes discovered this he shouted 'I have found it!' or 'Eureka!' in Greek and ran naked through the streets of Syracuse to give Hiero the news!

In fact, this story was never recorded by Archimedes himself and is found in the writings of a Roman architect from much later in the first century BCE called Vitruvius. Many who heard the story doubted it – including Galileo Galilei, who pointed out in his work 'The Little Balance' that Archimedes could have achieved a more precise result using a balance and the law of buoyancy he already knew. But the story persists, perhaps because it is a great way to visualize and so understand the concepts of displacement and density.

■ **Figure A2.11** A statue of Archimedes in a bathtub demonstrates the principle of the buoyant force. Located at Madatech, Israel's National Museum of Science, Technology and Space in Haifa

Consider: In what ways does the story of Archimedes resemble a thought experiment (see Topic A.1)? Do myths and stories serve always to obscure or confuse scientific truths? Can they sometimes enlighten us, too?

WORKED EXAMPLE A2.2

A piece of wood has a volume of $34\,cm^3$ and a mass of 29 g.

a Calculate its weight.

b Determine the volume of water that it will displace if it is completely under water.

c What buoyancy force will it experience while under water? (Assume density of water = $1000\,kg\,m^{-3}$.)

d What resultant force will act on the wood?

e State what will happen to the wood if it is free to move.

f Repeat a–e for the same piece of wood when it is surrounded by air (density $1.3\,kg\,m^{-3}$).

Answer

a weight = $mg = (29 \times 10^{-3}) \times 9.8 = 0.28\,N$ downwards

b $34\,cm^3$

c Weight of water displaced = $mg = V\rho g = (34 \times 10^{-6}) \times 1000 \times 9.8 = 0.33\,N$ upwards

d $0.33 - 0.28 = 0.05\,N$ upwards

e It will move (accelerate) up to the surface, where it will float.

f (see a–e below)

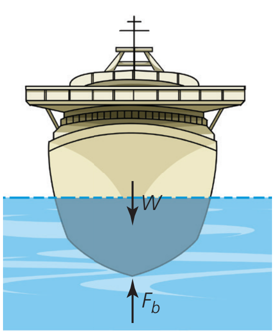
a Weight = 0.28 N downwards, as before

b $34\,cm^3$ as before

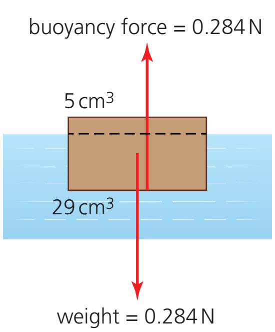
c Weight of air displaced = $mg = V\rho g = (34 \times 10^{-6}) \times 1.3 \times 9.8 = 4.3 \times 10^{-4}\,N$ upwards. Which is very small!

d $0.28 - (4.3 \times 10^{-4}) \approx 0.28\,N$ downwards. The buoyancy force in air has an insignificant effect on the wood.

e It will move (accelerate) down towards the Earth.



■ **Figure A2.12** A floating object



■ **Figure A2.13** Floating wood

Floating

An object placed on the surface of water (or any other liquid) will move lower until it displaces its own weight of water. See Figure A2.12. Then there will be no overall force acting on it, because the buoyancy force upwards (upthrust) will be equal to its weight downwards. If that is not possible, it will sink.

Continuing the numerical Worked example A2.2:

The wood has a weight of 0.28 N, so when floating it will displace water of this weight. Density of pure water = $1000\,kg\,m^{-3}$.

Weight = $0.28 = V\rho g = V \times 1000 \times 9.8$

$V = 2.9 \times 10^{-5}\,m^3$. That is, $29\,cm^3$. The wood will float with $29\,cm^3$ below the water surface and $5\,cm^3$ above the surface, as shown in Figure A2.13.

5 **a** Calculate the buoyancy force acting on a boy of mass 60 kg and volume 0.0590 m^3 (use $g = 9.81\ N\,kg^{-1}$)
  i in water of density 1000 $kg\,m^{-3}$
  ii in air of density 1.29 $kg\,m^{-3}$.
b Will the boy sink or float in water? Explain your answer.
c Suggest why he would float easily if he was in the Dead Sea. See Figure A2.14.

■ **Figure A2.14** Floating in the Dead Sea

d Calculate a value for the ratio: boy's weight / buoyancy force in air.

6 A wooden cube with a density of 880 $kg\,m^{-3}$ is floating on water (density 1000 $kg\,m^{-3}$). If the sides of the cube are 5.5 cm long and the cube is floating with a surface parallel to the water's surface, show that the depth of wood below the surface is 4.8 cm.

7 After the rock shown in Figure A2.10 begins to move downwards (sink) another force will act on it. State the name of that force.

8 Outline the reasons why a balloon filled with helium will rise (in air), while a balloon filled with air will fall.

9 Learning to scuba dive involves being able to remain 'neutrally buoyant', so that the diver stays at the same level under water. Explain why breathing in and out affects the buoyancy of a diver.

■ **Figure A2.15** How much of an iceberg is submerged?

10 It is commonly said that about 10% of an iceberg is above the surface of the sea (Figure A2.15). Use this figure to estimate a value for the density of sea ice. Assume the density of sea water is 1025 $kg\,m^{-3}$.

Elastic restoring forces

SYLLABUS CONTENT

▶ Elastic restoring force, F_H, following Hooke's law as given by: $F_H = -kx$, where k is the spring constant.

◆ **Elastic behaviour** A material regains its original shape after a force causing deformation has been removed.

◆ **Elastic limit** The maximum force and/or extension that a material, or spring, can sustain before it becomes permanently deformed.

When a force acts on an object it can change its shape: then we say that there is a deformation. Sometimes the deformation will be obvious, such as when someone sits on a sofa; sometimes the deformation will be too small to be seen, such as when we stand on the floor.

If an object returns to its original shape after the force has been removed, we say that the deformation was **elastic**. We hope and expect that most of the objects we use in everyday life behave elastically, because after we use them, we want them to return to the same condition as before their use. If they do not, we say that they have passed their **elastic limit**.

Common mistake

Rubber bands behave elastically and they are useful because they can stretch a lot and exert inwards forces on the objects they are wrapped around. Because of this behaviour, the word 'elastic' in common usage has also come to mean 'easy to stretch' – which is different from its true meaning in science. Most people would be surprised to learn that steel usually behaves elastically.

How deformation depends on force

How any object, or material, responds when forces act on them is obviously very important information when considering their use in practical situations.

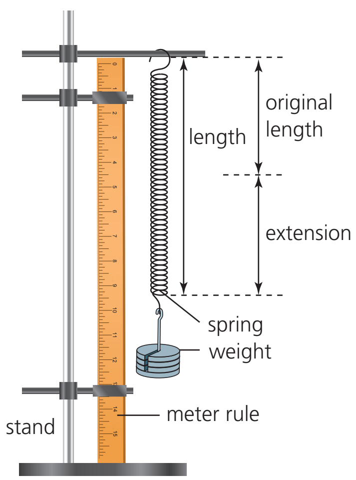
The deformation of a steel spring is a common starting investigation because it is easy to measure and it will usually stretch regularly and elastically (unless over-stretched). See Figure A2.16.

◆ **Extension** Displacement of the end of an object that is being stretched.

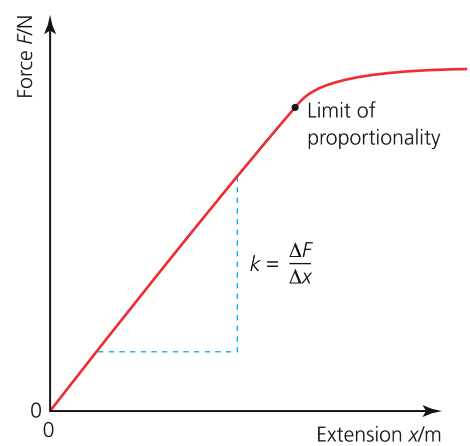
Figure A2.17 shows typical results. The weights provide the downwards force, *F*. In this case the deformation is called the **extension** of the spring, *x*, and it is usually plotted on the horizontal axis of graphs.

Top tip!

No material will behave elastically under all conditions. They all have their limits: *elastic limits*. For this reason, it is probably sensible not to describe a material as being 'elastic'. It is better to say that it behaved elastically under the conditions at that time.



■ **Figure A2.16** Steel spring investigation



■ **Figure A2.17** Results of stretching a steel spring

Most of the graph is a straight line passing through the origin. (The coils of the spring should not be touching each other at the beginning.) The conclusion is that the force, *F*, and the extension, *x*, are proportional to each other, up to a limit (as shown on the graph). The graph also shows that the spring gets easier to stretch after the limit of proportionality has been passed. For the linear part of the graph, starting at the origin: $F \propto x$.

The constant of proportionality is given the symbol *k*: $F = kx$.

◆ **Spring constant, *k*** The constant seen in **Hooke's law** that represents the stiffness of a spring (or other material).

k is a measure of the 'stiffness' of the spring and is commonly called the **spring constant** (or the *force constant*). It can be determined from the gradient of the graph:

$$k = \frac{\Delta F}{\Delta x}$$

k has the SI units $\mathrm{N\,m^{-1}}$. ($\mathrm{N\,cm^{-1}}$ is also widely used.)

Hooke's law

In the seventeenth century, Robert Hooke was famously the first to publish a quantitative study of springs. The physics law that describes his results is still used widely and bears his name:

Hooke's law for elastic stretching: restoring force, $\boldsymbol{F_H = -kx}$

◆ **Restoring force** Force acting in the opposite direction to displacement, returning an object to its equilibrium position.

This is essentially the same as the equation $F = kx$, but the symbol F_H has been used for the force (to show that it is Hooke's law stretching), and the force refers to the **restoring force** within the spring, tending to return it to its original shape – this force is equal in size but opposite in direction to the externally applied force from the weights. The negative sign has been included to indicate that the restoring force acts in the opposite direction to increasing extension.

LINKING QUESTION

- How does the application of a restoring force acting on a particle result in simple harmonic motion?

This question links to understandings in Topic C.1.

Nature of science: Models

Obeying the law

Sometimes, everyday language differs from scientific terminology (for example, when speaking about 'weight'). So, what are 'laws' in science? If the extension of a stretched material is proportional to the force, we describe it as 'obeying' Hooke's law. In what way is that similar / different to 'obeying' a legal law?

Archimedes' description of buoyancy forces is described as a 'principle'. How are scientific 'principles' different from scientific 'laws'?

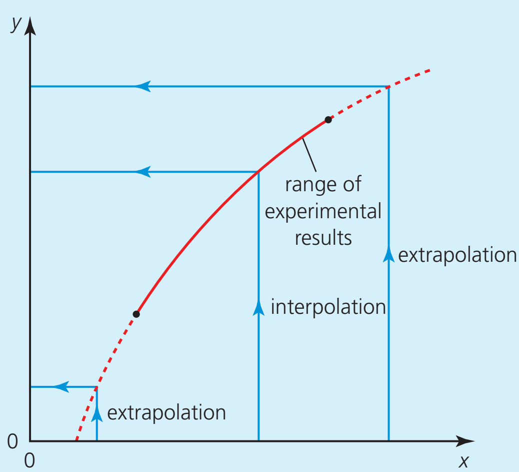
Research this online using search terms such as 'difference scientific principle and law'.

How might these concepts relate to theories and models in science?

Tool 3: Mathematics

Extrapolate and interpolate graphs

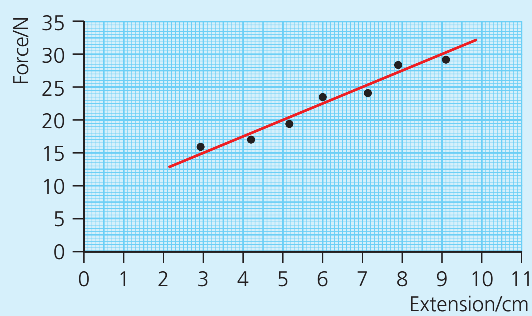
A curve of best fit is usually drawn to cover a specific range of measurements recorded in an experiment, as shown in Figure A2.18. The diagram indicates how values for y can be determined for a chosen values of x. If we want to predict other values within that range, we can usually do that with confidence. This is called **interpolation**.



■ **Figure A2.18** Interpolating and extrapolating to find values on the y-axis

If we want to predict what would happen outside the range of measurements (**extrapolation**) we need to extend the line of best fit. Lines are often extrapolated to see if they pass through the origin, or to find an intercept, as shown in Figure A2.18.

Predictions made by extrapolation should be treated with care, because it may be wrong to assume that the behaviour seen within the range of measurements also applies outside that range.



■ **Figure A2.19** F–x graph for stretching a spring

Force–extension graphs, such as seen in Figure A2.19, are an interesting example.

a Use the graph to determine values for extensions when the force was 25 N, 10 N and 35 N.
b Use the graph to determine a possible value for the intercept on the force axis, and explain what it represents.
c Comment on your answers.

◆ **Interpolate** Estimate a value within a known data range.

◆ **Extrapolate** Predict behaviour that it outside of the range of available data.

WORKED EXAMPLE A2.3

When a weight of 12.7 N was applied to a spring its length was 15.1 cm. When the force increased to 18.3 N, the length increased to 18.1 cm because the extension was proportional to the force.

a Determine the spring constant.

b Calculate the length of the spring when the force was 15.0 N.

c Explain why it is impossible to be sure what the length of the spring would be if the force was 25 N.

Answer

a $k = \frac{\Delta F}{\Delta x} = \frac{(18.3 - 12.7)}{(18.1 - 15.1)} = 1.87\,\mathrm{N\,cm^{-1}}$. Which is the same as $187\,\mathrm{N\,m^{-1}}$.

b Consider the extension from a length of 15.1 cm:

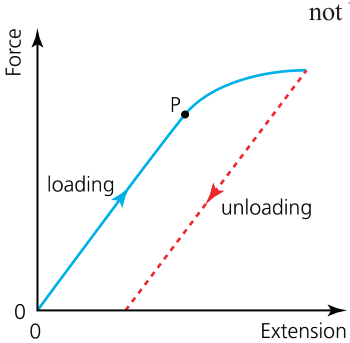
$$\Delta x = \frac{\Delta F}{k} = \frac{(15.0 - 12.7)}{1.87} = 1.23\text{ cm}$$

So that, length = 15.1 + 1.23 = 16.3 cm

c The spring may have passed its limit of proportionality.

The results shown in Figure A2.19 were probably taken as the spring was *loaded* (as the weight was increased). If the extension is measured as the weight is *reduced* the results will be similar, but only if the elastic limit has not been exceeded.

The elastic limit of the spring is not shown on the graph, but it is often assumed to be close to, or the same as, the limit of proportionality. In other words, when a spring stretches, such as its extension is proportional to the force, we assume that it is behaving elastically. That may or may not be true for other materials.



■ **Figure A2.20** Stretching a metal wire

Force–extension graphs and the concepts of elastic limits and 'spring constants' are not restricted to describing springs. They are widely used to represent the behaviour of many materials. Figure A2.20 shows a typical graph obtained when a metal wire is stretched and then the load is removed.

The force is proportional to the extension up until point P. During this time the particles in the metal are being pulled slightly further apart and we may assume that the metal is behaving elastically. But when the force is increased further, the wire begins to stretch more easily, the elastic limit is passed and a permanent deformation occurs. When the wire is unloaded the atoms move back closer together, so that the gradient of the graph is the same as for the loading graph, but the wire has a permanent deformation after all force has been removed.

11 A spring has a spring constant of $125\,\mathrm{N\,m^{-1}}$ and will become permanently deformed if its extension is greater than 20 cm.

a Assuming that it behaves elastically, what extension results from a tensile force of 18.0 N?

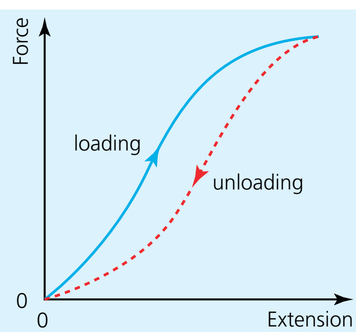
b What is the maximum force that should be used with this spring?

12 When a mass of 200 g was hung on a spring its length increased from 4.7 cm to 5.3 cm.

a Assuming that it obeyed Hooke's law, what was its spring constant?

b The spring behaves elastically if the force does not exceed 10 N. What is the length of the spring with that force?

13 Figure A2.21 shows a force–extension graph for a piece of rubber which was first loaded, then unloaded.



■ **Figure A2.21** Stretching rubber

a Does the rubber behave elastically? Explain your answer.

b Does the rubber obey Hooke's law under the circumstances shown by the graph? Explain your answer.

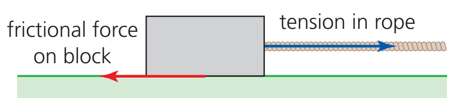
Surface friction

SYLLABUS CONTENT

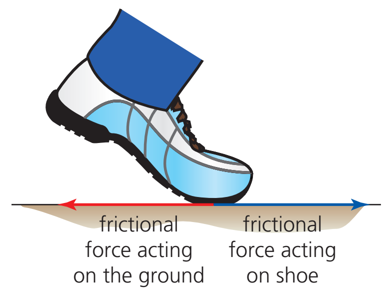
- Surface frictional force, F_f, acting in a direction parallel to the plane of contact between a body and a surface, on a stationary body as given by: $F_f \leq \mu_s F_N$, or a body in motion as given by: $F_f = \mu_d F_N$, where μ_s and μ_d are the coefficients of static and dynamic friction respectively.

◆ **Friction** Resistive forces opposing relative motion. Occurs between solid surfaces, but also with fluids. **Static friction** prevents movement, whereas **dynamic friction** occurs when there is already motion.

When we move an object over another surface (or try to move it), forces parallel to the surfaces will resist the movement. Collectively, these forces are known as surface **friction**. The causes of friction can be various, and it is well known that friction can often be difficult to analyse or predict. Figure A2.22 shows a typical simple frictional force diagram. (The frictional force acting on the ground is not shown.) The block is moving to the right and the frictional force is acting to the left.



■ **Figure A2.22** Frictional force on a block opposing its motion to the right

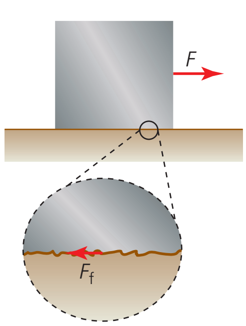


■ **Figure A2.23** We need friction to walk

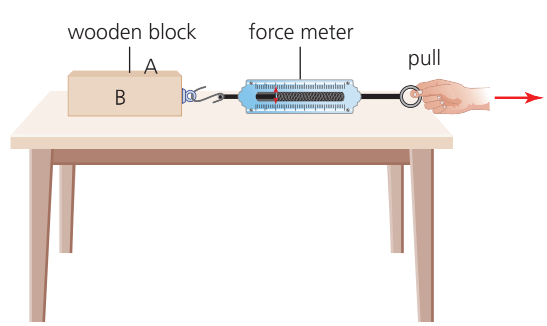
Friction is very useful: without friction we would not be able to walk. Similarly, a car's wheels would just spin on the same spot if there was no friction. Figure A2.23 explains why (the vertical forces are not shown). Because of friction, the shoe is able to push backwards, to the left, parallel to the ground, at the same time an equal frictional force pushes the shoe forward, to the right. (This is an example of Newton's third law of motion, which is discussed later in this topic.)

The roughness of both surfaces (see Figure A2.24) is certainly an important factor in producing friction: rougher surfaces generally increase friction, but this is not always true. For example, there may be considerable friction between very flat and smooth surfaces, like two sheets of glass. Friction can often be reduced by placing a lubricant, such as oil or water, between the surfaces.

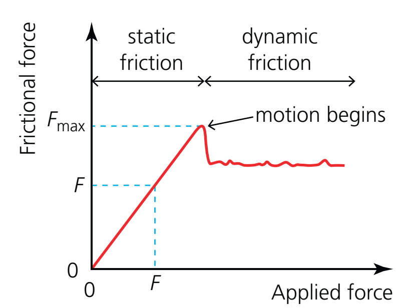
Figure A2.25 shows a basic laboratory investigation of the frictional forces between a wooden block and a horizontal table top.



■ **Figure A2.24** Even smooth surfaces have irregularities



■ **Figure A2.25** A simple experiment to measure frictional forces

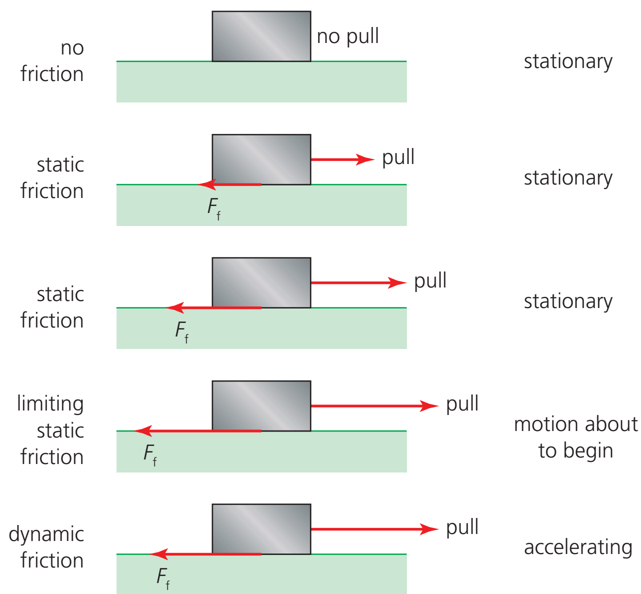


■ **Figure A2.26** Variation of friction with applied force

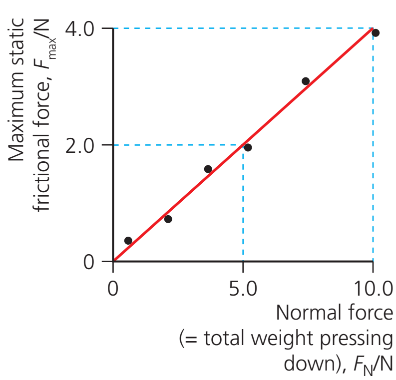
As the applied force (pull) is increased, the block will remain stationary until the force reaches a certain value, F_{max}. The block then starts to move, but after that, a steady force, which is less than F_{max}, will maintain a motion at constant speed. See Figure A2.26.

While the block is stationary (static) the force of friction adjusts, keeping equal to any applied force, but in the opposite direction. Under these circumstances the friction is called **static friction**. The size of the static friction force can increase from zero to a maximum value, F_{max}. Once an object is moving, the reduced friction is called **dynamic friction**, and its value is approximately constant at different speeds.

Figure A2.27 illustrates how frictional forces can change as a pulling force is increased.



■ **Figure A2.27** How frictional forces change as the force applied increases



■ **Figure A2.28** Typical variation of maximum static frictional force with normal force (a similar pattern of results will be obtained for dynamic friction)

The arrangement shown in Figure A2.25 can also be used to investigate how the *maximum* value of static friction depends on the force pushing the surfaces together: weights can be added on top of the block to increase the normal contact force, F_N. Figure A2.28 shows some typical results.

The graph shows that there is more static friction when there is a greater force pushing the surfaces together. In fact, frictional forces, F_f, are proportional to the normal contact forces, F_N. ($F_f \propto F_N$) The constant of proportionality equals the gradient of the graph and is called the **coefficient of friction**, μ (no units)

Just before motion begins: $F_f = F_{max} = \mu_s F_N$, where μ_s is the coefficient of static friction.

When there is no movement, static frictional force: $\boldsymbol{F_f \leq \mu_s F_N}$.

Table A2.1 shows some typical values for the coefficient of static friction between different materials.

◆ **Coefficient of friction, μ**
Constants used to represent the amount of friction between two different surfaces. Maybe static or dynamic.

Table A2.1 Approximate values for coefficients of static friction

Materials		Approximate coefficients of static friction, μ_s
steel	ice	0.03
ski	dry snow	0.04
Teflon™	steel	0.05
graphite	steel	0.1
wood	concrete	0.3
wood	metal	0.4
rubber tyre	grass	0.4
rubber tyre	road surface (wet)	0.5
glass	metal	0.6
rubber tyre	road surface (dry)	0.8
steel	steel	0.8
glass	glass	0.9
skin	metal	0.9

When there is movement, dynamic frictional force, $\boldsymbol{F}_f = \mu_d \boldsymbol{F}_N$, where μ_d is the coefficient of dynamic friction.

◆ **Constant** A number which is assumed to have the same numerical value under a specified range of circumstances.

◆ **Fundamental constants** Numbers which are assumed to have exactly the same numerical values under all circumstances and all times.

◆ **Coefficient** A multiplying constant placed before a variable, indicating a physical property.

Tool 3: Mathematics

Applying general mathematics: constants

A number which is assumed to be **constant** always has the same value under the specified circumstances. For example, the spring constant described earlier in this topic represents the properties of a spring, but only up to its limit of proportionality. In Topic A.1, the acceleration due to gravity was assumed to be constant at $9.8\,\text{m s}^{-2}$, but only if we limit precision to 2 significant figures and only apply it to situations close to the Earth's surface.

However, there are a few constants which are believed to have exactly the same value in all locations and for all time. They are called the **fundamental constants**, or universal constants. Two examples are the speed of light and the charge on an electron.

In general, a **coefficient** is a number (usually a constant) placed before a variable in an algebraic expression. For example, in the expression $5a - 2 = 8$, the number 5 is described as a coefficient. In physics, a coefficient is used to characterize a physical process under certain specified conditions.

We have seen that: dynamic frictional force, F_f = *coefficient* of dynamic friction × F_N

Another example (which is not in the IB course): when a metal rod is heated it expands so that increase in length for each 1 °C temperature rise
= *coefficient* of thermal expansion × original length.

Objects also experience friction when they move through liquids and gases (fluids). This is discussed in the next section.

ATL A2A: Research skills

Using search engines and libraries effectively

Tyres and road safety

Much of road safety is dependent on the nature of road surfaces and the tyres on vehicles. Friction between the road and a vehicle provides the forces needed for any change of velocity – speeding up, slowing down, and changing direction. Smooth tyres will usually have the most friction in dry conditions, but when the roads are wet, ridges and grooves in the tyres are needed to disperse the water (Figure A2.29).

To make sure that road surfaces produce enough friction, they cannot be allowed to become too smooth and they may need to be resurfaced every few years. This is especially important on sharp corners and hills. Anything that gets between the tyres and the road surface – for example, oil, water, soil, ice and snow – is likely to affect friction and may have a significant effect on road safety. Increasing the area of tyres on a vehicle will change the pressure underneath them and this may alter the nature of the contact between the surfaces. For example, a farm tractor may have a problem about sinking into soft ground, and such a situation is more complicated than simple friction between two surfaces. Vehicles that travel over soft ground need tyres with large areas to help avoid this problem.

Using a search engine, research online to find what materials are used in the construction of tyres and road surfaces to produce high coefficients of friction. Organize your data in a table, making sure to credit your sources using a recognized, standard method of referencing and citation.

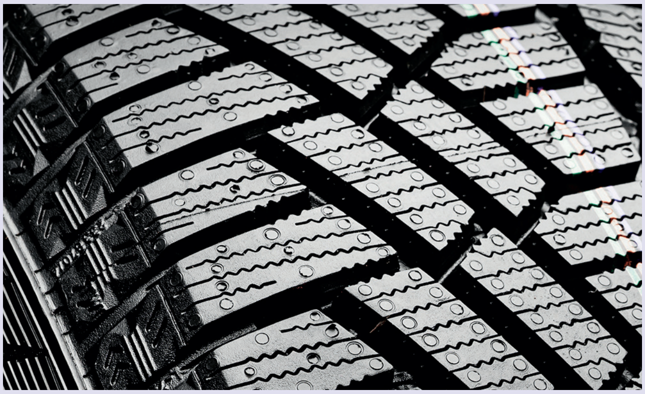


Figure A2.29 Tread on a car tyre

WORKED EXAMPLE A2.4

a Determine the coefficient of friction for the two surfaces represented in the graph shown in Figure A2.28.

b Assuming the results were obtained for apparatus like that shown in Figure A2.25, calculate the minimum force that would be needed to move a block of total mass:

- **i** 200 g
- **ii** 2000 g.
- **iii** Suggest why the answer to part **ii** is unreliable.

c Estimate a value for the dynamic frictional force acting on a mass of 200 g with the same apparatus:

- **i** for movement at 1.0 m s^{-1}
- **ii** for movement at 2.0 m s^{-1}.

Answer

a $\mu_s = \frac{F_{max}}{F_N} = \frac{4.0}{10.0} = 0.40$ (This is equal to the gradient of the graph.)

b **i** $F_f = \mu_s F_N = \mu_s mg = 0.40 \times 0.200 \times 9.8 = 0.78\,\text{N}$

ii $0.40 \times 2.000 \times 9.8 = 7.8\,\text{N}$

iii Because the answer is extrapolated from well outside the range of experimental results shown on the graph.

c **i** We would expect the dynamic frictional force to be a little less than the static frictional force, say about 0.6 N instead of 0.78 N.

ii The dynamic frictional force is usually assumed to be independent of speed, so the force would still be about 0.6 N at the greater speed.

Common mistake

Many students expect that, if the block in Figure A2.25 was rotated so that side B was in contact with the table (instead of the side parallel to A), there would be more friction because of the greater area of contact. However, the frictional force will remain (approximately) the same, because if, for example, the area doubles, the force acting down on each cm^2 will halve.

Use data from Table A2.1 where necessary.

14 If dynamic friction is 85% of the maximum static friction, estimate the frictional force acting on the steel skates of a 47 kg ice-skater moving across the ice.

15 A 54 kg wooden box is on a horizontal concrete floor.
- **a** Estimate the minimum force required to start it sliding sideways.
- **b** Suggest why your answer to part **a** may not be reliable.
- **c** If a force of 120 N keeps the box moving at a constant speed, what is the coefficient of dynamic friction?
- **d** What will happen to the box if the applied force increases above 120 N?

16
- **a** Predict the maximum frictional force possible between a dry road surface and each tyre of a stationary, 1500 kg four-wheeled family car.
- **b** Why will the force be less if the road is wet or icy?
- **c** Discuss how roads can be made safer under icy conditions.

17 Figure A2.30 shows the front of a Formula One racing car. Suggest how this design helps to increase the friction between the tyre and the race track.

Figure A2.30 Front of a Formula One racing car

18 A book of mass 720 g is being held in place next to a vertical wall as shown in Figure A2.31.
- **a** State the weight of the book.
- **b** Suggest an approximate value for the coefficient of static friction between the book and the wall.
- **c** Use your answer to part **b** to estimate the minimum force needed to keep the book stationary against the wall.

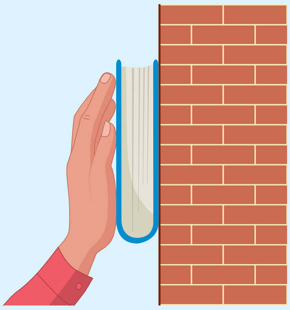


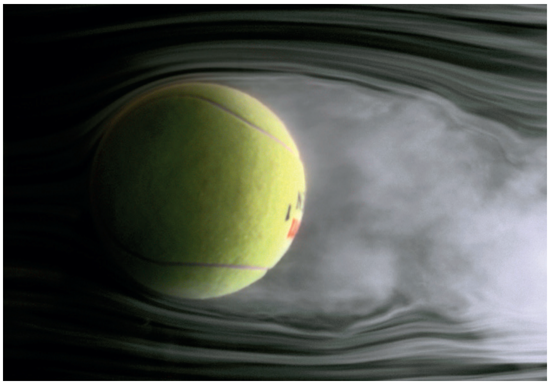
Figure A2.31 Book being held next to a vertical wall

Friction of objects with air and liquids

SYLLABUS COVERAGE

- 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.

Air resistance was briefly discussed in Topic A.1. The word *drag* is widely used to describe friction in air and liquids. We will use the symbol F_d for this type of force.



■ **Figure A2.32** Flow of air past a tennis ball in a wind tunnel.

There are a great number of applications of this subject, including moving vehicles, sports and falling objects. Wind tunnels are useful in the study of drag: the object is kept stationary while the speed of air flowing past it is varied. The flow of the air can be marked as shown in Figure A2.32.

Drag can be a complicated subject because the amount of drag experienced by an object moving through air, or a liquid, depends on many factors, including the object's size and shape, the nature of its surface, its speed v, and the nature of the fluid. Drag will also depend on the cross-sectional area of the object (perpendicular to its movement).

Typically, for small objects moving slowly $F_d \propto v$.

But for larger objects, moving more quickly, $F_d \propto v^2$.

Viscosity and Stokes's law

◆ **Viscosity** Resistance of a fluid to movement.

◆ **Viscous drag** The drag force acting on a moving object due to the viscosity of the fluid through which it is moving.

◆ **Turbulence** Flow of a fluid which is erratic and unpredictable.

◆ **Stokes's law** Equation for the viscous drag acting on a smooth, spherical object undergoing non-turbulent motion.

When an object moves through a fluid it has to push the fluid out of its path. A fluid's resistance to such movement is called its **viscosity**. Clearly, greater viscosity will tend to increase drag, and when this is the dominant factor, we refer to **viscous drag**.

Viscosity is given the symbol η (eta) and has the SI unit of Pa s (kg m^{-1} s^{-1}). Some typical values at 20 °C are given in Table A2.2. Viscosities of liquids can be very dependent on temperature.

■ **Table A2.2** Viscosities of some fluids

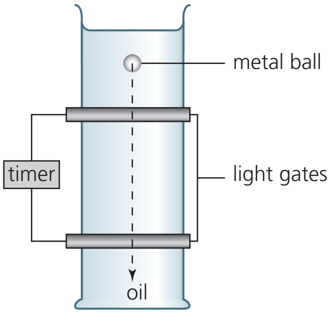
Fluid	**Viscosity η/Pa s**
'heavy' oil	0.7
'light' oil	0.1
water	1×10^{-3}
human blood	4×10^{-3}
gasoline (petrol)	6×10^{-4}
air	1.8×10^{-5}

In order to understand this further, we start by simplifying the situation, as is common in physics: by considering a smooth spherical object, of radius r, moving at a speed v, which is not great enough to cause **turbulence** (irregular movements) in the fluid.

Under these circumstances, the viscous drag, F_d, can be determined from the following equation (known as **Stokes's law**):

DB

viscous drag $\boldsymbol{F_d = 6\pi\eta r v}$



■ **Figure A2.33** Experiment to determine the viscosity of a liquid

Dropping small spheres through fluids is a widely used method for determining their viscosities and how they may depend on temperature. A method is shown in Figure A2.33, in which an electronic timer is started and stopped as the metal ball passes through the two light gates.

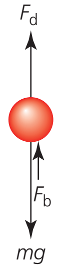
Inquiry 1: Exploring and designing

Designing

Look at the apparatus setup in Figure A2.33. Apply what you know about terminal speed (Topic A.1) and viscous fluid flow to design and explain a valid methodology for an experiment to obtain a single set of measurements. Include an explanation of:

1 why the metal ball is released such that it passes through some oil before reaching the first timing gate

2 why the tube should be as wide as possible.



■ **Figure A2.34** Forces on a sphere falling with terminal speed

If a sphere of mass m and radius r is moving with a constant terminal speed, v_t, then the upwards and downwards forces on it are balanced, as shown in Figure A2.34.

viscous drag, F_d + buoyancy force, F_b = weight, mg:

$$6\pi\eta rv + \rho Vg = mg$$

but:

$$V = \frac{4}{3}\pi r^3$$

so:

$$6\pi\eta rv + \frac{4}{3}\rho g\pi r^3 = mg$$

If the mass and radius of the sphere are measured and the terminal speed determined as shown in Figure A2.33, then this equation can be used to determine a value for the viscosity of the liquid, assuming that its density is known.

Inquiry 3: Concluding and evaluating

Evaluating

The experimental determination of a viscosity discussed above involved just one set of measurements and a calculation.

Explain improvements to increase the accuracy of the determination of the viscosity of a liquid by collecting sufficient data to enable a graph of the results to be drawn.

WORKED EXAMPLE A2.5

Calculate the force of viscous drag on a sphere of radius 1.0 mm moving at 1.0 cm s^{-1} through 'heavy' oil.

Answer

$F_d = 6\pi \times \eta \times r \times v = 6 \times 3.14 \times 0.7 \times (1.0 \times 10^{-3}) \times (1.0 \times 10^{-2}) = 1.3 \times 10^{-4}$ N

19 The air resistance acting on a car moving at 5.0 m s^{-1} was 120 N.
Assuming that this force was proportional to the speed squared, what was the air resistance when the car's speed increased to:
a 10 m s^{-1} **b** 15 m s^{-1}?

20 Show that the units of viscosity are Pa s.

21 Calculate the viscous drag force acting on a small metal sphere of radius 1.3 mm falling through oil of viscosity 0.43 Pa s at a speed of 7.6 cm s^{-1}.

22 A drop of water in a cloud had a mass of 0.52 g and radius of 0.50 mm (and volume of 0.52 mm^3).
a Assuming that the density of the surrounding air is 1.3 kg m^{-3}, calculate and compare the size of the three forces acting on the drop if it has just started to fall with a speed of 5.0 cm s^{-1}.
b Draw an annotated diagram to display your answers.
c Determine the subsequent movement of the drop.

23 In an experiment similar to that shown in Figure A2.33, a sphere of radius 8.9 mm and mass 3.1 g reached a terminal speed of 7.6 cm s^{-1} when falling through an oil of density 842 kg m^{-3}.
Determine a value for the viscosity of the liquid.

24 Use the internet to find out how the design of golf balls reduces drag forces in flight. Write a 100 word summary of your findings.

ATL A2B: Thinking skills

Evaluating and defending ethical positions

Air travel

Aircraft use a lot of fuel moving passengers and goods from place to place quickly, but we are all becoming more aware of the effects of planes on global warming and air pollution. Some people think that governments should put higher taxes on the use of planes to discourage people from using them too much. Improving railway systems, especially by operating trains at higher speeds, will also attract some passengers away from air travel. Of course, engineers try to make planes more efficient so that they use less fuel, but the laws of physics cannot be broken and jet engines, like all other *heat engines*, cannot be made much more efficient than they are already.

Planes will use a lower fuel if there is a lower air resistance acting on them. This can be achieved by designing planes with **streamlined** shapes, and also by flying at greater heights where the air is less dense. Flying more slowly than their maximum speed can also reduce the amount of fuel used for a particular trip, as it does with cars, but people generally want to spend as little time travelling as possible.

The pressure of the air outside an aircraft at its typical cruising height is far too low for the comfort and health of the passengers and crew, so the air pressure has to be increased inside the airplane, but this is still much lower than the air pressure near the Earth's surface. The difference in air pressure between the inside and outside of the aircraft would cause problems if the airplane had not been designed to withstand the extra forces.

Aircraft generally carry a large mass of fuel, and the weight of an aircraft decreases during a journey as the fuel is used up. The upwards force supporting the weight of an aircraft in flight comes from the air that it is flying through and will vary with the speed of the airplane and the density of the air. When the aircraft is lighter towards the end of its journey it can travel higher, where it will experience less air resistance.

Debate the issue in class. Break into groups. One group can represent the airline operators, another group can represent passengers, a third group can represent an environmental campaign group, while a fourth group could represent the government. In your groups, allocate roles for researchers and a spokesperson. Using the information above and your understanding of air resistance prepare a proposal from the point of view of your assigned group detailing different ways in which we can reduce the environmental impact of air travel.

To help your research and calculations, refer to the following guiding questions:

- How do airlines hope that in the future they can become 'carbon neutral'. What is 'SAF'?
- Find out how much fuel is used on a long-haul flight of, say, 12 hours.
- Compare your answer with the capacity of the fuel tank on an average sized car.
- On a short-haul flight it is often claimed that as much of 50% of an aircraft's fuel might be used for taxiing, taking off, climbing and landing, but on longer flights this can reduce to under 15%. Explain the difference.

◆ **Streamlined** Having a shape that reduces the drag forces acting on an object that is moving through a fluid.

◆ **Field (gravitational, electric or magnetic)** A region of space in which a mass (or a charge, or a current) experiences a force due to the presence of one or more other masses (charges, or currents – moving charges).

LINKING QUESTION

- How can knowledge of electrical and magnetic forces allow the prediction of changes to the motion of charged particles?

This question links to understandings in Topic D.3.

Field forces

SYLLABUS CONTENT

- 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

These three forces are very important in the study of physics but, apart from the gravitational force of weight, knowledge about them is not required in *this* topic.

These forces can act across empty space, without the need for any material in between. This can be difficult for the human mind to accept. One way of increasing our understanding is to develop the concept of force **fields** surrounding masses (gravitational fields), charges (electric fields) and magnets / electric currents (magnetic fields). Using this concept, we can give numerical values to points in space, for example, by stating that the gravitational field strength at the height of a particular satellite's orbit is 8.86 N kg^{-1}.

Free-body diagrams

SYLLABUS CONTENT

- Forces acting on a body can be represented in a free-body diagram.

Even the simplest of force diagrams can get confusing if all the forces are shown. To make the diagrams simpler we usually draw only one object and show only the forces acting on that one object. These drawings are called **free-body diagrams**. (Physicists use the words 'body' and 'object' interchangeably.) Some simple examples are shown in Figure A2.35.

◆ **Free-body diagram** Diagram showing all the forces acting on a single object, and no other forces.

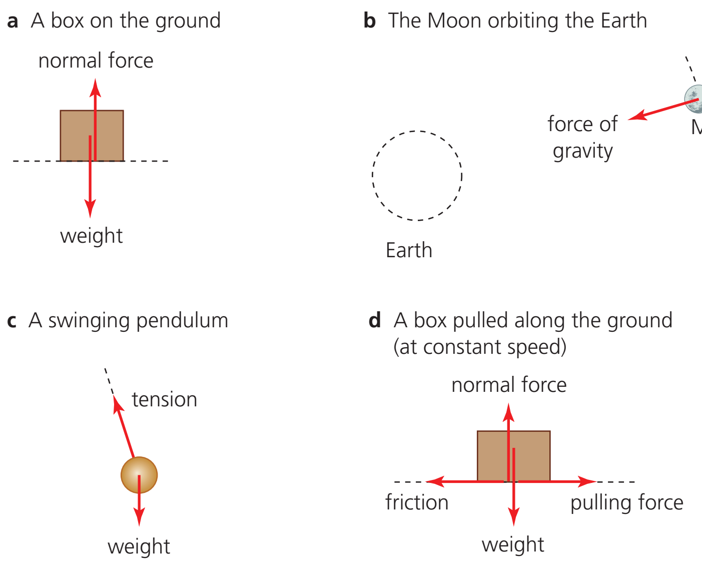


Figure A2.35 Free-body diagrams; the object has a solid outline and the forces are shown in red

The diagrams are often further simplified by representing the object as a small square, or circle, and considering it to be a **point particle / mass**.

◆ **Point particle, mass or charge** Theoretical concept used to simplify the discussion of forces acting on objects (especially in gravitational and electric fields).

Nature of science: Models

Point objects, particles and masses

A point particle is an idealized, simplified representation of any object, whatever its actual size and shape. As the name suggests, a point particle does not have any dimensions, or occupy any space. Typically, the 'point' will be located at the centre of mass of the object.

When the concept is used, we do not need to consider the complications and variations that are involved with extended objects. For example, if we consider an object as a point particle, all forces act through the same point and analysis can ignore any possible rotational effects caused by the forces acting on it.

Resultant forces and components

SYLLABUS CONTENT

- Free-body diagrams can be analysed to find the resultant force on a system.

Tool 3: Mathematics

Add and subtract vectors in the same plane

Vector addition is an important mathematical skill that occurs in several places in the IB Physics course, but the addition of forces is the most common application. Figure A2.36 shows an example of how to find the resultant of two force vectors.

A **resultant force** is represented in size and direction by the diagonal of the parallelogram (or rectangle) which has the two original force vectors as adjacent sides.

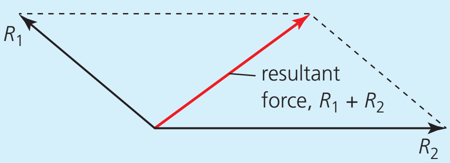


Figure A2.36 Adding two forces to determine a resultant

◆ **Resultant force** The vector sum of the forces acting on an object, sometimes called the unbalanced or net force.

◆ **Resultant** The single vector that has the same effect as the combination of two or more separate vectors.

◆ **Components (of a vector)** Any single vector can be considered as having the same effect as two parts (components) perpendicular to each other.

◆ **Inclined plane** Flat surface at an angle to the horizontal (but not perpendicular). A simple device that can be used to reduce the force needed to raise a load; sometimes called a ramp.

Tool 3: Mathematics

Resolve vectors

As we have seen, two forces can be combined to determine a single **resultant**. The 'opposite' process is very useful: a single force, F, can be considered as being equivalent to two smaller forces at right angles to each other. The two separate forces are called **components**.

This process is called resolving a force into two components. It can be used when the original force is not acting in a direction which is convenient for analysis. Because the two components are perpendicular to each other their effects can be considered separately. Figure A2.37 shows how a force can be resolved into two perpendicular components.

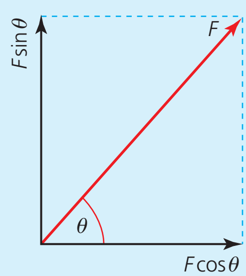


Figure A2.37 Force, F, resolved into two components

Any force, F, can be resolved into two independent components which are perpendicular to each other:

$F\sin\theta$ and $F\cos\theta$

WORKED EXAMPLE A2.6

a Draw a free-body diagram for an object which is stationary on a slope (**inclined plane**) which makes an angle of 35° with the horizontal.

b The object has a mass of 12.7 kg and just begins to slide down the slope if the angle is 35°. Using $g = 9.81\,\text{N kg}^{-1}$, calculate the component of the weight for this angle:

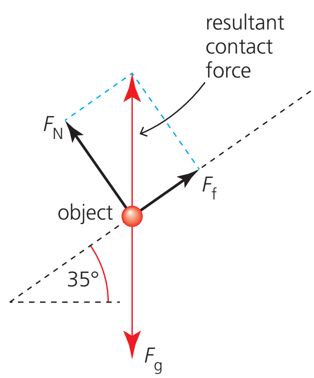
- **i** down the slope
- **ii** perpendicular into the slope.

c State values of the frictional force and the normal force acting on the object.

d Determine the coefficient of static friction in this situation.

Answer

a See Figure A2.38, which represents the object as a point. The resultant contact force from the slope on the object must be equal and opposite to the weight, F_g. The contact force can be considered as the combination of two perpendicular components: F_N perpendicular to the slope, and F_f, the frictional force stopping the object from sliding down the slope.



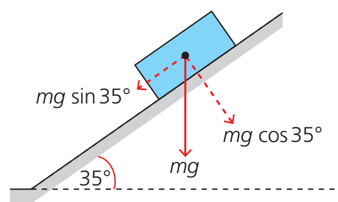
■ **Figure A2.38** Free-body diagram for an object on a slope

Sometimes it is preferred to represent the object as more than just a point. See Figure A2.39 for an example. However, this may cause confusion about exactly where the forces act.

b See Figure A2.39.

Component down slope $mg \sin 35° = 12.7 \times 9.81 \times 0.574 = 71.5\,\text{N}$

Component into slope $= mg \cos 35° = 12.7 \times 9.81 \times 0.819 = 102\,\text{N}$



■ **Figure A2.39** Components of weight

c Frictional force equals component down the slope, but in the opposite direction = 71.5 N up the slope.

Normal force equals component into the slope, but in the opposite direction = 102 N upwards.

d $F_f = \mu_s F_N$

$$\mu_s = \frac{F_f}{F_N} = \frac{71.5}{102} = 0.70 \text{ (which is equal to } \tan\theta)$$

25 Draw fully labelled free-body diagrams for:

- **a** a car moving horizontally with a constant velocity
- **b** an aircraft moving horizontally at constant velocity
- **c** a boat decelerating after the engine has been switched off
- **d** a car accelerating up a hill.

26 A wooden block of mass 2.7 kg rests on a slope which is inclined at 22° to the horizontal.

- **a** Make calculations which will enable you to draw a free-body diagram, similar to Figure A2.38, but giving numerical values for the forces.
- **b** If the angle is increased, the block will slide down the slope. Calculate the coefficient of friction.
- **c** State whether your answer to part **b** is for static or kinetic friction.

27 A pendulum on the end of a string has a mass of 158 g.

- **a** Draw a free-body diagram representing the situation when the string is making an angle of 20° to the vertical.
- **b** By adding components of weight to your diagram, show that the tension in the string is 1.5 N.
- **c** What effect does the other component ($mg \sin\theta$) have on the pendulum?
- **d** Discuss how the tension in the string changes while the pendulum is swinging from side to side.

28 Parallel forces of 1 N, 2 N and 3 N can act on an object at the same time. State the values of all the possible resultant forces.

29 Calculate the resultant force (size and direction) of 4.7 N and 5.9 N which are perpendicular to each other and acting away from a point mass.

30 Show that a mass on an inclined plane will just begin to slip down the slope when the tangent of the angle to the horizontal equals the coefficient of static friction.

31 Determine by scale drawing or calculation the size and direction of the resultant force acting on the hook shown in Figure A2.40.

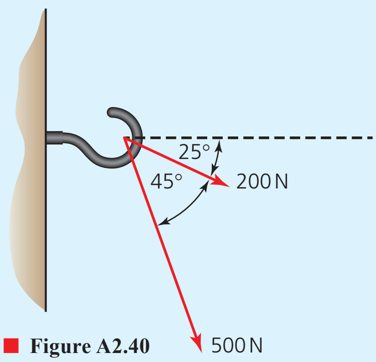


Figure A2.40

◆ **Newton's laws of motion** **First law**: an object will remain at rest, or continue to move in a straight line at a constant speed, unless a resultant force acts on it; **Second law**: acceleration is proportional to resultant force; **Third law**: whenever one body exerts a force on another body, the second body exerts exactly same force on the first body, but in the opposite direction.

◆ **Balanced forces** If an object is in mechanical equilibrium, we describe the forces acting on it as 'balanced'.

◆ **Equilibrium** An object is in equilibrium if it is unchanging under the action of two or more influences (e.g. forces). Different types of equilibrium include **translational**, **rotational** and **thermal**.

◆ **Translational** Changing position.

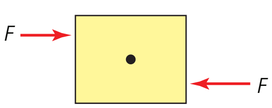


Figure A2.41 The object is in translational equilibrium, but not in rotational equilibrium

Newton's laws of motion

SYLLABUS CONTENT

- Newton's three laws of motion.

Newton's three laws of motion are among the most famous in classical physics. They describe the relationships between force and motion. Although they were first stated more than three hundred years ago, they are equally important today and are essential for an understanding of all motion (except when a speed of motion is close to the speed of light, as discussed in Topic A.5).

Newton's first law of motion

Newton's first law of motion states that an object will remain at rest or continue to move in a straight line at a constant speed, unless a resultant force acts on it.

In other words, a resultant force will produce an acceleration (change in velocity).

When the influences on any system are **balanced**, so that the system does not change, we describe it as being in **equilibrium**. (As another example, if an object stays at the same temperature, we say that it is in **thermal equilibrium**.)

When there is no resultant force on an object, we say that it is in **translational equilibrium**.

The term **translational** refers to movement from place to place. An object is in translational equilibrium if it remains at rest or continues to move with a constant velocity (in a straight line at a constant speed), as described by Newton's first law.

In passing, it should be noted that, if equal forces act in opposite directions, an object will be in translational equilibrium, but if the forces are not aligned (see Figure A2.41) then the object may start to rotate, so it will not be in **rotational equilibrium**. The subject of rotational dynamics is covered in Topic A.4.

Nature of science: Observations

Natural philosophy

'Forces are needed to keep an object moving and, without those forces, movement will stop.' This accepted 'fact' is not true, but it is still widely believed. It was the basis of theories of motion from the time of Aristotle (about 2350 years ago) until the seventeenth century, when scientists began to understand that the forces of friction were responsible for stopping movement.

Aristotle is one of the most respected figures in the early development of human thought. He appreciated the need for wide-ranging explanations of natural phenomena but the 'science' of that time – called natural philosophy – did not involve careful observations, measurements, mathematics or experiments.

Aristotle believed that everything in the world was made of a combination of the four elements of earth, fire, air and water. The Earth was the centre of everything and each of the four Earthly elements had its natural place. When something was not in its natural place, then it would tend to return – in this way he explained why rain falls, and why flames and bubbles rise, for example.

Modern science (characterized by experimentation and the development of unbiased, testable theories) began in the seventeenth century. It includes the work of famous physicists mentioned in this topic: Hooke, Galileo and Newton.

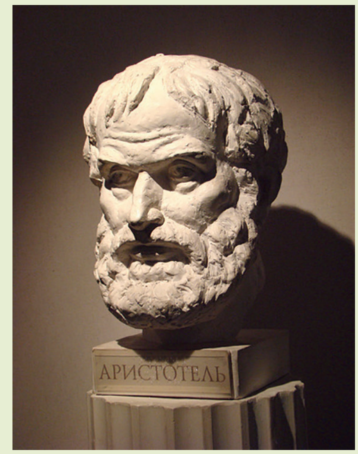


Figure A2.42 A representation of Aristotle

◆ **Natural philosophy** The name used to describe the (philosophical) study of nature and the universe before modern science.

Examples of translational equilibrium

Because all objects on Earth have weight, it is not possible for an object to be in equilibrium because there are no forces acting on it. So, all translational equilibrium arises when two or more forces are balanced.

- A book on a horizontal table (Figure A2.8) is in equilibrium because its downwards weight is balanced by the upwards normal contact force.
- A stationary block on a slope (Figures A2.38 and A2.39) is in equilibrium because the component of its weight down the slope is balanced by surface friction up the slope and the component of its weight into the slope is balanced by the normal component of the contact force.
- A cyclist moving with constant speed (Figure A2.43) is in equilibrium because their weight is balanced by the sum of the two normal contact forces and the frictional force from the road is balanced by the drag.

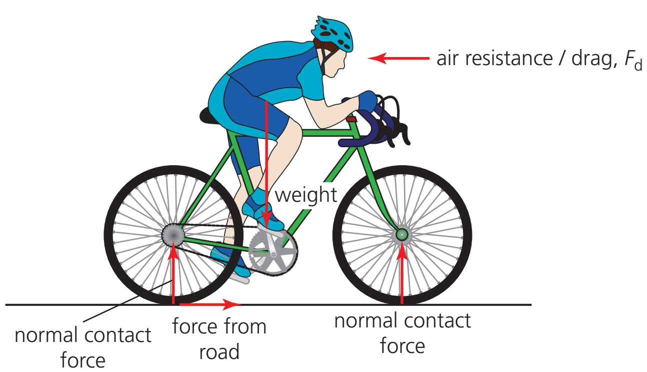


Figure A2.43 A cyclist moving at constant speed in translational equilibrium

Falling through the air at terminal speed

Figure A2.44 shows three positions of a falling ball. In part **a** the ball is just starting to move and there is no air resistance / drag. In part **b** the ball has accelerated and has some air resistance acting against its motion, but there is still a resultant force and an acceleration downwards. In part **c** the speed of the falling ball has increased to the point where the increasing air resistance has become equal and opposite to the weight. There is then no resultant force and the ball is in translational equilibrium, falling with a constant velocity called its terminal velocity or terminal speed. (Any buoyancy forces are considered to be negligible under these circumstances.) Terminal speed was introduced in Topic A.1.

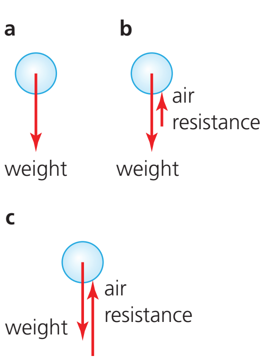


Figure A2.44 The resultant force on a falling object changes as it gains speed

Three forces in equilibrium

If two forces are acting on an object such that it is not in equilibrium, then to produce equilibrium a third force can be added that is equal in size to the resultant of the other two, but in the opposite direction. All three forces must act through the same point. For example, Figure A2.45 shows a free-body diagram of a ball on the end of a piece of string kept in equilibrium by a sideways pull that is equal in magnitude to the resultant of the weight and the tension in the string.

The translational equilibrium of three forces can be investigated in the laboratory simply by connecting three force meters together with string just above a horizontal surface, as shown in Figure A2.46. The three forces and the angles between them can be measured for a wide variety of different values, each of which maintains the system stationary.

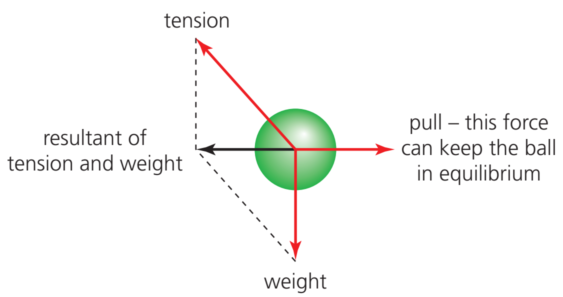


Figure A2.45 Three forces keeping a suspended ball in equilibrium

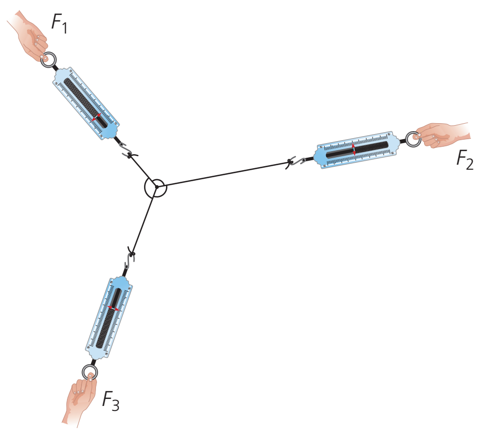


Figure A2.46 Investigating three forces in equilibrium

WORKED EXAMPLE A2.7

A ladder is leaning against a wall, as shown in Figure A2.47. Friction at point P is stopping the ladder from slipping, but there is no need for any friction acting at point Q.

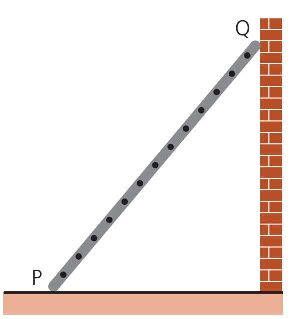


Figure A2.47 A ladder leaning against a wall

a Draw a free-body diagram of the ladder, including its weight and the normal force from the wall.

b The resultant force on the ladder from the ground must be directed at the point where the lines of action of the other two forces intersect. Add this line to your diagram.

c Complete the diagram by adding the two perpendicular components of the force from the ground on the ladder.

Answer

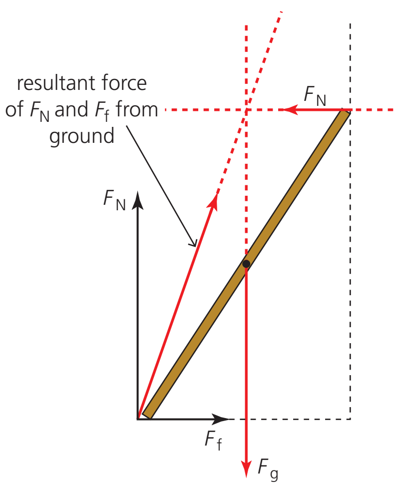


Figure A2.48

32 Under what circumstances will a moving car be in translational equilibrium?

33 If you are in an elevator (lift) without windows discuss whether it is possible to know if you are moving up, moving down or stationary.

34 Figure A2.49 shows a mountain climber who, at that moment, is stationary.

a Draw a free-body diagram that shows that he is in equilibrium.

b Outline the features of your diagram which show that the climber is in equilibrium.

35 Can the Moon be described as being in translational equilibrium? Explain your answer.

Figure A2.49

Newton's second law of motion

We have seen that Newton's first law establishes that there is a connection between resultant force and acceleration. Newton's second law takes this further and states the mathematical connection: when a resultant force acts on a (constant) mass, the acceleration is proportional to the resultant force: $a \propto F$.

Both force and acceleration are vector quantities and the acceleration is in the same direction as the force.

Investigating the effects of different forces and different masses on the accelerations that they produce is an important part of most physics courses, although reducing the effects of friction is essential for consistent results.

Inquiry 1: Exploring and designing

Exploring

Aristotle's understanding of motion was formed through making observations of the behaviour of objects in motion, but without any deep understanding of the concept of force he was unable to account for the effects of friction or air resistance. What methods are available for reducing friction in investigations into the effects of different forces and masses on an object's acceleration?

In groups, brainstorm how experiments can be designed to reduce or to cancel the effects of frictional forces. Decide on a selection of search terms or phrases that can be used by individual students for internet research. Use your research to formulate a research question and hypothesis.

Such experiments also show that when the same resultant force is applied to different masses, the acceleration produced is inversely proportional to the mass, m: $a \propto 1/m$

Combining these results, we see that acceleration, $a \propto \frac{F}{m}$.

Newton's second law can be written as: $F \propto ma$

If we define the SI unit of force, the newton, to be the force that accelerates 1 kg by 1 m s^{-2}, then we can write: force (N) = mass (kg) × acceleration (m s^{-2})

Newton's second law of motion: resultant force, $F = ma$

◆ **Proportional relationship** Two variables are (directly) proportional to each other if they always have the same ratio.

◆ **Uncertainty bars** Vertical and horizontal lines drawn through data points on a graph to represent the uncertainties in the two values.

This version of Newton's second law assumes that the mass of the object is constant. We will see later in this topic that there is an alternative version which allows for changing mass.

When discussing a gravitational force, weight, we have used the symbol F_g and the acceleration involved is g, the acceleration of free fall.

So, the equation $F = ma$ becomes the familiar:

$$F_g = mg$$

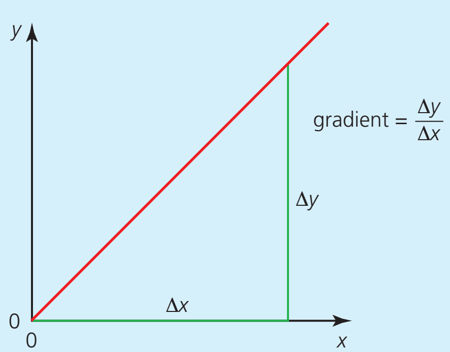
Tool 3: Mathematics

On a best-fit linear graph, construct lines of maximum and minimum gradients with relative accuracy (by eye) considering all uncertainty bars

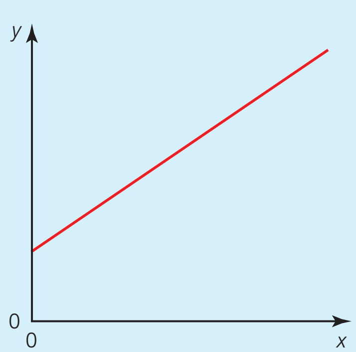
Many basic physics experiments are aimed at investigating if there is a **proportional relationship** between two variables, and this is usually best checked by drawing a graph.

If two variables are (directly) proportional, then their graph will be a straight line passing through the origin

Figure A2.50 represents a proportional relationship. It is important to stress that a linear graph that does not pass through the origin does *not* represent proportionality (Figure A2.51).



■ **Figure A2.50** A proportional relationship

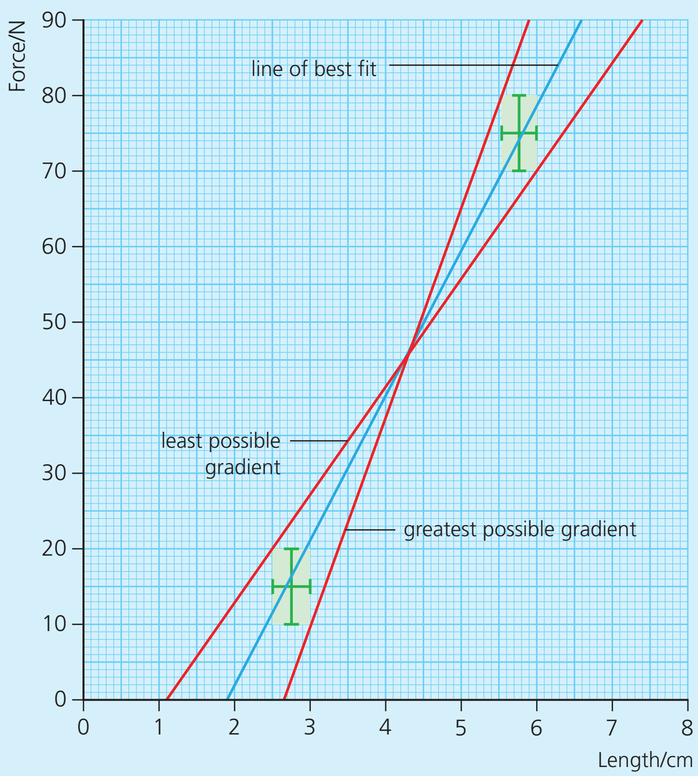


■ **Figure A2.51** A linear relationship that is not proportional does not pass through the origin. **See also Tool 3: Mathematics (Understand direct and inverse proportionality) on page 129.**

Uncertainty in gradients and intercepts

It is often possible to draw a range of different straight lines, all of which pass through the **uncertainty bars** representing experimental data.

We usually assume that the line of best fit is midway between the lines of maximum possible gradient and minimum possible gradient. Figure A2.52 shows an example (for simplicity, only the first and last error bars are shown, but in practice all the error bars need to be considered when drawing the lines).



■ **Figure A2.52** Finding maximum and minimum gradients for a spring-stretching experiment

Figure A2.52 shows how the length of a metal spring changed as the force applied was increased. We know that the measurements were not very precise because the uncertainty bars are large. The line of best fit has been drawn midway between the other two. This is a linear graph (a straight line) and it is known that the gradient of the graph represents the force constant (stiffness) of the spring and the horizontal intercept represents the original length of the spring. Taking measurements from the line of best fit, we can make the following calculations:

$$\text{force constant} = \text{gradient} = \frac{(90 - 0)}{(6.6 - 1.9)} = 19\,\text{N cm}^{-1}$$

$$\text{original length} = \text{horizontal intercept} = 1.9\,\text{cm}$$

To determine the uncertainty in the calculations of gradient and intercept, we need only consider the range of straight lines that could be drawn through the first and last error bars. The uncertainty will be the maximum difference between these extreme values obtained from graphs of maximum and minimum possible gradients and the value calculated from the line of best fit. In this example it can be shown that: force constant is between 14 N cm^{-1} and 28 N cm^{-1}, original length is between 1.1 cm and 2.6 cm.

The final result can be quoted as:
force constant = 19 ± 9 N cm^{-1}, original length = 1.9 ± 0.8 cm. Clearly, the large uncertainties in these results confirm that the experiment lacked precision.

Table A2.3 shows the results that a student obtained when investigating the effects of a resultant force on a constant mass. Plot a graph of these readings, including uncertainty bars. Then draw lines of maximum and minimum gradients through the error bars. Finally, use your graph to determine the mass that the student used in the experiment and the uncertainty in your answer.

Table A2.3

Resultant force, N, ± 0.5 N	Acceleration, m s^{-2}, ± 0.2 m s^{-2}
1.0	0.7
2.0	1.3
3.0	2.0
4.0	2.8
5.0	3.3
6.0	4.1

Common mistake

Many students believe that the force involved when an object hits the ground is its weight. In reality, the force will depend on the nature of the impact. The longer the duration of the impact, the smaller the force, as explained below.

Non-mathematical applications of Newton's second law

We can use Newton's second law to explain why, for example, a glass will break when dropped on the floor, but may survive being dropped onto a sofa. A collision with the floor will be for a much shorter duration, which means the deceleration will be greater and (using $F = ma$) the force will be greater, and probably more destructive. Similar arguments can be used to explain how forces can be reduced in road accidents.

WORKED EXAMPLE A2.8

A car of mass 1450 kg is accelerated from rest by an initial resultant force of 3800 N.

a Calculate the acceleration of the car.

b If the force and acceleration are constant, what will its speed be after 4.0 s?

c Determine how far it will have travelled in this time.

d After 4.0 s the resistive forces acting on the car are 1800 N. Show that the new force required to maintain the same acceleration is approximately 5.5 kN.

Answer

a $a = \frac{F}{m} = \frac{3800}{1450} = 2.62\,\text{m s}^{-2}$

b $v = u + at = 0 + (2.62 \times 4.0) = 10.5\,\text{m s}^{-1}$

c $s = \frac{(u + v)}{2} \times t = \frac{(0 + 10.5)}{2} \times 4.0 = 21.0\,\text{m}$

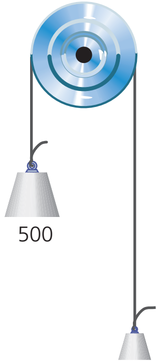
d $3800 + 1800 = 5600\,\text{N} \approx 5500\,\text{N} = 5.5\,\text{kN}$

WORKED EXAMPLE A2.9

Figure A2.53 shows two masses attached by a string which passes over a fixed pulley. Assuming that there is no friction in the system and that the string has negligible mass, determine:

a the acceleration of the system

b the tension in the string.



■ **Figure A2.53** Two masses attached by a string which passes over a fixed pulley

Answer

a The resultant force on the system of two masses = weight of the 500 g mass − weight of 100 g mass = (0.500 − 0.100) × 9.8 = 3.9 N

$$a = \frac{F}{m} = \frac{3.9}{(0.500 + 0.100)} = 6.5\,\mathrm{m\,s^{-2}}$$

The 500 g mass will accelerate down while the 100 g mass accelerates up at the same rate.

b Consider the 100 g mass: the resultant force acting = tension, T, in the string upwards – weight acting downwards = T – (0.100 × 9.8) = T – 0.98

$F = ma$

$(T - 0.98) = 0.100 \times 6.5$

$T = 1.6\,\mathrm{N}$

Equally, we could consider the 500 g mass:
the resultant force acting =
weight acting downwards − tension, T, in the string upwards =
$(0.500 \times 9.8) - T = 4.9 - T$

$F = ma$

$(4.9 - T) = 0.500 \times 6.5$

$T = 1.6\,\mathrm{N}$

36 A laboratory trolley accelerated at 80 cm s^{-2} when a resultant force of 1.7 N was applied to it. What was its mass?

37 When a force of 6.4 N was applied to a mass of 2.1 kg on a horizontal surface, it accelerated by 1.9 m s^{-2}. Determine the average frictional force acting on the mass.

38 When a hollow rubber ball of mass 120 g was dropped on a concrete floor the velocity of impact was 8.0 m s^{-1} and it reduced to zero in 0.44 s (before bouncing back).

a Calculate:

i the ball's average deceleration

ii the average force exerted on the ball.

b Repeat the calculations for a solid steel ball of the same size, 10 times the mass, but with the same impact velocity. Assume that its speed reduced to zero in 0.080 s.

c Outline why the steel ball can do more damage to a floor than the rubber ball.

39 A small aircraft of mass 520 kg needs to take off with a speed of 30 m s^{-1} from a runway in a distance of 200 m.

a Show that the aircraft needs to have an average acceleration of 2.3 m s^{-2}.

b What average resultant force is needed during the take off?

40 Discuss why the forces on the long-jumper shown in Figure A2.54 are reduced because he is landing in sand.

■ **Figure A2.54** Impact in a sand-pit reduces force

41 a What resultant force is needed to accelerate a train of total mass 2.78×10^6 kg from rest to $20\,m\,s^{-1}$ in 60 s?

b If the same train was on a sloping track which had an angle of 5.0° to the horizontal, what is the component of its weight parallel to the track?

c Suggest why railway designers try to avoid hills.

42 Calculate the average force needed to bring a 2160 kg car travelling at $21\,m\,s^{-1}$ to rest in 68 m.

43 Use Newton's second law to explain why it will hurt you more if you are struck by a hard ball than by a soft ball of the same mass and speed.

44 A trolley containing sand is pulled across a frictionless horizontal surface with a small but constant resultant force. Describe and explain the motion of the trolley if sand can fall through a hole in the bottom of the trolley.

45 A man of mass 82.5 kg is standing still in an elevator that is accelerating upwards at $1.50\,m\,s^{-2}$.

a What is the resultant force acting on the man?

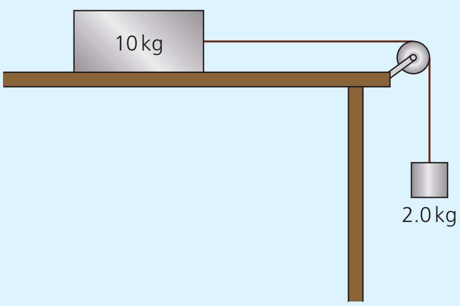
b What is the normal contact force acting upwards on him from the floor?

46 Figure A2.55 shows two masses connected by a light string passing over a pulley.

a Assuming there is no friction, calculate the acceleration of the two blocks.

b What resultant force is needed to accelerate the 2.0 kg mass by this amount?

c Draw a fully labelled free-body diagram for the 2 kg mass, showing the size and direction of all forces.



■ **Figure A2.55** Two masses connected by a light string passing over a pulley

47 Outline how air bags (and/or seat belts) reduce the injuries to drivers and passengers in car accidents.

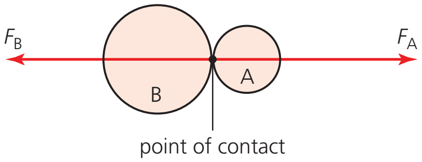
◆ **Inertia** Resistance to a change of motion. Depends on the mass of the object.

Newton's second law offers us a different way of understanding mass: larger masses accelerate less than smaller masses under the action of the same resultant force. So, mass can be considered as a measure of an object's resistance to acceleration. Physicists use the term **inertia** to describe an object's resistance to a change of motion.

Mass is a measure of inertia.

Newton's third law of motion

Whenever any two objects come in contact with each other, or otherwise interact, they exert forces on each other (Figure A2.56). Newton's third law compares these two forces.



■ **Figure A2.56** When two bodies interact, $F_A = -F_B$

Newton's third law of motion states that whenever one body exerts a force on another body, the second body exerts a force of the same magnitude on the first body, but in the opposite direction.

Essentially this law means that forces must always occur in equal pairs, although it is important to realize that the two forces must act on different bodies and in opposite directions, so that only one of each force pair can be seen in any free-body diagram. The two forces are always of the same type, for example gravity/gravity or friction/friction. Sometimes the law is quoted in the form used by Newton: 'to every action there is an equal and opposite reaction'. In everyday terms, it is simply not possible to push something that does not push back on you. Here are some examples:

- If you pull a rope, the rope pulls you.
- If the Earth pulls a person, the person pulls the Earth (Figure A2.57).
- If a fist hits a cheek, the cheek hits the fist (Figure A2.58).

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