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EDEXCEL INTERNATIONAL GCSE (9–1)

eBook included

PHYSICS

Student Book

Brian Arnold, Penny Johnson, Steve Woolley

Pearson

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UNIT 1

FORCES AND MOTION

UNIT 2

ELECTRICITY

UNIT 3

WAVES

UNIT 4

ENERGY RESOURCES AND ENERGY TRANSFER

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UNIT 5

SOLIDS, LIQUIDS AND GASES

UNIT 6

MAGNETISM AND ELECTROMAGNETISM

UNIT 7

RADIOACTIVITY AND PARTICLES

UNIT 8

ASTROPHYSICS

PHYSICS ONLY

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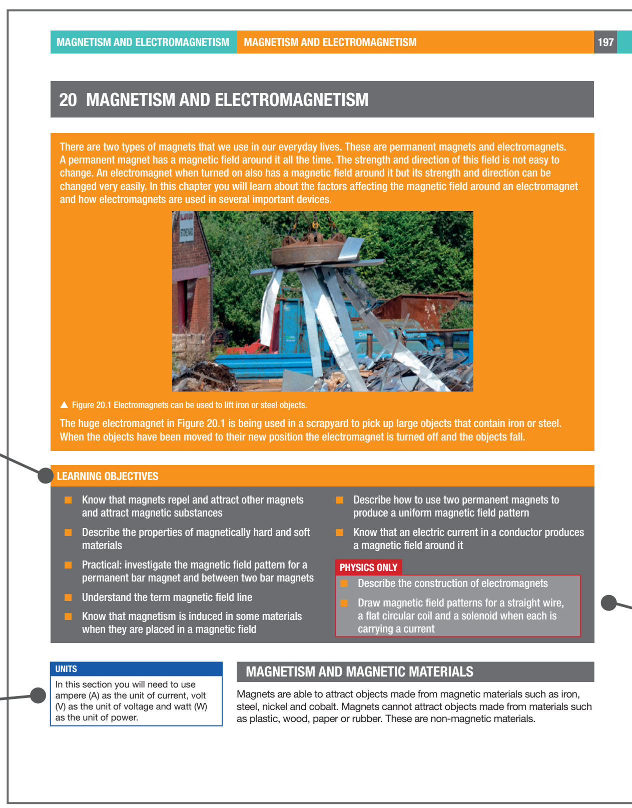
ABOUT THIS BOOK

This book is written for students following the Edexcel International GCSE (9–1) Physics specification and the Edexcel International GCSE (9–1) Science Double Award specification. You will need to study all of the content in this book for your Physics examination. However, you will only need to study some of it if you are taking the Double Award specification. The book clearly indicates which content is in the Physics examination and not in the Double Award specification. To complete the Double Award course you will also need to study the Biology and Chemistry parts of the course.

In each unit of this book, there are concise explanations and worked examples, plus numerous exercises that will help you build up confidence. The book also describes the methods for carrying out all of the required practicals.

The language throughout this textbook is graded for speakers of English as an additional language (EAL), with advanced Physics specific terminology highlighted and defined in the glossary at the back of the book. A list of command words, also at the back of the book, will help you to learn the language you will need in your examination.

You will also find that questions in this book have Progression icons and Skills tags. The Progression icons refer to Pearson's Progression scale. This scale – from 1 to 12 – tells you what level you have reached in your learning and will help you to see what you need to do to progress to the next level. Furthermore, Edexcel have developed a Skills grid showing the skills you will practise throughout your time on the course. The skills in the grid have been matched to questions in this book to help you see which skills you are developing. You can find Pearson's Progression scale and Edexcel's Skills grid at www.pearsonschoolsandfecolleges.co.uk along with guidelines on how to use them.


MAGNETISM AND ELECTROMAGNETISM MAGNETISM AND ELECTROMAGNETISM 197

20 MAGNETISM AND ELECTROMAGNETISM

There are two types of magnets that we use in our everyday lives. These are permanent magnets and electromagnets. A permanent magnet has a magnetic field around it all the time. The strength and direction of this field is not easy to change. An electromagnet when turned on also has a magnetic field around it but its strength and direction can be changed very easily. In this chapter you will learn about the factors affecting the magnetic field around an electromagnet and how electromagnets are used in several important devices.

▲ Figure 20.1 Electromagnets can be used to lift iron or steel objects.

The huge electromagnet in Figure 20.1 is being used in a scrapyard to pick up large objects that contain iron or steel. When the objects have been moved to their new position the electromagnet is turned off and the objects fall.

LEARNING OBJECTIVES

- Know that magnets repel and attract other magnets and attract magnetic substances
- Describe the properties of magnetically hard and soft materials
- Practical: investigate the magnetic field pattern for a permanent bar magnet and between two bar magnets
- Understand the term magnetic field line
- Know that magnetism is induced in some materials when they are placed in a magnetic field
- Describe how to use two permanent magnets to produce a uniform magnetic field pattern
- Know that an electric current in a conductor produces a magnetic field around it

PHYSICS ONLY

- Describe the construction of electromagnets
- Draw magnetic field patterns for a straight wire, a flat circular coil and a solenoid when each is carrying a current

UNITS

In this section you will need to use ampere (A) as the unit of current, volt (V) as the unit of voltage and watt (W) as the unit of power.

MAGNETISM AND MAGNETIC MATERIALS

Magnets are able to attract objects made from magnetic materials such as iron, steel, nickel and cobalt. Magnets cannot attract objects made from materials such as plastic, wood, paper or rubber. These are non-magnetic materials.

Learning Objectives show what you will learn in each Chapter.

Units boxes tell you which units – for example, metres, grams and seconds – you will need to know and use for the study of a topic.

Physics Only sections show the content that is on the Physics specification only and not the Double Award specification. All other content in this book applies to Double Award students.

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Key Point boxes summarise the essentials.

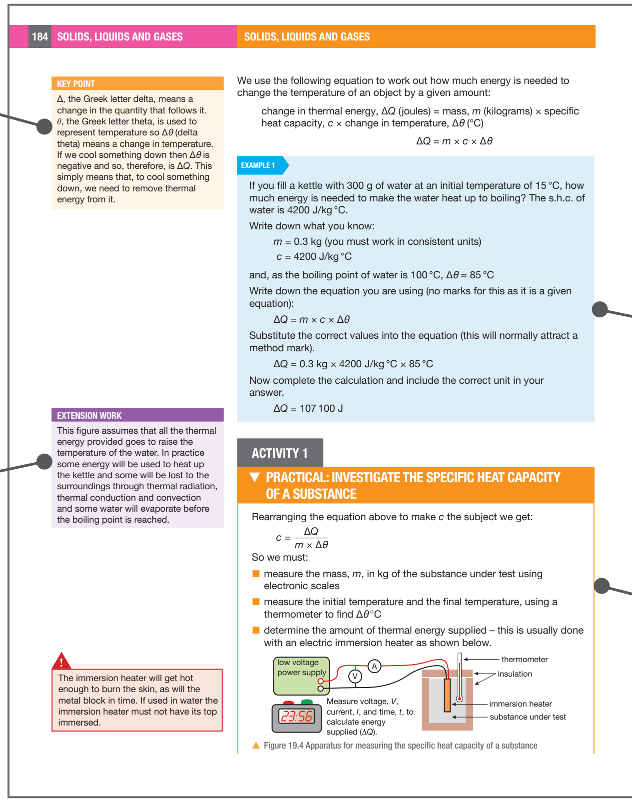
Extension Work boxes include content that is not on the specification and which you do not have to learn for your examination. However, the content will help to extend your understanding of the topic.

Hint boxes give you tips on important points to remember in your examination.

Looking Ahead tells you what you would learn if you continued your study of Physics to a higher level, such as International A Level.

Examples provide a clear, instructional framework.

Practicals describe the methods for carrying out all of the practicals you will need to know for your examination.



184 SOLIDS, LIQUIDS AND GASES | SOLIDS, LIQUIDS AND GASES

KEY POINT

Δ, the Greek letter delta, means a change in the quantity that follows it. θ, the Greek letter theta, is used to represent temperature so Δθ (delta theta) means a change in temperature. If we cool something down then Δθ is negative and so, therefore, is ΔQ. This simply means that, to cool something down, we need to remove thermal energy from it.

We use the following equation to work out how much energy is needed to change the temperature of an object by a given amount:

change in thermal energy, ΔQ (joules) = mass, m (kilograms) × specific heat capacity, c × change in temperature, Δθ (°C)

$\Delta Q = m \times c \times \Delta\theta$

EXAMPLE 1

If you fill a kettle with 300 g of water at an initial temperature of 15 °C, how much energy is needed to make the water heat up to boiling? The s.h.c. of water is 4200 J/kg °C.

Write down what you know:

m = 0.3 kg (you must work in consistent units)

c = 4200 J/kg °C

and, as the boiling point of water is 100 °C, Δθ = 85 °C

Write down the equation you are using (no marks for this as it is a given equation):

$\Delta Q = m \times c \times \Delta\theta$

Substitute the correct values into the equation (this will normally attract a method mark).

ΔQ = 0.3 kg × 4200 J/kg °C × 85 °C

Now complete the calculation and include the correct unit in your answer.

ΔQ = 107 100 J

EXTENSION WORK

This figure assumes that all the thermal energy provided goes to raise the temperature of the water. In practice some energy will be used to heat up the kettle and some will be lost to the surroundings through thermal radiation, thermal conduction and convection and some water will evaporate before the boiling point is reached.

ACTIVITY 1

PRACTICAL: INVESTIGATE THE SPECIFIC HEAT CAPACITY OF A SUBSTANCE

Rearranging the equation above to make c the subject we get:

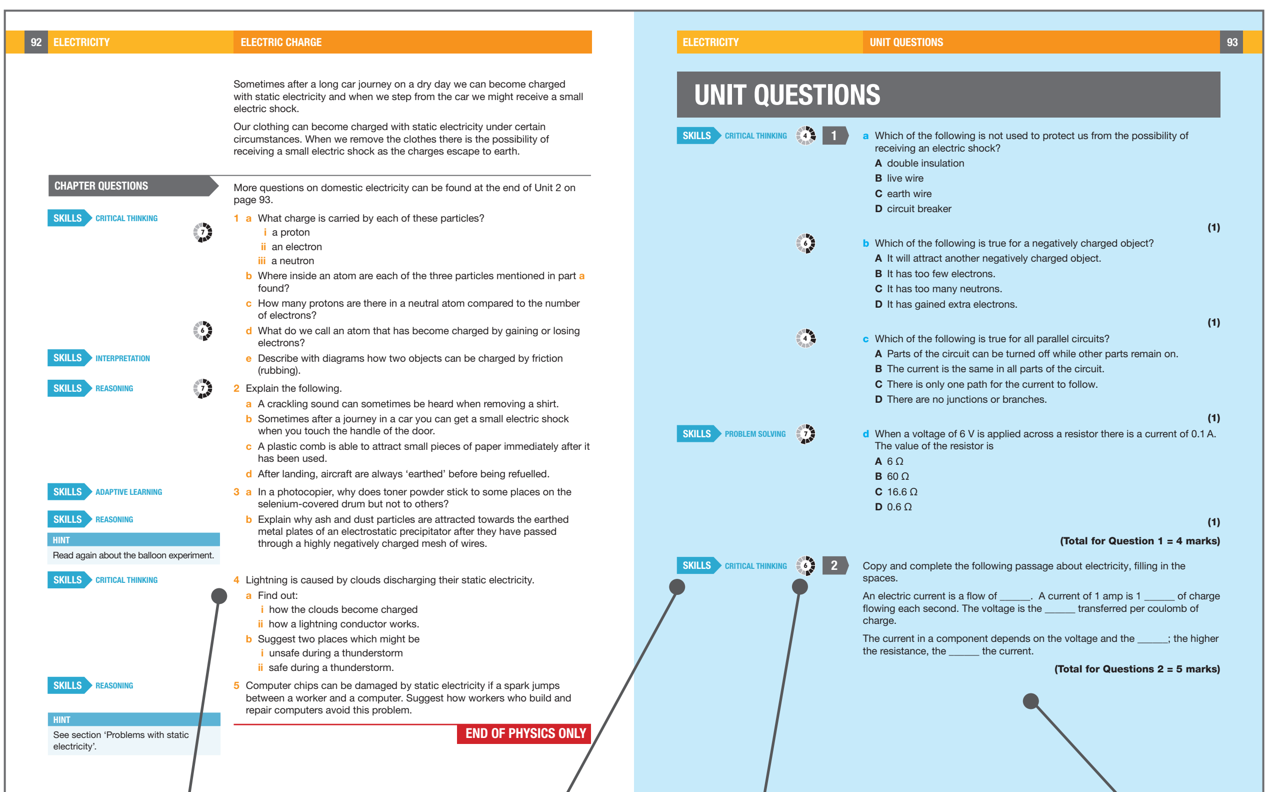
$c = \dfrac{\Delta Q}{m \times \Delta\theta}$

So we must:

- measure the mass, m, in kg of the substance under test using electronic scales
- measure the initial temperature and the final temperature, using a thermometer to find Δθ °C
- determine the amount of thermal energy supplied – this is usually done with an electric immersion heater as shown below.

The immersion heater will get hot enough to burn the skin, as will the metal block in time. If used in water the immersion heater must not have its top immersed.

Figure 19.4 Apparatus for measuring the specific heat capacity of a substance



92 ELECTRICITY | ELECTRIC CHARGE

Sometimes after a long car journey on a dry day we can become charged with static electricity and when we step from the car we might receive a small electric shock.

Our clothing can become charged with static electricity under certain circumstances. When we remove the clothes there is the possibility of receiving a small electric shock as the charges escape to earth.

CHAPTER QUESTIONS

More questions on domestic electricity can be found at the end of Unit 2 on page 93.

SKILLS CRITICAL THINKING

1 a What charge is carried by each of these particles?
i a proton
ii an electron
iii a neutron
b Where inside an atom are each of the three particles mentioned in part a found?
c How many protons are there in a neutral atom compared to the number of electrons?
d What do we call an atom that has become charged by gaining or losing electrons?

SKILLS INTERPRETATION

e Describe with diagrams how two objects can be charged by friction (rubbing).

SKILLS REASONING

2 Explain the following.
a A crackling sound can sometimes be heard when removing a shirt.
b Sometimes after a journey in a car you can get a small electric shock when you touch the handle of the door.
c A plastic comb is able to attract small pieces of paper immediately after it has been used.
d After landing, aircraft are always 'earthed' before being refuelled.

SKILLS ADAPTIVE LEARNING

3 a In a photocopier, why does toner powder stick to some places on the selenium-covered drum but not to others?

SKILLS REASONING

b Explain why ash and dust particles are attracted towards the earthed metal plates of an electrostatic precipitator after they have passed through a highly negatively charged mesh of wires.

HINT

Read again about the balloon experiment.

SKILLS CRITICAL THINKING

4 Lightning is caused by clouds discharging their static electricity.
a Find out:
i how the clouds become charged
ii how a lightning conductor works.
b Suggest two places which might be
i unsafe during a thunderstorm
ii safe during a thunderstorm.

SKILLS REASONING

5 Computer chips can be damaged by static electricity if a spark jumps between a worker and a computer. Suggest how workers who build and repair computers avoid this problem.

HINT

See section 'Problems with static electricity'.

END OF PHYSICS ONLY

ELECTRICITY | UNIT QUESTIONS 93

UNIT QUESTIONS

SKILLS CRITICAL THINKING

1 a Which of the following is not used to protect us from the possibility of receiving an electric shock?
A double insulation
B live wire
C earth wire
D circuit breaker
(1)

b Which of the following is true for a negatively charged object?
A It will attract another negatively charged object.
B It has too few electrons.
C It has too many neutrons.
D It has gained extra electrons.
(1)

c Which of the following is true for all parallel circuits?
A Parts of the circuit can be turned off while other parts remain on.
B The current is the same in all parts of the circuit.
C There is only one path for the current to follow.
D There are no junctions or branches.
(1)

SKILLS PROBLEM SOLVING

d When a voltage of 6 V is applied across a resistor there is a current of 0.1 A. The value of the resistor is
A 6 Ω
B 60 Ω
C 16.6 Ω
D 0.6 Ω
(1)

(Total for Question 1 = 4 marks)

SKILLS CRITICAL THINKING

2 Copy and complete the following passage about electricity, filling in the spaces.

An electric current is a flow of ______. A current of 1 amp is 1 ______ of charge flowing each second. The voltage is the ______ transferred per coulomb of charge.

The current in a component depends on the voltage and the ______; the higher the resistance, the ______ the current.

(Total for Questions 2 = 5 marks)

Chapter Questions test your knowledge of the topic in that chapter.

Skills tags tell you which skills you are practising in each question.

Progression icons show the level of difficulty according to the Pearson International GCSE Science Progression Scale.

Unit Questions test your knowledge of the whole unit and provide quick, effective feedback on your progress.

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ASSESSMENT OVERVIEW

The following tables give an overview of the assessment for this course.

We recommend that you study this information closely to help ensure that you are fully prepared for this course and know exactly what to expect in the assessment.

PAPER 1	SPECIFICATION	PERCENTAGE	MARK	TIME	AVAILABILITY
Written examination paper Paper code 4PH1/1P and 4SD0/1P Externally set and assessed by Edexcel	Physics Double Award	61.1%	110	2 hours	January and June examination series First assessment June 2019
PAPER 2	**SPECIFICATION**	**PERCENTAGE**	**MARK**	**TIME**	**AVAILABILITY**
Written examination paper Paper code 4PH1/2P Externally set and assessed by Edexcel	Physics	38.9%	70	1 hour 15 mins	January and June examination series First assessment June 2019

If you are studying Physics then you will take both Papers 1 and 2. If you are studying Science Double Award then you will only need to take Paper 1 (along with Paper 1 for each of the Biology and Chemistry courses).

ASSESSMENT OBJECTIVES AND WEIGHTINGS

ASSESSMENT OBJECTIVE	DESCRIPTION	% IN INTERNATIONAL GCSE
AO1	Knowledge and understanding of physics	38%–42%
AO2	Application of knowledge and understanding, analysis and evaluation of physics	38%–42%
AO3	Experimental skills, analysis and evaluation of data and methods in physics	19%–21%

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EXPERIMENTAL SKILLS

In the assessment of experimental skills, students may be tested on their ability to:

- solve problems set in a practical context
- apply scientific knowledge and understanding in questions with a practical context
- devise and plan investigations, using scientific knowledge and understanding when selecting appropriate techniques
- demonstrate or describe appropriate experimental and investigative methods, including safe and skilful practical techniques
- make observations and measurements with appropriate precision, record these methodically and present them in appropriate ways
- identify independent, dependent and control variables
- use scientific knowledge and understanding to analyse and interpret data to draw conclusions from experimental activities that are consistent with the evidence
- communicate the findings from experimental activities, using appropriate technical language, relevant calculations and graphs
- assess the reliability of an experimental activity
- evaluate data and methods taking into account factors that affect accuracy and validity.

CALCULATORS

Students are permitted to take a suitable calculator into the examinations. Calculators with QWERTY keyboards or that can retrieve text or formulae will not be permitted.

UNIT 1 FORCES AND MOTION

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Forces make things move, like this Atlas V rocket carrying the Cygnus spacecraft up to the International Space Station. Forces hold the particles of matter together and keep us on the Earth. Forces can make things slow down. This is useful when we apply the brakes when driving a car! Forces can change the shape of things, sometimes temporarily and sometimes permanently. Forces make things rotate and change direction.

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1 MOVEMENT AND POSITION

It is very useful to be able to make predictions about the way moving objects behave. In this chapter you will learn about some equations of motion that can be used to calculate the speed and acceleration of objects, and the distances they travel in a certain time.

▲ Figure 1.1 The world is full of speeding objects.

LEARNING OBJECTIVES

- Plot and explain distance–time graphs
- Know and use the relationship between average speed, distance moved and time taken:

  $$\text{average speed} = \frac{\text{distance moved}}{\text{time taken}}$$

- Practical: investigate the motion of everyday objects such as toy cars or tennis balls
- Know and use the relationship between acceleration, change in velocity and time taken:

  $$\text{acceleration} = \frac{\text{change in velocity}}{\text{time taken}} \qquad a = \frac{(v-u)}{t}$$

- Plot and explain velocity–time graphs
- Determine acceleration from the gradient of a velocity–time graph
- Determine the distance travelled from the area between a velocity–time graph and the time axis
- Use the relationship between final speed, initial speed, acceleration and distance moved:

  $$(\text{final speed})^2 = (\text{initial speed})^2 + (2 \times \text{acceleration} \times \text{distance moved})$$

  $$v^2 = u^2 + (2 \times a \times s)$$

UNITS

PHYSICS ONLY

- torque (turning effect): newton metre (N m)
- momentum: kilogram metre per second (kg m/s).

In this section you will need to use kilogram (kg) as the unit of mass, metre (m) as the unit of length, and second (s) as the unit of time, You will find measurements of mass made in subdivisions of the kilogram, like grams (g) and milligrams (mg), measurements of length in multiples of the metre, like the kilometre (km), and subdivisions like the centimetre (cm) and millimetre (mm). You will also be familiar with other units for time: minutes, hours, days and years etc. You will need to take care to convert units in calculations to the base units of kg, m and s when you meet these subdivisions and multiples.

Other units come from these base units. In the first chapter you will meet the units for:

- speed and velocity: metre per second (m/s)
- acceleration: metre per second squared (m/s^2).

In later chapters you will meet the units for:

- force: newton (N)
- gravitational field strength: newton per kilogram (N/kg)

KEY POINT

Sometimes average speed is shown by the symbols $v_{average}$ or $\bar{v}$ but in this book v will be used.

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Speed is a term that is often used in everyday life. Action films often feature high-speed chases. Speed is a cause of fatal accidents on the road. Sprinters aim for greater speed in competition with other athletes. Rockets must reach a high enough speed to put communications satellites in **orbit** around the Earth. This chapter will explain how speed is defined and measured and how distance–time graphs are used to show the movement of an object as time passes. We shall then look at changing speed – **acceleration** and **deceleration**. We shall use velocity–time graphs to find the acceleration of an object. We shall also find how far an object has travelled using its velocity–time graph. You will find out about the difference between speed and velocity on page 6.

AVERAGE SPEED

KEY POINT

Sometimes you may see '*d*' used as the symbol for distance travelled, but in this book '*s*' will be used to be consistent with the symbol used in A level maths and physics.

A car travels 100 kilometres in 2 hours so the average speed of the car is 50 km/h. You can work this out by doing a simple calculation using the following definition of speed:

$$\text{average speed, } v = \frac{\text{distance moved, } s}{\text{time taken, } t}$$

$$v = \frac{s}{t}$$

The average speed of the car during the journey is the total distance travelled, divided by the time taken for the journey. If you look at the speedometer in a car you will see that the speed of the car changes from instant to instant as the accelerator or brake is used. The speedometer therefore shows the instantaneous speed of the car.

UNITS OF SPEED

Typically the distance moved is measured in metres and time taken in seconds, so the speed is in metres per second (m/s). Other units can be used for speed, such as kilometres per hour (km/h), or centimetres per second (cm/s). In physics the units we use are **metric**, but you can measure speed in miles per hour (mph). Many cars show speed in both mph and kilometres per hour (kph or km/h). Exam questions should be in metric units, so remember that m is the abbreviation for metres (and not miles).

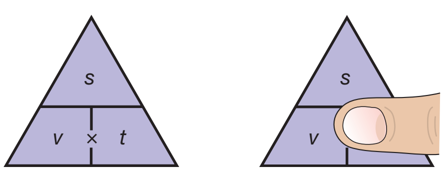
REARRANGING THE SPEED EQUATION

If you are given information about speed and time taken, you will be expected to rearrange the speed equation to make the distance moved the subject:

$$\text{distance moved, } s = \text{average speed, } v \times \text{time, } t$$

and to make the time taken the subject if you are given the distance moved and speed:

$$\text{time taken, } t = \frac{\text{distance moved, } s}{\text{average speed, } v}$$



▲ Figure 1.2 You can use the triangle method for rearranging equations like $s = v \times t$.

REMINDER

To use the triangle method to rearrange an equation, cover up the part of the triangle that you want to find. For example, in Figure 1.2, if you want to work out how long (t) it takes to move a distance (s) at a given speed (v), covering t in Figure 1.2 leaves $\frac{s}{v}$, or distance divided by speed. If an examination question asks you to write out the equation for calculating speed, distance or time, always give the actual equation (such as $s = v \times t$). You may not get the mark if you just draw the triangle.

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SPEED TRAP!

▲ Figure 1.3 A stopwatch will measure the time taken for the vehicle to travel the distance.

Suppose you want to find the speed of cars driving down your road. You may have seen the police using a mobile speed camera to check that drivers are keeping to the speed limit. Speed guns use microprocessors (computers on a 'chip') to produce an instant reading of the speed of a moving vehicle, but you can conduct a very simple experiment to measure car speed.

Measure the distance between two points along a straight section of road with a tape measure or 'click' wheel. Use a stopwatch to measure the time taken for a car to travel the measured distance. Figure 1.4 shows you how to operate your 'speed trap'.

1 Measure 50 m from a start point along the side of the road.
2 Start a stopwatch when your partner signals that the car is passing the start point.
3 Stop the stopwatch when the car passes you at the finish point.

▲ Figure 1.4 How to measure the speed of cars driving on the road

! No measurements should be taken on the public road or pavement but it is possible to do so within the school boundary within sight of the road.

KEY POINT

You can convert a speed in m/s into a speed in km/h.

If the car travels 12.8 metres in one second it will travel

12.8 × 60 metres in 60 seconds (that is, one minute) and

12.8 × 60 × 60 metres in 60 minutes (that is, 1 hour), which is

46 080 metres in an hour or 46.1 km/h (to one decimal place).

We have multiplied by 3600 (60 × 60) to convert from m/s to m/h, then divided by 1000 to convert from m/h to km/h (as there are 1000 m in 1 km).

Rule: to convert m/s to km/h simply multiply by 3.6.

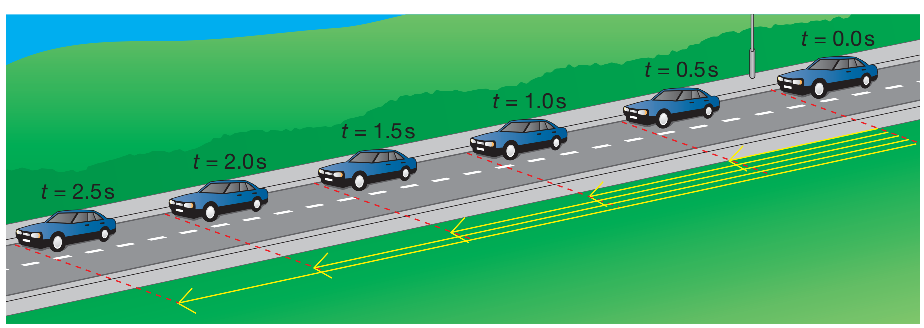
Using the measurements made with your speed trap, you can work out the speed of the car. Use the equation:

$$\text{average speed, } v = \frac{\text{distance moved, } s}{\text{time taken, } t}$$

So if the time measured is 3.9 s, the speed of the car in this experiment is:

$$\text{average speed, } v = \frac{50\,\text{m}}{3.9\,\text{s}}$$
$$= 12.8\text{ m/s}$$

DISTANCE–TIME GRAPHS



▲ Figure 1.5 A car travelling at constant speed

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Figure 1.5 shows a car travelling along a road. It shows the car at 0.5 second intervals. The distances that the car has travelled from the start position after each 0.5 s time interval are marked on the picture. The picture provides a record of how far the car has travelled as time has passed. The table below shows the data for this car. You will be expected to plot a graph of the distance travelled (**vertical** axis) against time (horizontal axis) as shown in Figure 1.6.

Time from start/s	0.0	0.5	1.0	1.5	2.0	2.5
Distance travelled from start/m	0.0	6.0	12.0	18.0	24.0	30.0

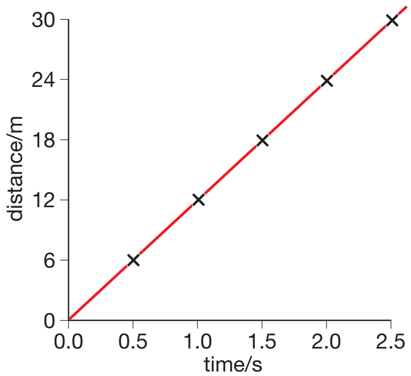

Figure 1.6 Distance–time graph for the travelling car in Figure 1.5

KEY POINT

A curved line on distance–time graphs means that the speed or velocity of the object is changing. To find the speed at a particular instant of time we would draw a tangent to the curve at that instant and find the gradient of the tangent.

The distance–time graph tells us about how the car is travelling in a much more convenient form than the series of drawings in Figure 1.5. We can see that the car is travelling equal distances in equal time intervals – it is moving at a steady or constant speed. This fact is shown immediately by the fact that the graph is a straight line. The slope or **gradient** of the line tells us the speed of the car – the steeper the line the greater the speed of the car. So in this example:

$$\text{speed} = \text{gradient} = \frac{\text{distance}}{\text{time}} = \frac{30\text{ m}}{2.5\text{ s}} = 12\text{ m/s}$$

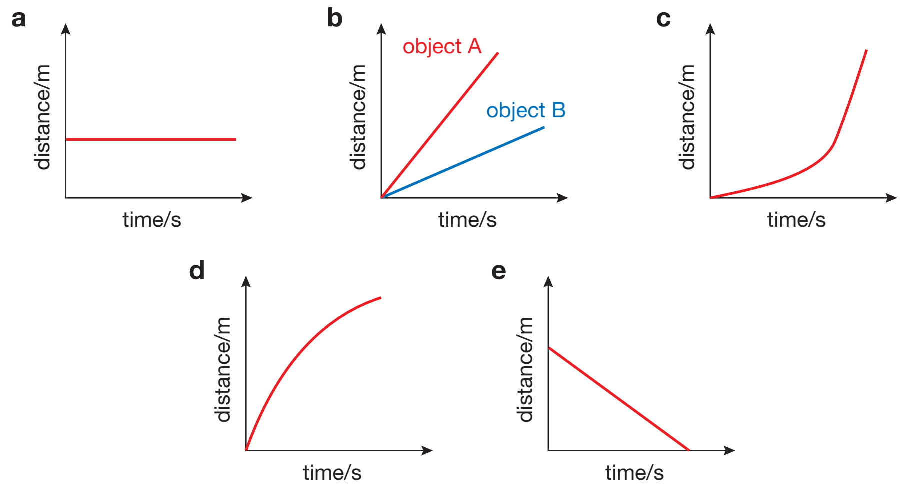

Figure 1.7 Examples of distance–time graphs

In Figure 1.7a the distance is not changing with time – the line is horizontal. This means that the speed is zero. In Figure 1.7b the graph shows how two objects are moving. The red line is steeper than the blue line because object A is moving at a higher speed than object B. In Figure 1.7c the object is speeding up (**accelerating**) shown by the graph line getting steeper (gradient getting bigger). In Figure 1.7d the object is slowing down (decelerating).

THE DIFFERENCE BETWEEN SPEED AND VELOCITY

Some displacement–time graphs look like the one shown in Figure 1.7e. It is a straight line, showing that the object is moving with constant speed, but the line is sloping down to the right rather than up to the right. The gradient of such a line is negative because the distance that the object is from the starting point is now decreasing – the object is going back on its path towards the start. **Displacement** means 'distance travelled in a particular direction' from a specified point. So if the object was originally travelling in a northerly direction, the negative gradient of the graph means that it is now travelling south.

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KEY POINT

A vector is a quantity that has both size and direction. Displacement is distance travelled in a particular direction. **Force** is another example of a vector that you will meet in Chapter 2. The size of a force and the direction in which it acts are both important.

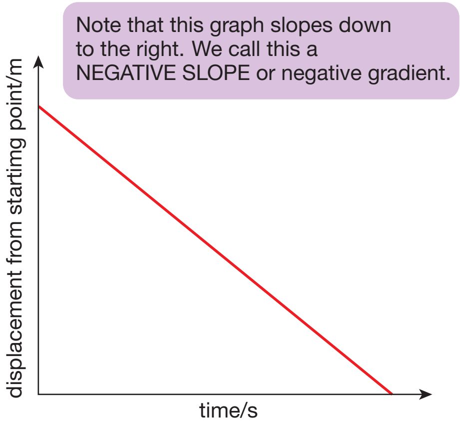


Figure 1.8 In this graph displacement is decreasing with time.

KEY POINT

Always show your working when answering questions. You should show your working by putting the values given in the question into the equation.

Displacement is an example of a vector. Vector quantities have magnitude (size) and a specific direction.

Velocity is also a vector. Velocity is speed in a particular direction. If a car travels at 50 km/h around a bend, its speed is constant but its velocity will be changing for as long as the direction that the car is travelling in is changing.

$$\text{average velocity} = \frac{\text{increase in displacement}}{\text{time taken}}$$

EXAMPLE 1

The global positioning system (GPS) in Figure 1.9 shows two points on a journey. The second point is 3 km north-west of the first.

a A walker takes 45 minutes to travel from the first point to the second. Calculate the average velocity of the walker.

b Explain why the average speed of the walker must be greater than this.

a Write down what you know:

increase in displacement is 3 km north-west

time taken is 45 min (45 min = 0.75 h)

$$\text{average velocity} = \frac{\text{increase in displacement}}{\text{time taken}}$$

$$= 4 \text{ km/h north-west}$$

b The walker has to follow the roads, so the distance walked is greater than the straight-line distance between A and B (the displacement). The walker's average speed (calculated using distance) must be greater than his average velocity (calculated using displacement).

Figure 1.9 The screen of a global positioning system (GPS). A GPS is an aid to navigation that uses orbiting satellites to locate its position on the Earth's surface.

ACTIVITY 1

PRACTICAL: INVESTIGATE THE MOTION OF EVERYDAY OBJECTS SUCH AS TOY CARS OR TENNIS BALLS

You can use the following simple **apparatus** to investigate the motion of a toy car.

You could use this to measure the average speed, v of the car for different values of h.

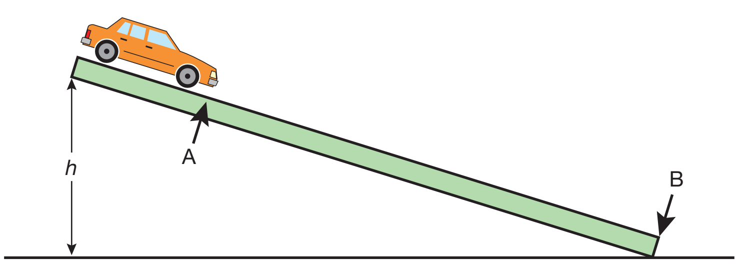


Figure 1.10 Investigating how a toy car rolls down a slope

! Heavy wooden runways need to be stacked and moved carefully. They are best used at low level rather than being placed on benches or tables where they may fall off. If heavy trolleys are used as 'vehicles', a 'catch box' filled with bubble wrap or similar material should be placed at the end of the runway.

You need to measure the height, *h*, of the raised end of the wooden track. The track must be securely clamped at the height under test and *h* should be measured with a metre rule making sure that the rule is **perpendicular** to the bench surface. Make sure that you always measure to the same point or mark on the raised end of the track (a fiducial mark).

To find the average speed you will use the equation:

$$\text{average speed, } v = \frac{\text{distance moved, } s}{\text{time taken, } t}$$

so you will need to measure the distance AB with a metre rule and measure the time it takes for the car to travel this distance with a stop clock. When timing with a stop clock, human **reaction** time will introduce measurement errors. To make these smaller the time to travel distance AB should, for a given value of *h*, be measured at least three times and an average value found. Always start the car from the same point, A. If one value is quite different from the others it should be treated as anomalous (the result is not accurate) and ignored or repeated.

The results should be presented in a table like the one below.

You do not need to include these equations in your table headings but you may be asked to show how you did the calculations.

Distance/m	AB:

Height, h/m	Time, *t*/s			Average time, *t*/s $t = (t1 + t2 + t3) \div 3$	Average speed, *v*/m/s $v = AB \div t$
	*t*1	*t*2	*t*3		

In a question you may be given a complete set of results or you may be required to complete the table by doing the necessary calculations. You may be asked to plot a graph (see general notes above) and then draw a conclusion. The conclusion you draw must be explained with reference to the graph, for example, if the best fit line through the plotted points is a straight line and it passes through the origin (the 0, 0 point) you can conclude that there is a **proportional** relationship between the quantities you have plotted on the graph.

Some alternative methods

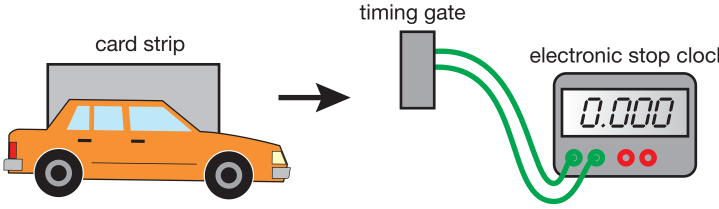
You could investigate the motion of moving objects using photographic methods either by:

- carrying out the experiment in a darkened room using a **stroboscope** to light up the object at regular known intervals (found from the **frequency** setting on the stroboscope) with the camera adjusted so that the shutter is open for the duration of the movement, or
- using a video camera and noting how far the object has travelled between each frame – the frame rate will allow you to calculate the time between each image.

In either case a clearly marked measuring scale should be visible.

Or you could use an electronically operated stop clock and electronic timing gates. This will let you measure the time that it takes for the moving object to travel over a measured distance. This has the advantage of removing timing errors produced by human reaction time.

You can also use timing gates to measure how the speed of the object changes as it moves.



▲ Figure 1.11 Using a timing gate is a more accurate method for measuring time taken to travel a distance.

In this arrangement the stop clock will time while the card strip attached to the moving car passes through the timing gate. Measuring the length of the card strip and the time it takes for the card strip to pass through the timing gate allows you to calculate the average speed of the car as it passes through the timing gate.

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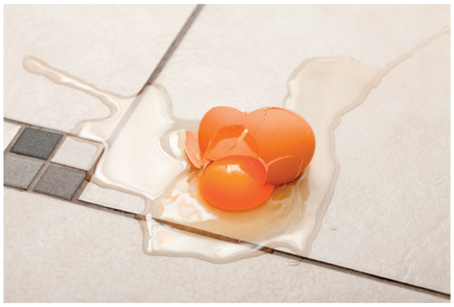
ACCELERATION

Figure 1.12 shows some objects whose speed is changing. The plane must accelerate to reach take-off speed. In ice hockey, the puck (small disc that the player hits) decelerates only very slowly when it slides across the ice. When the egg hits the ground it is forced to decelerate (decrease its speed) very rapidly. Rapid deceleration can have destructive results.

▲ Figure 1.12 Acceleration …

… constant speed …



… and deceleration

Acceleration is the rate at which objects change their velocity. It is defined as follows:

$$\text{acceleration, } a = \frac{\text{change in velocity}}{\text{time taken, } t} \text{ or } \frac{\text{final velocity, } v - \text{initial velocity, } u}{\text{time taken, } t}$$

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

Why u? Simply because it comes before v!

Acceleration, like velocity, is a vector because the direction in which the acceleration occurs is important as well as the size of the acceleration.

UNITS OF ACCELERATION

Velocity is measured in m/s, so increase in velocity is also measured in m/s. Acceleration, the rate of increase in velocity with time, is therefore measured in m/s/s (read as 'metres per second per second'). We normally write this as m/s^2 (read as 'metres per second **squared**'). Other units may be used – for example, cm/s^2.

EXAMPLE 2

A car is travelling at 20 m/s. It accelerates steadily for 5 s, after which time it is travelling at 30 m/s. Calculate its acceleration.

Write down what you know:

initial or starting velocity, u = 20 m/s

final velocity, v = 30 m/s

time taken, t = 5 s

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

$$= \frac{30\,\text{m/s} - 20\,\text{m/s}}{5\,\text{s}}$$

$$= \frac{10\,\text{m/s}}{5\,\text{s}}$$

The car is accelerating at 2 m/s^2.

HINT

It is good practice to include units in equations – this will help you to supply the answer with the correct unit.

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DECELERATION

Deceleration means slowing down. This means that a decelerating object will have a smaller final velocity than its starting velocity. If you use the equation for finding the acceleration of an object that is slowing down, the answer will have a negative sign. A negative acceleration simply means deceleration.

EXAMPLE 3

An object hits the ground travelling at 40 m/s. It is brought to rest in 0.02 s. What is its acceleration?

Write down what you know:

initial velocity, u = 40 m/s

final velocity, v = 0 m/s

time taken, t = 0.02 s

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

$$= \frac{0\,\text{m/s} - 40\,\text{m/s}}{0.02\,\text{s}}$$

$$= \frac{-40\,\text{m/s}}{0.02\,\text{s}}$$

$$= -2000\,\text{m/s}^2$$

In Example 3, we would say that the object is decelerating at 2000 m/s^2. This is a very large deceleration. Later, in Chapter 3, we shall discuss the consequences of such a rapid deceleration!

MEASURING ACCELERATION

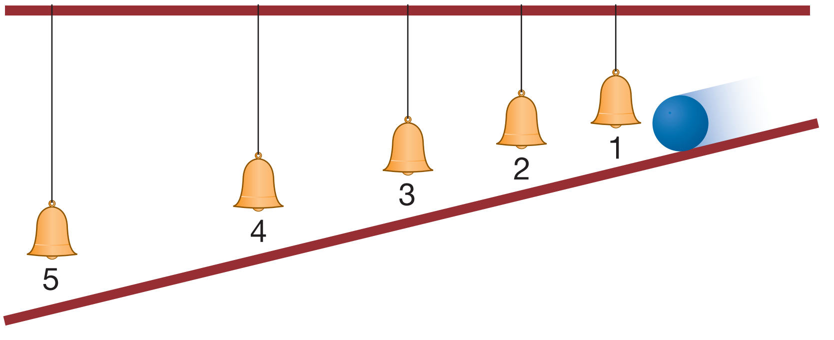
EXTENSION WORK

Galileo was an Italian scientist who was born in 1564. He developed a telescope, which he used to study the movement of the planets and stars. He also carried out many experiments on motion (movement).

EXTENSION WORK

Though Galileo did not have a clock or watch (let alone an electronic timer), he used his pulse (the sound of his heart) and a type of water clock to achieve timings that were accurate enough for his experiments.

When a ball is rolled down a slope it is clear that its speed increases as it rolls – that is, it accelerates. Galileo was interested in how and why objects, like the ball rolling down a slope, speed up, and he created an interesting experiment to learn more about acceleration. A version of his experiment is shown in Figure 1.13.



▲ Figure 1.13 Galileo's experiment. A ball rolling down a slope, hitting small bells as it rolls

Galileo wanted to discover how the distance travelled by a ball depends on the time it has been rolling. In this version of the experiment, a ball rolling down a slope strikes a series of small bells as it rolls. By adjusting the positions of the bells carefully it is possible to make the bells ring at equal intervals of time as the ball passes. Galileo noticed that the distances travelled in equal time intervals increased, showing that the ball was travelling faster as time passed. Galileo did not have an accurate way of measuring time (there were no digital stopwatches in seventeenth-century Italy!) but it was possible to judge equal time intervals accurately simply by listening.

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Galileo also noticed that the distance travelled by the ball increased in a predictable way. He showed that the rate of increase of speed was steady or uniform. We call this uniform acceleration. Most acceleration is non-uniform – that is, it changes from instant to instant – but we shall only deal with uniformly accelerated objects in this chapter.

VELOCITY–TIME GRAPHS

The table below shows the distances between the bells in an experiment such as Galileo's.

Bell	1	2	3	4	5
Time/s	0.5	1.0	1.5	2.0	2.5
Distance of bell from start/cm	3	12	27	48	75

We can calculate the average speed of the ball between each bell by working out the distance travelled between each bell, and the time it took to travel this distance. For the first bell:

$$\text{velocity, } v = \frac{\text{distance moved, } s}{\text{time taken, } t}$$

$$= \frac{3\,\text{cm}}{0.5\,\text{s}} = 6\,\text{cm/s}$$

This is the average velocity over the 0.5 second time interval, so if we plot it on a graph we should plot it in the middle of the interval, at 0.25 seconds.

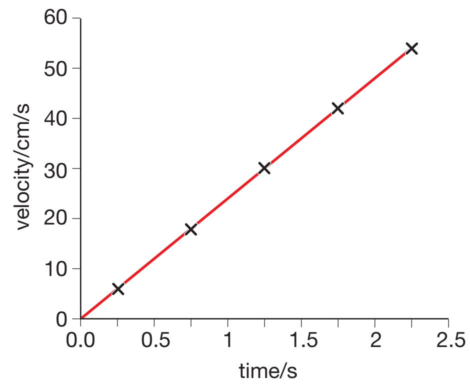
Repeating the above calculation for all the results gives us the following table of results. We can use these results to draw a graph showing how the velocity of the ball is changing with time. The graph, shown in Figure 1.14, is called a velocity–time graph.

Time/s	0.25	0.75	1.25	1.75	2.25
Velocity/cm/s	6	18	30	42	54

KEY POINT

The equations of motion we have learned work for uniform or constant acceleration only – therefore for objects with velocity–time graphs that are straight lines.

The graph in Figure 1.14 is a straight line. This tells us that the velocity of the rolling ball is increasing by equal amounts in equal time periods. We say that the acceleration is uniform in this case.



▲ Figure 1.14 Velocity–time graph for an experiment in which a ball is rolled down a slope. (Note that as we are plotting average velocity, the points are plotted in the middle of each successive 0.5 s time interval.)

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A MODERN VERSION OF GALILEO'S EXPERIMENT

! A cylinder vacuum cleaner (or similar) used with the air-track should be placed on the floor as it may fall off a bench or stool. Also, beware of any trailing leads.

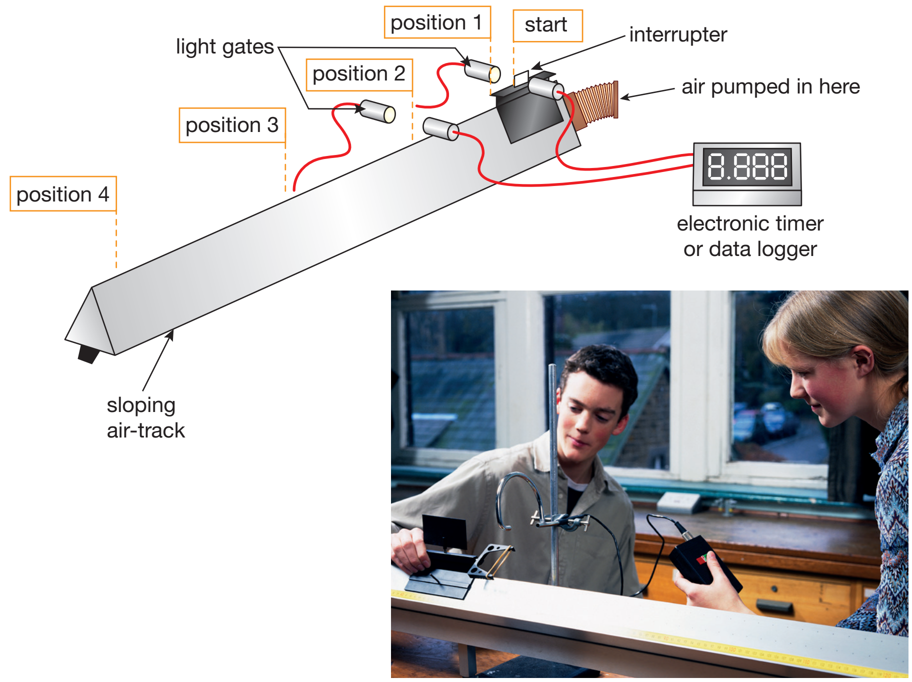
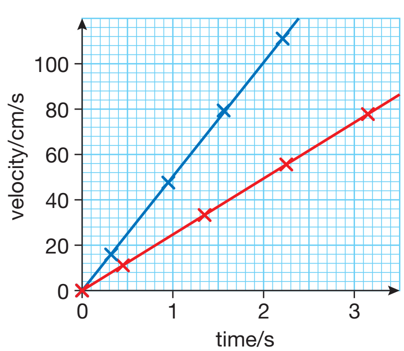


Figure 1.15 Measuring acceleration

Today we can use data loggers to make accurate direct measurements that are collected and analysed by a computer. A spreadsheet program can be used to produce a velocity–time graph. Figure 1.15 shows a glider on a slightly sloping air-track. The air-track reduces **friction** because the glider rides on a cushion of air that is pushed continuously through holes along the air-track. As the glider accelerates down the sloping track the card stuck on it breaks a light beam, and the time that the glider takes to pass is measured electronically. If the length of the card is measured, and this is entered into the spreadsheet, the velocity of the glider can be calculated by the spreadsheet program using $v = \frac{s}{t}$.

Figure 1.16 shows velocity–time graphs for two experiments done using the air-track apparatus. In each experiment the track was given a different slope. The steeper the slope of the air-track the greater the glider's acceleration. This is clear from the graphs: the greater the acceleration the steeper the gradient of the graph.

The gradient of a velocity–time graph gives the acceleration.



Air-track at 1.5°		Air-track at 3.0°	
Time/s	Av Vel. /cm/s	Time/s	Av Vel. /cm/s
0.00	0.0	0.00	0.0
0.45	11.1	0.32	15.9
1.35	33.3	0.95	47.6
2.25	55.6	1.56	79.4
3.15	77.8	2.21	111.1

Figure 1.16 Results of two air-track experiments. (Note, once again, that because we are plotting average velocity in the velocity–time graphs, the points are plotted in the middle of each successive time interval – see page 11)

MORE ABOUT VELOCITY–TIME GRAPHS

GRADIENT

The results of the air-track experiments in Figure 1.16 show that the slope of the velocity–time graph depends on the acceleration of the glider. The slope or gradient of a velocity–time graph is found by dividing the increase in the velocity by the time taken for the increase, as shown in Figure 1.17. In this example an object is travelling at u m/s at the beginning and accelerates uniformly (at a constant rate) for t s. Its final velocity is v m/s. Increase in velocity divided by time is, you will recall, the definition of acceleration (see page 9), so we can measure the acceleration of an object by finding the slope of its velocity–time graph. The meaning of the slope or gradient of a velocity–time graph is summarised in Figure 1.17.

HINT

1. When finding the gradient of a graph, draw a big triangle.
2. Choose a convenient number of units for the length of the base of the triangle to make the division easier.

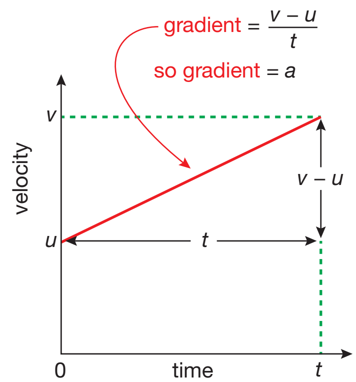


Figure 1.17 Finding the gradient of a velocity–time graph

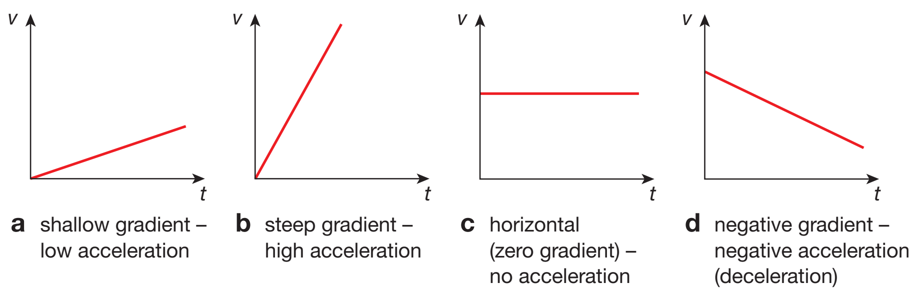


Figure 1.18 The gradient of a velocity–time graph gives you information about the motion of an object at a glance.

AREA UNDER A VELOCITY–TIME GRAPH GIVES DISTANCE TRAVELLED

Figure 1.19a shows a velocity–time graph for an object that travels with a constant velocity of 5 m/s for 10 s. A simple calculation shows that in this time the object has travelled 50 m. This is equal to the shaded (coloured) area under the graph. Figure 1.19b shows a velocity–time graph for an object that has accelerated at a constant rate. Its average velocity during this time is given by:

$$\text{average velocity} = \frac{\text{initial velocity} + \text{final velocity}}{2} \text{ or } \frac{u+v}{2}$$

In this example the average velocity is, therefore:

$$\text{average velocity} = \frac{0\,\text{m/s} + 10\,\text{m/s}}{2}$$

which works out to be 5 m/s. If the object travels, on average, 5 metres in each second it will have travelled 20 metres in 4 seconds. Notice that this, too, is equal to the shaded area under the graph (given by the area equation for a triangle: area = $\frac{1}{2}$ base × height).

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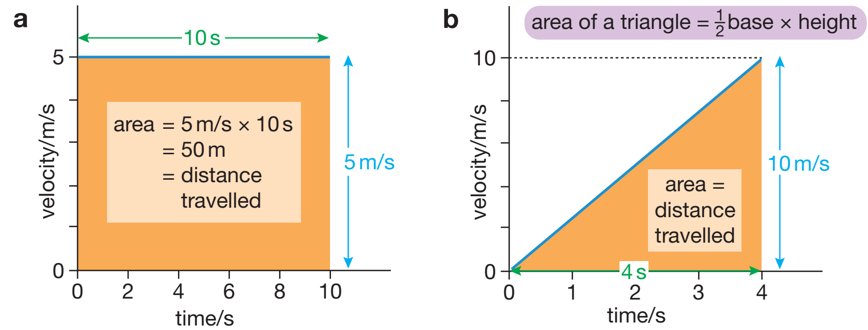
HINT

Find the distance travelled for more complicated velocity–time graphs by dividing the area beneath the graph line into rectangles and triangles. Take care that units on the velocity and time axes use the same units for time, for example, m/s and s, or km/h and h.

The area under a velocity–time graph is equal to the distance travelled by (displacement of) the object in a particular time interval.



▲ Figure 1.19 a An object travelling at constant velocity; b An object accelerating at a constant rate

EQUATIONS OF UNIFORMLY ACCELERATED MOTION

You must remember the equation:

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

and be able to use it to calculate the acceleration of an object.

You may need to rearrange the equation to make another term the subject.

EXAMPLE 4

A stone accelerates from rest uniformly at 10 m/s^2 when it is dropped down a deep well. It hits the water at the bottom of the well after 5 s. Calculate how fast it is travelling when it hits the water.

You will need to make v the subject of this equation:

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

You can use the triangle method to show that $v - u = a \times t$

then add u to both sides of the equation to give:

$$v = u + at$$

(In words this tells you that the final velocity is the initial velocity plus the increase in velocity after accelerating for t seconds.)

State the things you have been told:

initial velocity, u = 0 m/s (It was stationary (standing still) at the start.)

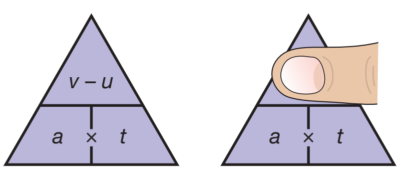
acceleration, a = 10 m/s^2

time, t, of the acceleration = 5 s

Substitute these into the equation: v = 0 m/s + (10 m/s^2 × 5 s)

Then calculate the result.

The stone hit the water travelling at 50 m/s (downwards).



▲ Figure 1.20 Cover $v - u$ to find $v - u = a \times t$

You will also be required to use the following equation of uniformly accelerated motion:

(final speed)^2, v^2 = (initial speed)^2, u^2 + (2 × acceleration, a × distance moved, s)

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

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EXAMPLE 5

A cylinder containing a vaccine is dropped from a helicopter hovering at a height of 200 m above the ground. The acceleration due to **gravity** is 10 m/s^2. Calculate the speed at which the cylinder will hit the ground.

You are given the acceleration, a = 10 m/s^2, and the distance, s = 200 m, through which the cylinder moves. The initial velocity, u, is not stated, but you assume it is 0 m/s as the helicopter is hovering (staying in one place in the air). Substitute these values in the given equation:

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

$$= 0 \text{ m/s}^2 + (2 \times 10 \text{ m/s}^2 \times 200 \text{ m})$$

$$= 4000 \text{ m}^2/\text{s}^2$$

$$\text{therefore } v = \sqrt{(4000 \text{ m}^2/\text{s}^2)}$$

$$= 63.25 \text{ m/s}$$

LOOKING AHEAD

The equations you have seen in this chapter are called the equations of uniformly accelerated motion. This means that they will give you correct answers when solving any problems that have objects moving with constant acceleration. In your exam you will only see problems where this is the case or very nearly so. Examples in which objects accelerate or decelerate (slow down) at a constant rate often have a constant acceleration due to the Earth's gravity (which we take as about 10 m/s^2).

In real life, problems may not be quite so simple! Objects only fall with constant acceleration if we ignore air resistance and the distance that they fall is quite small.

These equations of uniformly accelerated motion are often called the 'suvat' equations, because they show how the terms s (distance moved), u (velocity at the start), v (velocity at the finish), a (acceleration) and t (time) are related.

CHAPTER QUESTIONS

More questions on speed and acceleration can be found at the end of Unit 1 on page 55.

SKILLS PROBLEM SOLVING

7

1 A sprinter runs 100 metres in 12.5 seconds. Calculate the speed in m/s.

8

2 A jet can travel at 350 m/s. Calculate how far it will travel at this speed in:

- a 30 seconds
- b 5 minutes
- c half an hour.

3 A snail crawls at a speed of 0.0004 m/s. How long will it take to climb a garden stick 1.6 m high?

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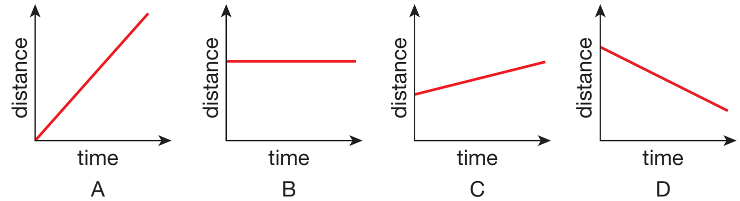
SKILLS ANALYSIS

4 Look at the following distance–time graphs of moving objects.



Identify in which graph the object is:

a moving backwards

b moving slowly

c moving quickly

d not moving at all.

SKILLS INTERPRETATION

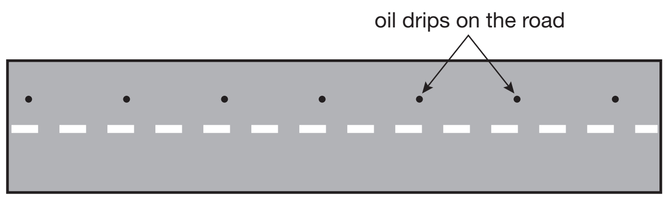
5 Sketch a distance–time graph to show the motion of a person walking quickly, stopping for a moment, then continuing to walk slowly in the same direction.

6 Plot a distance–time graph using the data in the following table. Draw a line of best fit and use your graph to find the speed of the object concerned.

Distance/m	0.00	1.60	3.25	4.80	6.35	8.00	9.60
Time/s	0.00	0.05	0.10	0.15	0.20	0.25	0.30

SKILLS PROBLEM SOLVING

7 The diagram below shows a trail of oil drips made by a car as it travels along a road. The oil is dripping from the car at a steady rate of one drip every 2.5 seconds.



a Describe the way the car is moving.

b The distance between the first and the seventh drip is 135 metres. Determine the average speed of the car.

8 A car is travelling at 20 m/s. It accelerates uniformly at 3 m/s^2 for 5 s.

a Sketch a velocity–time graph for the car during the period that it is accelerating. Include numerical detail on the axes of your graph.

b Calculate the distance the car travels while it is accelerating.

SKILLS INTERPRETATION

9 Explain the difference between the following terms:

a average speed and instantaneous speed

b speed and velocity.

SKILLS PROBLEM SOLVING

10 A sports car accelerates uniformly from rest to 24 m/s in 6 s. Calculate the acceleration of the car.

SKILLS INTERPRETATION

11 Sketch velocity–time graphs for an object:

a moving with a constant velocity of 6 m/s

b accelerating uniformly from rest at 2 m/s^2 for 10 s

c decelerating to rest at 4 m/s^2 for 5 s.

Include numbers and units on the velocity and time axes in each case.

SKILLS PROBLEM SOLVING

12 A plane starting from rest accelerates at 3 m/s^2 for 25 s. Calculate the increase in velocity after:

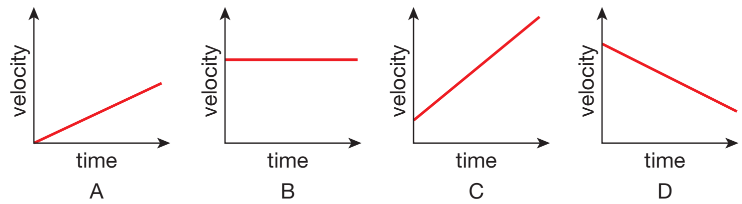
a 1 s

b 5 s

c 25 s.

SKILLS ANALYSIS

13 Look at the following sketches of velocity–time graphs of moving objects.



In which graph is the object:

a not accelerating

b accelerating from rest

c decelerating

d accelerating at the greatest rate?

SKILLS INTERPRETATION

14 Sketch a velocity–time graph to show how the velocity of a car travelling along a straight road changes if it accelerates uniformly from rest for 5 s, travels at a constant velocity for 10 s, then brakes hard to come to rest in 2 s.

15 **a** Plot a velocity–time graph using the data in the following table:

Velocity/m/s	0.0	2.5	5.0	7.5	10.0	10.0	10.0	10.0	10.0	10.0
Time/s	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0

Draw a line of best fit and use your graph to find:

b the acceleration during the first 4 s

c the distance travelled in:

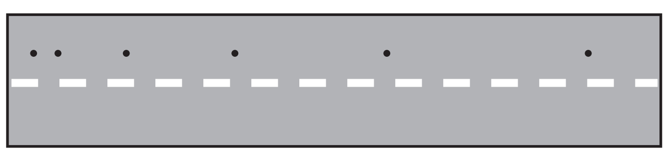
i the first 4 s of the motion shown

ii the last 5 s of the motion shown

d the average speed during the 9 seconds of motion shown.

SKILLS CRITICAL THINKING

16 The dripping car from Question 7 is still on the road! It is still dripping oil but now at a rate of one drop per second. The trail of drips is shown on the diagram below as the car travels from left to right.



Describe the motion (the way the car is moving) using the information in this diagram.

SKILLS PROBLEM SOLVING

17 This question uses the equation $v^2 = u^2 + 2as$.

a Explain what each of the terms in this equation represents.

b A ball is thrown vertically upwards at 25 m/s. Gravity causes the ball to decelerate at 10 m/s^2. Calculate the maximum height the ball will reach.

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2 FORCES AND SHAPE

Forces are acting on us, and on objects all around us, all the time. In this chapter you will learn about different kinds of forces, how they may change the speed and direction of objects and how they can affect the shape of objects.

▲ Figure 2.1 Forces include pulling, falling due to gravity and squashing

LEARNING OBJECTIVES

- Describe the effects of forces between bodies such as changes in speed, shape or direction
- Identify different types of force such as gravitational or electrostatic
- Understand how vector quantities differ from scalar quantities
- Understand that force is a vector quantity
- Calculate the resultant force of forces that act along a line
- Know that friction is a force that opposes motion
- Practical: investigate how extension varies with applied force for helical springs, metal wires and rubber bands
- Know that the initial linear region of a force–extension graph is associated with Hooke’s law
- Describe elastic behaviour as the ability of a material to recover its original shape after the forces causing deformation have been removed

Forces are simply pushes and pulls of one thing on another. Sometimes we can see their effects quite clearly. In Figure 2.1, the tug is pulling the tanker; the bungee jumper is being pulled to Earth by the force of gravity, and then (hopefully before meeting the ground) being pulled back up by the stretched elastic rope; the force applied by the crusher permanently changes the shape of the cars. In this chapter we will discuss different types of forces and look at their effects on the way that objects move.

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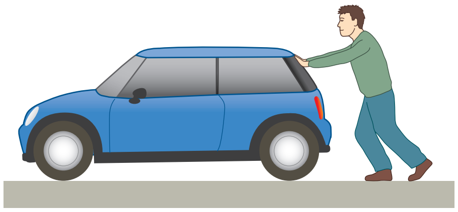
ALL SORTS OF FORCES

If you are to study forces, first you need to notice them! As we have already said, sometimes they are easy to see and their effect is obvious. Look at Figure 2.2 and try to identify any forces that you think are involved.

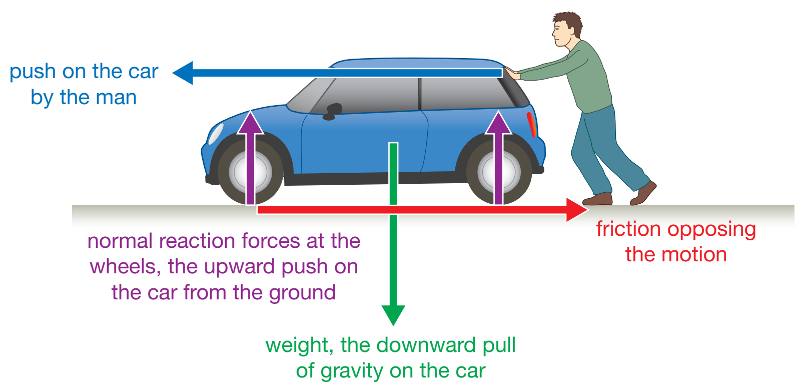


▲ Figure 2.2 What forces do you think are working here?

You will immediately see that the man is applying a force to the car – he is pushing it. But there are quite a few more forces in the picture. To make the task a little easier we will limit our search to just those forces acting on the car. We will also ignore forces that are very small and therefore have little effect.

The man is clearly struggling to make the car move. This is because there is a force acting on the car trying to stop it moving. This is the force of friction between the moving parts in the car engine, gears, wheel axles and so on. This unhelpful force opposes the motion that the man is trying to achieve. However, when the car engine is doing the work to make the car go, the friction between the tyres and the road surface is vital. On an icy road even powerful cars may not move forward because there is not enough friction between the tyres and the ice.

Another force that acts on the car is the pull of the Earth. We call this a gravitational force or simply **weight**. If the car were to be pushed over the edge of a cliff, the effect of the gravitational force would be very clear as the car fell towards the sea. This leads us to realise that yet another force is acting on the car in Figure 2.2 – the road must be stopping the car from being pulled into the Earth. This force, which acts in an upward direction (going up) on the car, is called the reaction force. (A more complete name is **normal** reaction force. Here the word 'normal' means acting at 90° to the road surface.) All four forces that act on the car are shown in Figure 2.3.



▲ Figure 2.3 There are four types of force at work.

You will have realised by now that it is not just the size of the force that is important – the direction in which the force is acting is important, too.

Force is another example of a vector.

KEY POINT

Like displacement, velocity and acceleration, force is a *vector quantity* because both its size and direction matter. Some quantities, such as temperature, have no direction connected with them. They are known as *scalar quantities*.

UNITS OF FORCE

The unit used to measure force is the newton (N), named after Sir Isaac Newton. Newton's study of forces is vital to our understanding of them today.

A force of one newton will make a **mass** of one kilogram accelerate at one metre per second squared.

This is explained more fully later (see Chapter 3). To give you an idea of the size of the newton, the force of gravity on a kilogram bag of sugar (its weight) is about 10 N; an average-sized apple weighs 1 N.

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▲ Figure 2.4 More forces!

SOME OTHER EXAMPLES OF FORCES

It is not always easy to spot forces acting on objects. The compass needle in Figure 2.4a, which is a magnet, is affected by the magnetic force between it and the other magnet. Magnetic forces are used to make electric motors **rotate**, to hold fridge doors shut, and in many other situations.

If you comb your hair, you sometimes find that some of your hair sticks to the comb as shown in Figure 2.4b. This happens because of an electrostatic force between your hair and the comb. You can see a similar effect using a Van de Graaff **generator**, as shown in Figure 9.6 on page 87.

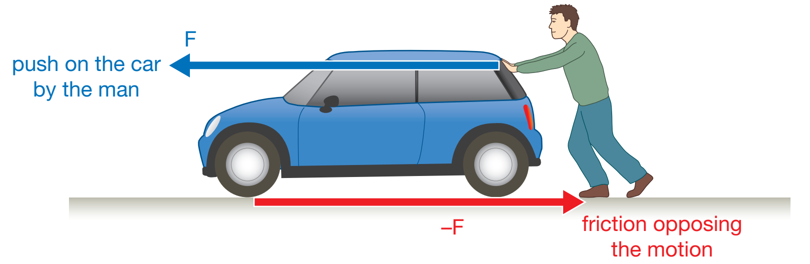
A parachute causes the parachutist to descend more slowly because an upward force acts on the parachute called air resistance or drag. Air resistance is like friction – it tries to oppose movement of objects through the air. Designers of cars, high-speed trains and other fast-moving objects try to reduce the effects of this force. Objects moving through liquids also experience a drag force – fast-moving animals that live in water have streamlined (smooth and efficient) shapes to reduce this force.

Hot air balloons are carried upwards in spite of the pull of gravity on them because of a force called **upthrust**. This is the upward push of the surrounding air on the balloon. An upthrust force also acts on objects in liquids.

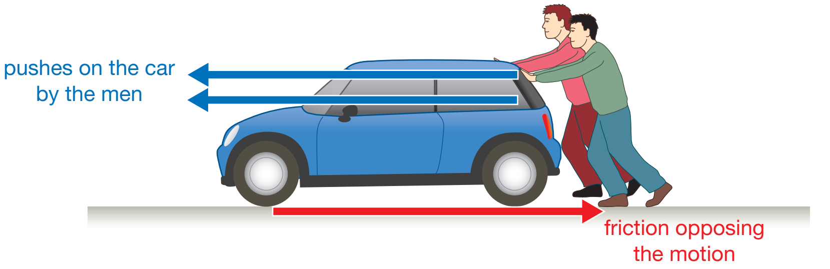
More types of force, such as electric and **nuclear** forces, are mentioned in other chapters of this book. The rest of this chapter will look at the effects of forces.

MORE THAN ONE FORCE

As we saw earlier, in most situations there will be more than just one force acting on an object. Look at the man trying to push the car, shown in Figure 2.5. The two forces act along the same line, but in opposite directions. This means that one is negative (because it acts in the opposite direction to the other) and, if they are equal in size, they add up to zero and the car will not move.



▲ Figure 2.5 The **resultant force** is zero because the two forces are balanced.



▲ Figure 2.6 The total pushing force is the **sum** of the two individual forces.

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If the man gets someone to help him push the car, the forward force is bigger. Both of the forces pushing the car are acting in the same direction, so you can find the total forward force by adding the two forces together. If both people are pushing with a force of 300 N, then:

total forward force = 300 N + 300 N
= 600 N

This means we can just add all the forces together to find the resultant force. As force is a vector quantity, we also need to think about the directions in which the forces are acting, and we do this by deciding which direction is the positive (+) direction. In this case, we can think of the force from the people as positive and the force from friction as negative. The + and – signs just show that the forces are acting in opposite directions.

So, if the force from friction is 300 N:

unbalanced force = 300 N + 300 N – 300 N
= 300 N

BALANCED AND UNBALANCED FORCES

Figure 2.7 Balanced forces and unbalanced forces

Figure 2.7 shows two situations in which forces are acting on an object. In the tug of war contest the two teams are pulling on the rope in opposite directions. For much of the time the rope doesn't move because the two forces are balanced. This means that the forces are the same size but act in opposite directions along the line of the rope. There is no unbalanced force in one direction or the other. When the forces acting on something are balanced, the object does not change the way it is moving. In this case if the rope is stationary, it remains stationary. Eventually, one of the teams will become tired and its pull will be smaller than that of the other team. When the forces acting on the rope are unbalanced the rope will start to move in the direction of the greater force. There will be an unbalanced force in that direction. Unbalanced forces acting on an object cause it to change the way it is moving. The rope was stationary and the unbalanced forces acting on it caused it to accelerate.

The car in Figure 2.7 is designed to have an enormous acceleration from rest. As soon as it starts to move the forces that oppose motion – friction and drag – must be overcome. The **thrust** of the engine is, to start with, much greater than the friction and drag forces. This means that the forces acting on the car in the horizontal direction are unbalanced and the result is a change in the way that the car is moving – it accelerates! Once the friction forces balance the thrust the car no longer accelerates – it moves at a steady speed.

FRICTION

Friction is the force that causes moving objects to slow down and finally stop. The **kinetic energy** of the moving object is transferred to heat as work is done by the friction force. For the ice skater in Figure 2.8 the force of friction is very small so she is able to glide for long distances without having to do any work. It is also the force that allows a car's wheels to grip the road and make it accelerate – very quickly in the case of the racing cars in Figure 2.8.

Scientists have worked hard for many years to develop some materials that reduce friction and others that increase friction. Reducing friction means that machines work more efficiently (wasting less energy) and do not wear out so quickly. Increasing friction can help to make tyres that grip the road better and to make more effective brakes.

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Figure 2.8 The ice skater can glide because friction is low. The cars need friction to grip the road.

Friction occurs when solid objects rub against other solid objects and also when objects move through fluids (liquids and gases). Sprint cyclists and Olympic swimmers now wear special materials to reduce the effects of fluid friction so they can achieve faster times in their races. Sometimes fluid friction is very desirable – for example, when someone uses a parachute after jumping from a plane!

INVESTIGATING FRICTION

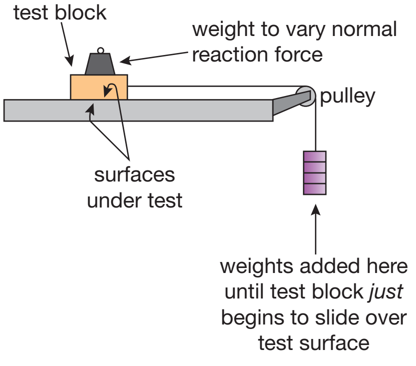

Figure 2.9 This apparatus can be used to investigate friction.

! A 'catch box' filled with bubble wrap (or similar) under the suspended masses keeps hands and feet out of the 'drop zone'.

The simple apparatus shown in Figure 2.9 can be used to discover some basic facts about friction. The weight force on the line running over the pulley pulls the block horizontally along the track and friction acts on the block to oppose this force. The weight is increased until the block just starts to move; this happens when the pull of the weight force just overcomes the friction force. The friction force between the block and the track has maximum value.

The apparatus can be used to test different factors that may affect the size of the friction force, such as the surfaces in contact – the bottom of the block and the surface of the track. If the track surface is replaced with a rough surface, like a sheet of sandpaper, the force required to overcome friction will be greater.

It is important to remember friction when you are investigating forces and motion. Friction affects almost every form of motion on Earth. However it is possible to do experiments in the science laboratory in which the friction force on a moving object is reduced to a very low value. Such an object can be set in motion with a small push and it will continue to move at a constant speed even when the force is no longer acting on it. An experiment like this is shown in Figure 2.10.

You may also have seen scientists working in space demonstrating that objects keep moving in a straight line at constant speed, once set in motion. They do this in space because the objects are **weightless** and the force of air resistance acting on them is very small.

EXTENSION WORK

Objects in orbit, such as spacecraft, are described as 'weightless' because they do not appear to have weight. However the Earth's gravity is still acting on them, and on the spacecraft. You can think of a spacecraft in orbit as 'falling around the Earth'. As the objects inside the spacecraft are also falling around the Earth at the same rate, they do not seem to fall inside the spacecraft.

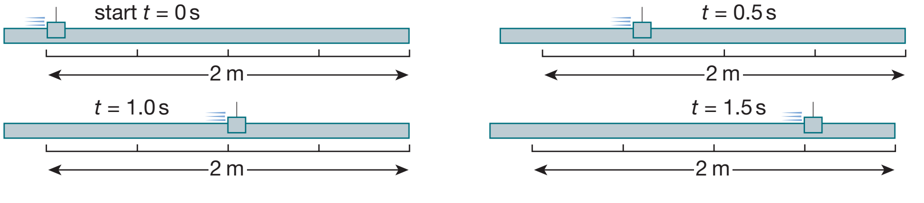

Figure 2.10 A linear (straight line) air-track reduces friction dramatically. The glider moves equal distances in equal time intervals. Its velocity is constant.

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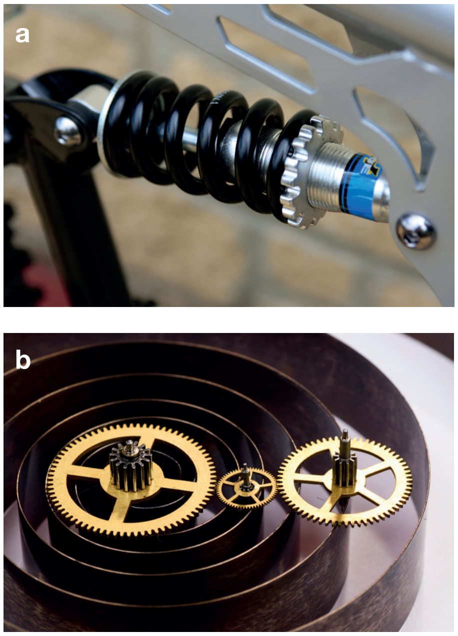

Figure 2.11 Forces can cause changes in shape.

CHANGING SHAPES

We have seen that forces can make things start to move, accelerate or decelerate. The examples in Figure 2.11 show another effect that forces can have – they can change the shape of an object.

Sometimes the change of shape is temporary, as in the suspension spring in the mountain bike (Figure 2.11a). Sometimes the shape of the object is permanently changed, like a crushed can or a car that has collided with another object. A temporary change of shape may provide a useful way of absorbing and storing energy, as in the spring in a clock (Figure 2.11b). A permanent change may mean the failure of a structure like a bridge to support a load. Next we will look at temporary changes in the lengths of springs and elastic bands.

TEMPORARY CHANGES OF SHAPE

If you apply a force to an elastic band, its shape changes – the band stretches and gets longer. All materials will stretch a little when you put them under tension (that is, pull them) or shorten when you compress or squash them. You can stretch a rubber band quite easily, but a huge force is needed to cause a noticeable extension in a piece of steel of the same length.

Some materials, like glass, do not change shape easily and are brittle, breaking rather than stretching noticeably. Elastic materials do not break easily and tend to return to their original shape when the forces acting on them are removed, like the spring in Figure 2.11b. Other materials, like putty and modelling clay, are not elastic but plastic, and they change shape when even quite small forces are applied to them.

We will look at elastic materials, like rubber, metal wires and metals formed into springs, in the next part of this chapter.

SPRINGS AND WIRES

Springs are coiled lengths of certain types of metal, which can be stretched or **compressed** by applying a force to them. They are used in many different situations. Sometimes they are used to absorb raised bumps in the road as suspension springs in a car or bicycle. In beds and chairs they are used to make sleeping and sitting more comfortable. They are also used in door locks to hold them closed and to make doors close automatically.

To choose the right spring for a particular use, we must understand some important features of springs. A simple experiment with springs shows us that:

> *Springs change length when a force acts on them and they return to their original length when the force is removed.*

This is true provided you do not stretch them too much. If springs are stretched beyond a certain point they do not spring back to their original length.

HOOKE'S LAW

Robert Hooke discovered another important property of springs. He used simple apparatus like that shown in Figure 2.12.

Hooke measured the increase in length (extension) produced by different load forces on springs. The graph he obtained by plotting force against extension was a straight line passing through the origin. This shows that the extension of the spring is proportional to the force. This relationship is known as Hooke's law.

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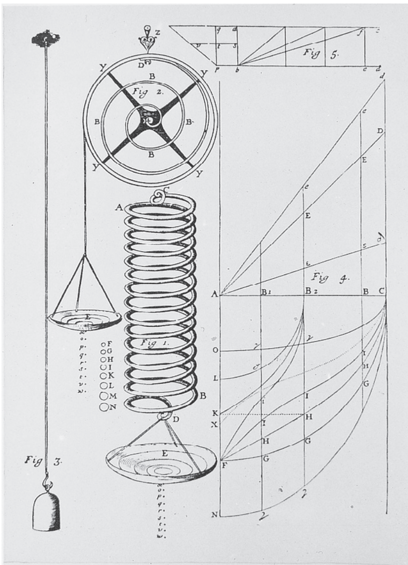

Figure 2.12 Robert Hooke (1635–1703) was a contemporary of Sir Isaac Newton. This is a drawing of the apparatus Hooke used in his experimental work on the extension of a spring.

! Wear eye protection if heavy loads are being used and clamp stands securely to a bench or table. Keep hands and feet away from beneath the load. Do not use excessively large loads.

ACTIVITY 1

▼ PRACTICAL: INVESTIGATE HOW THE EXTENSION OF A SPRING CHANGES WITH LOAD

Figure 2.13a shows apparatus that may be used to investigate the relationship between the force applied to a spring and its extension.

The length of the unstretched spring is measured with a half-metre rule then the spring is loaded with different weights. The extension for each load is measured against a scale using a set square to improve measurement accuracy.

A table of results is recorded and a graph of load force against extension plotted as shown in Figure 2.13b. The extension measurements can be checked by unloading the weights one at a time and remeasuring the extension for each load.

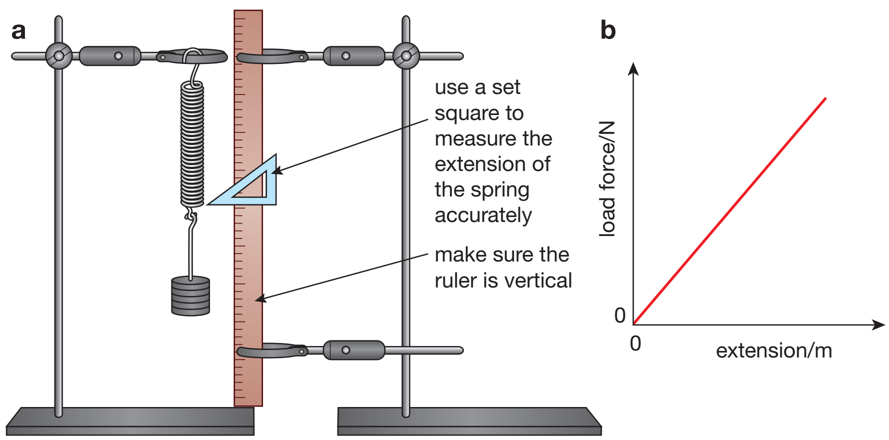

Figure 2.13 **a** Apparatus for the investigation **b** Graph showing expected result

Here the result is a straight line graph passing through the origin of the axes. The spring obeys Hooke's law.

Hooke's law only applies if you do not stretch a spring too far. Figure 2.14 shows what happens if you stretch a spring too far. You can see that the line starts to curve at a point called the limit of proportionality. This is the point where the spring stops obeying Hooke's law and starts to stretch more for each increase in the load force. If the load is increased more, a point called the elastic limit is reached. Once you have stretched a spring beyond the elastic limit it will not return to its original length as you take the weights off the spring.

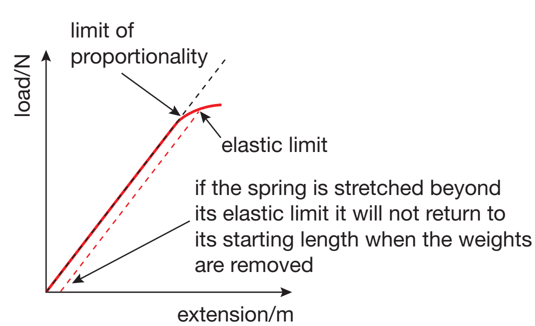

Figure 2.14 Graph of load v extension showing spring going beyond elastic limit

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Hooke's law also applies to wires. If you stretch a wire, you will find that the extension is proportional to the load up to a certain load then it may behave as the spring shown in Figure 2.14. Wires made of different metals will behave in different ways – some will obey Hooke's law until the wire breaks; other types of metal will stretch elastically and then plastically before breaking.

ELASTIC BANDS

Wear eye protection because if the elastic band breaks it can fly back with enough energy to cause serious eye damage.

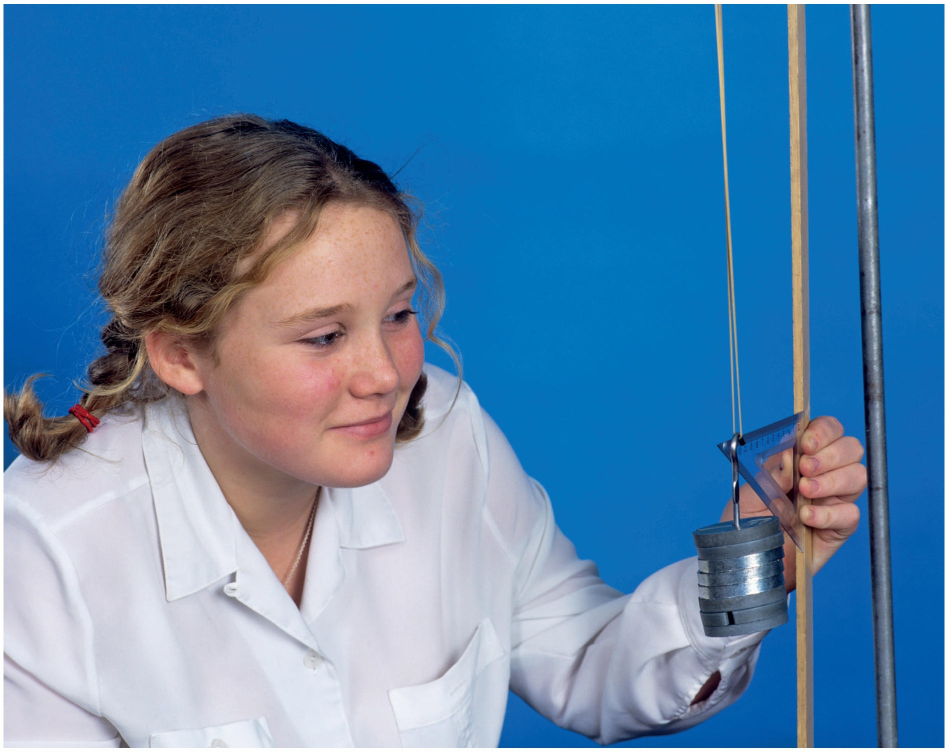


Figure 2.15 Stretching an elastic band

REMINDER

A wire that stretches elastically will return to its original length once the stretching force is removed. A wire that stretches plastically will not return to its original length once the stretching force is removed and may show signs of narrowing (necking).

Elastic bands are usually made of rubber. You can use the same apparatus shown in Figure 2.13a to investigate how an elastic band stretches under load. If you stretch an elastic band with increasing load forces, you get a graph like that shown in Figure 2.16. The graph is not a straight line, showing that elastic bands do not obey Hooke's law. You may also find that the extension produced by a given load force is different when you are increasing the load force to when you decrease the load force.

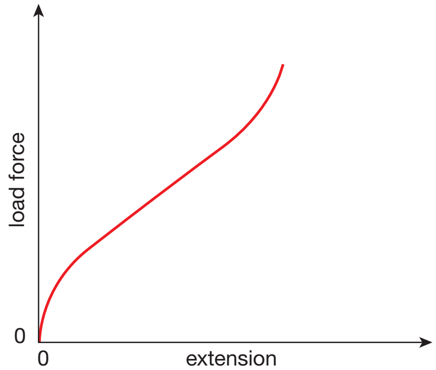


Figure 2.16 Rubber bands do not obey Hooke's law – the extension is not directly proportional to the force causing it.

CHAPTER QUESTIONS

More questions on forces can be found at the end of Unit 1 on page 55.

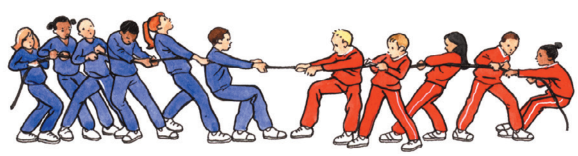
SKILLS CRITICAL THINKING

1 Name the force that:
   a causes objects to fall towards the Earth
   b makes a ball rolled across level ground eventually stop
   c stops a car sinking into the road surface.

2 Name two types of force that oppose motion.

SKILLS PROBLEM SOLVING

3 The drawing shows two tug-of-war teams. Each person in the red team is pulling with a force of 250 N. Each person in the blue team is pulling with a force of 200 N.

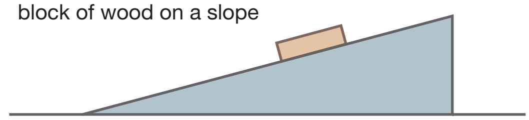


   a What is the total force exerted by the blue team?
   b What is the total force exerted by the red team?
   c What is the resultant (unbalanced) force on the rope?
   d Which team will win?

SKILLS INTERPRETATION

4 The diagram below shows a block of wood on a sloping surface. Copy the diagram and label all the forces that act on the block of wood.

block of wood on a slope



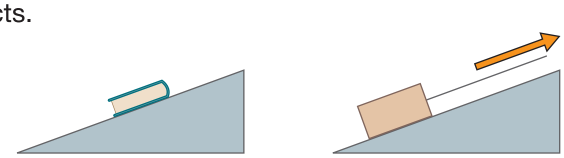
5 A car is travelling along a level road at constant velocity (that is, its speed and direction are not changing). Draw a labelled diagram to show the forces that act on the car.

SKILLS CRITICAL THINKING

6 Describe two things that it would be impossible to do without friction.

SKILLS INTERPRETATION

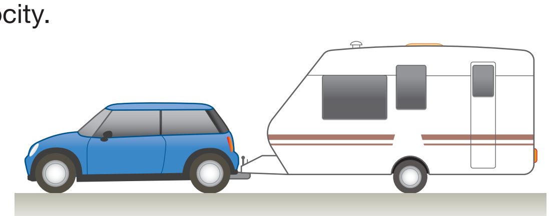
7 Copy the diagrams below and label the direction in which friction is acting on the objects.



a a book on a sloping surface

b a block of wood being pulled up a slope

8 The drawing below shows a car pulling a caravan. They are travelling at constant velocity.



   a Copy the drawing. Label the forces that are acting on the caravan with arrows showing the direction that they act in.
   b Label the forces that act on the car.

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SKILLS PROBLEM SOLVING

9 The information in the following table was obtained from an experiment with a spring of original (unstretched) length 5 cm.

Load force on spring /newtons	Length of spring /cm	Extension of spring /cm
0	5.0	
2	5.8	
4	6.5	
6	7.4	
8	8.3	
10	9.7	
12	12.9	

5 **a** Copy and complete the table by calculating the extensions produced by each load.

SKILLS INTERPRETATION

6 **b** Use your table to plot a graph of force (*y*-axis) against extension (*x*-axis).

4 **c** Mark on your graph the part that shows Hooke's law.

SKILLS REASONING

5 **d** Sketch the shape of the graph you would expect if you carried out the same experiment using an elastic band instead of a spring.

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3 FORCES AND MOVEMENT

The way an object moves depends upon its mass and the unbalanced force acting upon it. In this chapter you will find out how forces affect the way an object will move, particularly in the context of car safety.

a


b


▲ Figure 3.1 **a** This aircraft has only a short distance to travel before taking off and **b** a very short distance to land back on the aircraft carrier.

LEARNING OBJECTIVES

- Know and use the relationship between unbalanced force, mass and acceleration:

  force = mass × acceleration

  $F = m \times a$

- Know and use the relationship between weight, mass and gravitational field strength:

  weight = mass × gravitational field strength

  $W = m \times g$

- Know that the stopping distance of a vehicle is made up of the sum of the thinking distance and the braking distance
- Describe the factors affecting vehicle stopping distance, including speed, mass, road condition and reaction time
- Describe the forces acting on falling objects (and explain why falling objects reach a terminal velocity)

The aircraft in Figure 3.1 must accelerate to a very high speed in a very short time when taking off and decelerate quickly when landing back on the aircraft carrier. The unbalanced force on the plane causes the acceleration. The forces that act horizontally on the aircraft are the friction force between the wheels and the flight deck (where planes land on a ship), and air resistance, when the aircraft starts to move. At the start, the forward thrust of the aircraft engines is much greater than air resistance and friction, so there is a large unbalanced force to cause the acceleration. When the aircraft lands on the flight deck it must decelerate to stop in a short distance. Parachutes and drag wires are used to provide a large unbalanced force acting in the opposite direction to the aircraft's movement. An unbalanced force is sometimes referred to as a resultant force. In this chapter we look at how acceleration is related to the force acting on an object.

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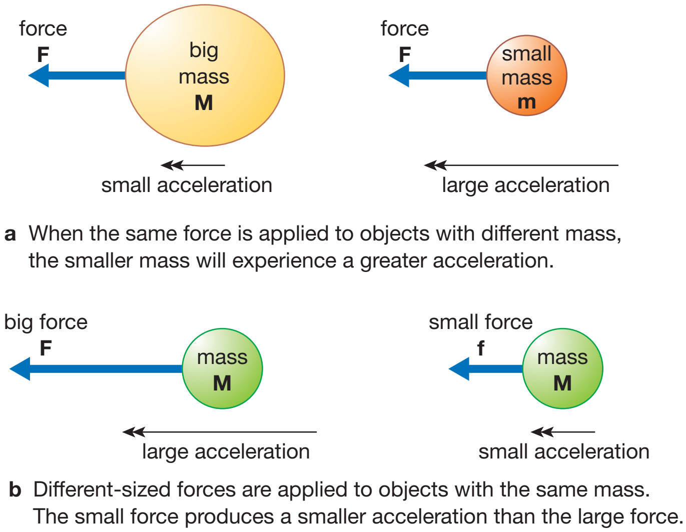
FORCE, MASS AND ACCELERATION

An object will not change its velocity (accelerate) unless there is an unbalanced force acting on it. For example, a car travelling along a motorway at a constant speed is being pushed along by a force from its engine, but this force is needed to balance the forces of friction and air resistance acting on the car. At a constant speed, the unbalanced force on the car is zero.

If there are unbalanced forces acting on an object, the object may accelerate or decelerate depending on the direction of the unbalanced force. The acceleration depends on the size of the unbalanced force and the mass of the object.



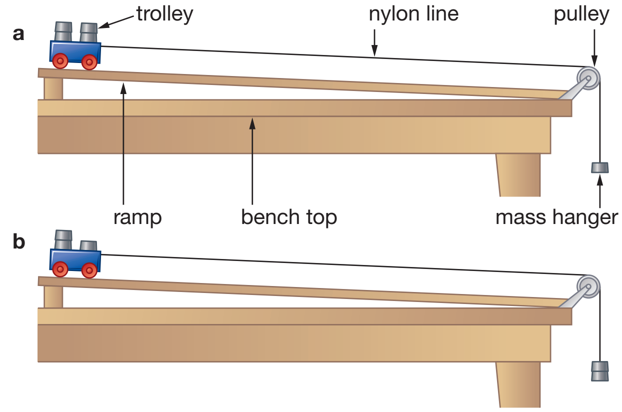
▲ Figure 3.2 The acceleration of an object is affected by both its mass and the force applied to it.

INVESTIGATING FORCE, MASS AND ACCELERATION

The experiment shown in Figure 3.3 shows how the relationship between force, mass and acceleration can be investigated. It uses a trolley on a slightly sloping ramp. The slope of the ramp is adjusted so that the trolley keeps moving down it if you push it gently. The slope is intended to overcome the friction in the trolley's wheels that could affect the results.

!

Heavy wooden runways need to be stacked and moved carefully. They are best used at low level rather than being placed on benches or tables where they may fall off. If heavy trolleys are used as 'vehicles', a 'catch box' filled with bubble wrap or similar material should be placed at the end of the runway.



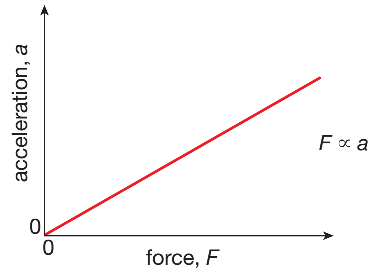
▲ Figure 3.3 You can use a trolley to find the acceleration caused by a particular force.

The force acting on the trolley is provided by the masses on the end of the nylon line. These masses accelerate as well as the trolley, so the force is increased by transferring one of the masses from the trolley to the mass hanger (Figure 3.3b). This increases the pulling force (explained later in this chapter) on the trolley, while keeping the total mass of the system the same.

The acceleration of the trolley can be measured by taking a series of pictures at equal time intervals using a digital video camera. Alternatively, a pair of **light gates** and a data logger can be used to find the speed of the trolley near the top of the ramp and near the end. The equation on page 9 can then be used to work out the acceleration.

EXTENSION WORK

The acceleration can be found using a digital video camera by measuring the distance travelled from the start for each image. Since the time between each image is known, a graph of displacement against time can be drawn. The gradient of the displacement–time graph gives the velocity at a particular instant, so data for a velocity–time graph can be obtained. The gradient of the velocity–time graph produced is the acceleration of the trolley.



▲ Figure 3.4 Force is proportional to acceleration.

Figure 3.4 shows a graph of force against acceleration when the mass of the trolley and hanging masses is constant and the accelerating force is varied.

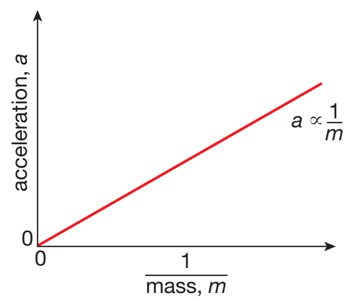
The graph is a straight line passing through the origin, which shows that:

force is proportional to acceleration

$$F \propto a$$

So doubling the force acting on an object doubles its acceleration.

In a second experiment, the accelerating force is kept constant and the mass of the trolley is varied.



▲ Figure 3.5 Acceleration is inversely proportional to mass.

Figure 3.5 shows the acceleration of the trolley plotted against $\frac{1}{m}$. This is also a straight line passing through the origin, showing that:

acceleration is **inversely proportional** to mass

$$a \propto \frac{1}{m}$$

This means that for a given unbalanced force acting on an object, doubling the mass of the object will halve the acceleration.

Combining these results gives us:

force, F (N) = mass, m (kg) × acceleration, a (m/s^2)

$$F = m \times a$$

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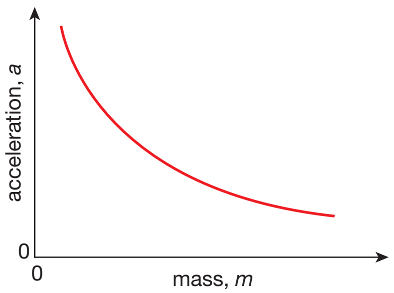
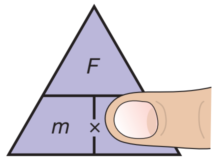


▲ Figure 3.6 The graph of *a* against *m* is a curve. Plotting *a* against $\frac{1}{m}$ (while keeping the force constant) gives a straight line. This makes it easier to spot the way that *a* is affected by *m*.

Force is measured in newtons (N), mass is measured in kilograms (kg), and acceleration is measured in metres per second squared (m/s^2). From this we see that:

One newton is the force needed to make a mass of one kilogram accelerate at one metre per second squared.



▲ Figure 3.7 The equation can be rearranged using the triangle method. If you need to find the acceleration that results when a known force acts on an object of known mass, cover up *a*; you can see that $a = \frac{F}{m}$.

HINT

If an examination question asks you to write out the equation for calculating force, mass or acceleration, always give the actual equation (such as $F = m \times a$). You may not get the mark if you just draw the triangle.

DECELERATION IN A COLLISION

REMINDER

v is the final velocity, *u* is the initial velocity and *t* is the time for the change in velocity to take place.

REMINDER

The minus sign in Example 1 for velocity change indicates that the velocity has decreased.

If you are designing a car for high acceleration, the equation $F = ma$ tells you that the car should have low mass and the engine must provide a high accelerating force. You must also consider the force needed to stop the car.

When a moving object is stopped, it decelerates.

A negative acceleration is a deceleration.

If a large deceleration is needed then the force causing the deceleration must be large, too. Usually a car is stopped by using the brakes in a controlled way so that the deceleration is not excessive (too much). In an accident the car may collide with another vehicle or obstacle, causing a very rapid deceleration.

EXAMPLE 1

A car travelling at 20 m/s collides with a stationary lorry and stops completely in just 0.02 s. Calculate the deceleration of the car.

$$\text{acceleration} = \frac{\text{change in velocity}}{\text{time taken}} \text{ (see page 9)}$$

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

$$= \frac{0\,\text{m/s} - 20\,\text{m/s}}{0.02\,\text{s}}$$

$$= \frac{-20\,\text{m/s}}{0.02\,\text{s}}$$

$$= -1000\,\text{m/s}^2$$

A person of mass 50 kg in the car experiences the same deceleration when she comes into contact with a hard surface in the car. This could be the dashboard or the windscreen. Calculate the force that the person experiences.

$$F = m \times a$$

$$= 50\,\text{kg} \times 1000\,\text{m/s}^2$$

$$= 50\,000\,\text{N}$$

In Chapter 4 you will learn about ways in which cars can be designed to reduce the forces on passengers in an accident.

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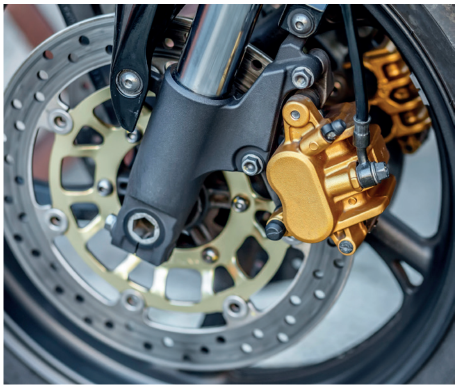
FRICTION AND BRAKING



▲ Figure 3.8 Motorcycle disc brakes work using friction. Friction is necessary if we want things to stop.

The 'tread' of a tyre is the grooved pattern moulded into the rubber surface. It is designed to keep the rubber surface in contact with the road by throwing water away from the tyre surface.

Brakes on cars and bicycles work by increasing the friction between the **rotating** wheels and the body of the vehicle, as shown in Figure 3.8.

The friction force between the tyres and the road depends on the condition of the tyres and the surface of the road. It also depends on the weight of the vehicle. If the tyres have a good tread, are properly inflated (filled with air) and the road is dry, the friction force between the road and the tyres will be at its maximum.

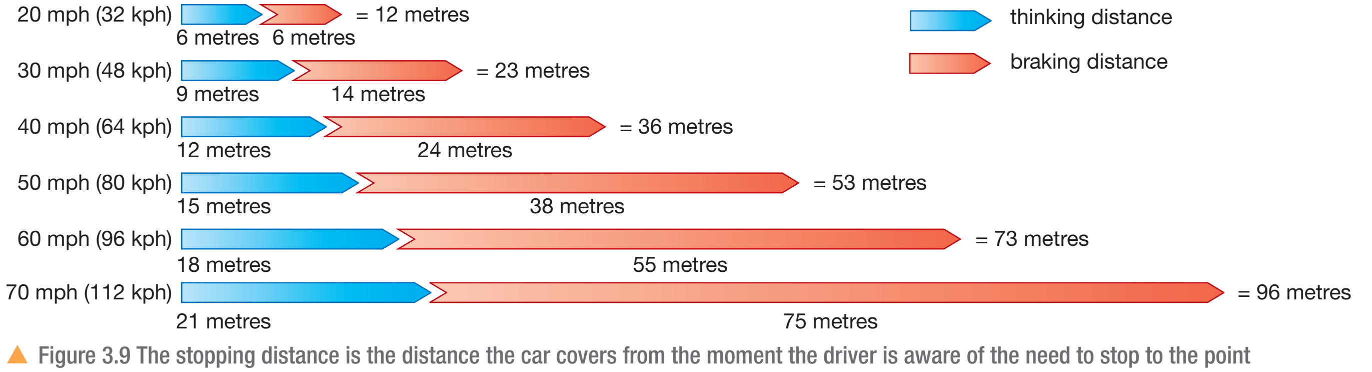
Unfortunately, we do not always travel in ideal conditions. If the road is wet or the tyres are in bad condition the friction force will be smaller. If the brakes are applied too hard, the tyres will not grip the road surface and the car will skid (slide out of control). Once the car is skidding the driver no longer has control and it will take longer to stop. Skidding can be avoided by applying the brakes in the correct way, so that the wheels do not lock. Most modern cars are fitted with ABS (anti-lock braking system) to reduce the chance of a skid occurring. ABS is a computer-controlled system that senses when the car is about to skid and releases the brakes for a very short time.

SAFE STOPPING DISTANCE

The Highway Code used in the United Kingdom gives stopping distances for cars travelling at various speeds. The stopping distance is the sum of the thinking distance and the braking distance. The faster the car is travelling the greater the stopping distance will be.

THINKING DISTANCE

When a driver suddenly sees an object blocking the way ahead, it takes time for him or her to respond to the new situation before taking any action, such as braking. This time is called reaction time and will depend on the person driving the car. It will also depend on a number of other factors including whether the driver is tired or under the influence of alcohol or other drugs that slow reaction times. Poor visibility (for example, fog) may also make it difficult for a driver to identify a danger and so cause him or her to take longer to respond. Clearly, the longer the driver takes to react, the further the car will travel before braking even starts – that is, the longer the thinking distance will be. Equally clear is the fact that the higher the car's speed, the further the car will travel during this 'thinking time'. If the distance between two cars is not at least the thinking distance then, in the event of an emergency stop by the vehicle in front, a violent accident is inevitable.



▲ Figure 3.9 The stopping distance is the distance the car covers from the moment the driver is aware of the need to stop to the point at which the vehicle comes to a complete stop.

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BRAKING DISTANCE

With ABS (anti-lock braking system) braking, in an emergency you brake as hard as you can. This means that the braking force will be a maximum and we can work out the deceleration using the equation below.

$F = m \times a$, rearranged to give:

$a = \frac{F}{m}$ (shown in Figure 3.7)

It is worth pointing out here that vehicles with large masses, like lorries, will have smaller rates of deceleration for a given braking force – they will, therefore, travel further while braking.

Chapter 1 shows that the distance travelled by a moving object can be found from its velocity–time graph. The area under the graph gives the distance travelled. Look at the velocity–time graphs in Figures 3.10 and 3.11.

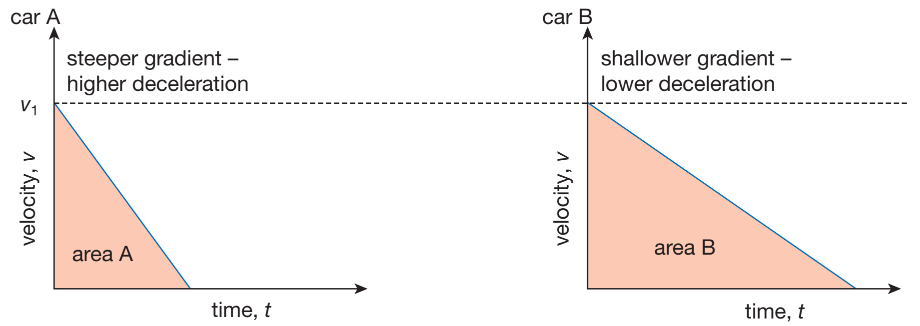

Figure 3.10 Velocity–time graphs for two cars braking at different rates from the same speed, v_1, to rest.

Figure 3.10 shows two cars, A and B, braking from the same velocity. Car A is braking harder than car B and comes to rest in a shorter time. Car B travels further before stopping, as you can see from the larger area under the graph. Remember that the maximum rate of deceleration depends on how hard you can brake without skidding – in poor conditions the braking force will be lower.

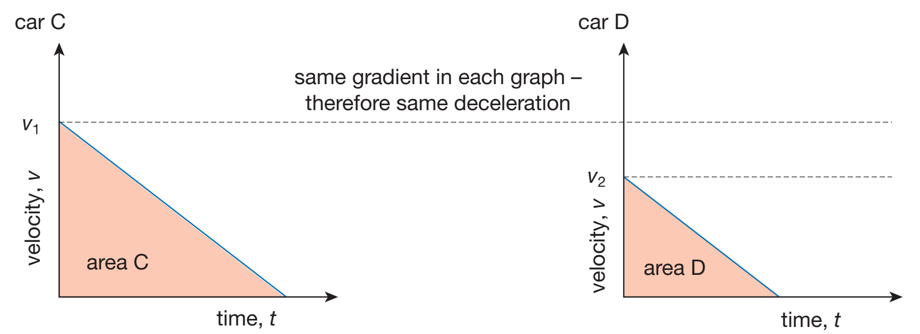

Figure 3.11 Velocity–time graphs for two cars braking at the same rate to rest, from different speeds, v_1 and v_2.

Figure 3.11 shows two cars, C and D, braking at the same rate, as you can see from the gradients. Car C is braking from a higher velocity and so takes longer to stop. Again, the greater area under the graph for car C shows that it travels further whilst stopping than car D.

Vehicles cannot stop instantly! Remember also that the chart in Figure 3.9 shows stopping distances in ideal conditions. If the car tyres or brakes are in poor condition, or if the road surface is wet, icy or slippery, then the car will travel further before stopping.

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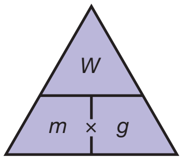
WEIGHT

The weight of an object is the force that acts on it because of gravity. The weight of an object depends on its mass and the strength of gravity. The **gravitational field strength** (*g*) is the force that acts on each kilogram of mass. We can work out the weight of an object by using this equation:

weight, *W* (N) = mass, *m* (kg) × gravitational field strength, *g* (N/kg)

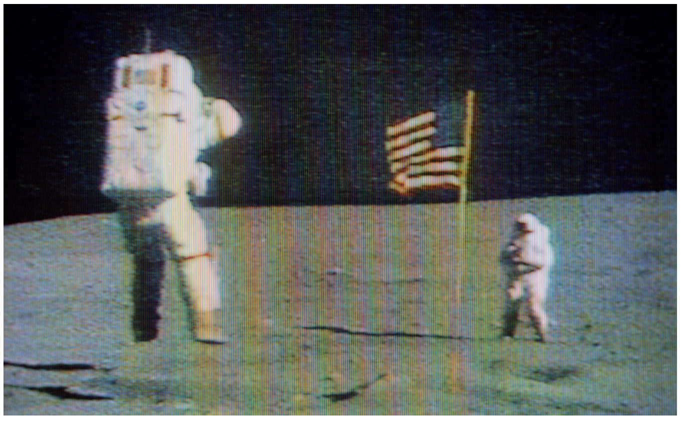
$$W = m \times g$$

You can use the triangle method to rearrange this equation.



▲ Figure 3.12 Rearranging $W = m \times g$ using the triangle method

Near and on the Earth's surface the gravitational field strength is approximately 9.8 N/kg, but we often use 10 N/kg to make calculations easier. The gravitational field strength on the Moon is about 1.6 N/kg, so an object taken from the Earth to the Moon will have less weight even though it has the same mass.



▲ Figure 3.13 An astronaut jumping on the Moon enjoying the effect of low gravity

EXAMPLE 2

An astronaut in a space suit with a complete life support pack has a mass of 140 kg. How much will the astronaut weigh **a** on the Earth, and **b** on Mars where the gravitational field strength is about one third of that on Earth? (Take the strength of the Earth's gravitational field as 10 N/kg.)

The force of gravity or weight of an object is given by:

weight, *W* = mass, *m* × gravitational field strength, *g*

a weight on Earth = 140 kg × 10 N/kg

= 1400 N

b g on Mars = $\frac{10\text{ N/kg}}{3}$ = 3.34 N/kg

weight on Mars = 140 kg × 3.34 N/kg

= 468 N

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AIR RESISTANCE AND TERMINAL VELOCITY

An object moving through air experiences a force that opposes its movement. This force is called air resistance or drag. The size of the drag force acting on an object depends on its shape and its speed. Cars are designed to have a low **drag coefficient**. The drag coefficient is a measure of how easily an object moves through the air. High-speed trains have an efficient streamlined shape so that air flows more smoothly around them. Streamlined, smooth surfaces produce less drag.

It is particularly important to make fast-moving objects streamlined because the drag force increases with the speed of the object. The fact that drag increases with speed affects the way that dropped objects accelerate, because the faster they move the greater the drag force opposing their motion becomes.

Objects falling through the air experience two significant forces: the weight force (that is, the pull of gravity on the object) and the opposing drag force.

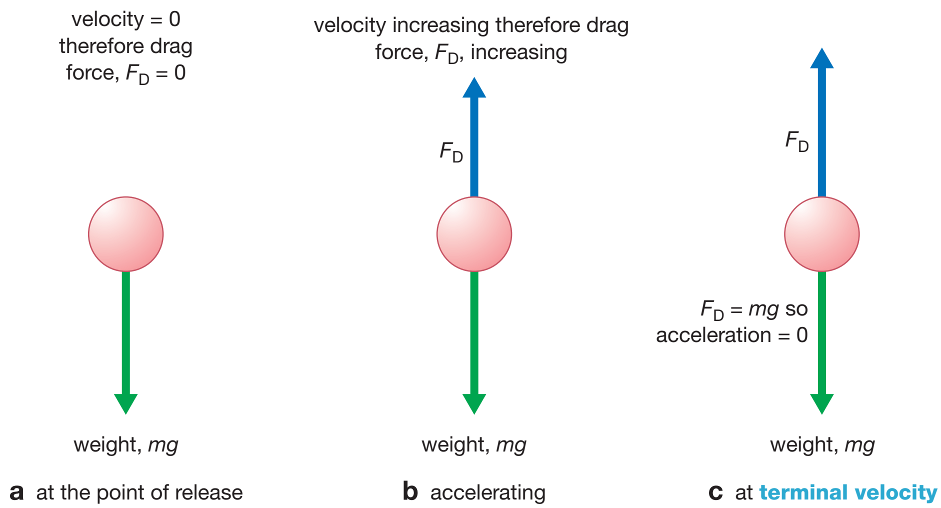

Figure 3.14 How the forces acting on a object change as its velocity changes

In Figure 3.14a the object has just been released and has a starting velocity of 0 m/s. This means that there is no drag. (Remember that the drag force acts on moving objects.) The resulting downward-acting force is just the weight force. This force makes the object accelerate towards the Earth.

Figure 3.14b shows the object now moving. Because it is moving it has a drag force, F_D, acting on it. The drag force acts upwards (up) against the movement. This means that the resulting downward force (acting down) on the object is ($mg - F_D$). You can see that the drag force has made the resulting downward force smaller, so the acceleration is smaller. All the time that the object is accelerating it is getting faster. The faster the object moves the bigger the drag force is.

In Figure 3.14c the drag force has increased to the point where it exactly balances the weight force – since there is now no unbalanced force on the object its acceleration is also zero. The object has reached its terminal velocity and although it is still falling it will not get any faster. Figure 3.15 shows a velocity–time graph for an object falling through air and reaching terminal velocity.

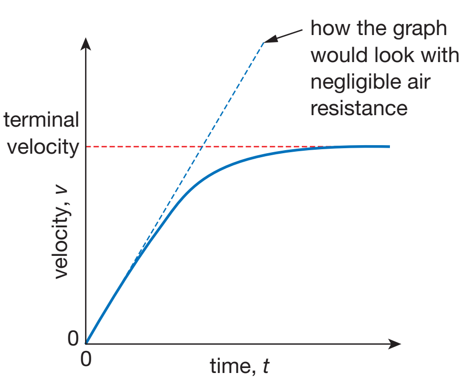

Figure 3.15 The velocity–time graph for an object accelerating until it reaches terminal velocity

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PARACHUTES

Figure 3.16 These skydivers have just left the aeroplane. They will accelerate until they reach terminal velocity.

When a skydiver jumps from a plane she will accelerate for a time and eventually reach terminal velocity. Typically this will be between 150 and 200 kph. When she opens her parachute this will cause a sudden increase in the drag force. At this velocity (around 200 kph) the drag force of the parachute is greater than the weight of the skydiver. This means that the unbalanced force acting on the parachutist acts upwards and, for a while, she will decelerate. As she slows down the size of the drag force decreases and, eventually, a new terminal velocity is reached. Obviously the new terminal velocity depends on the design of the parachute, but it must be slow enough to allow the parachutist to land safely. Figure 3.17 shows a velocity–time graph for a skydiver.

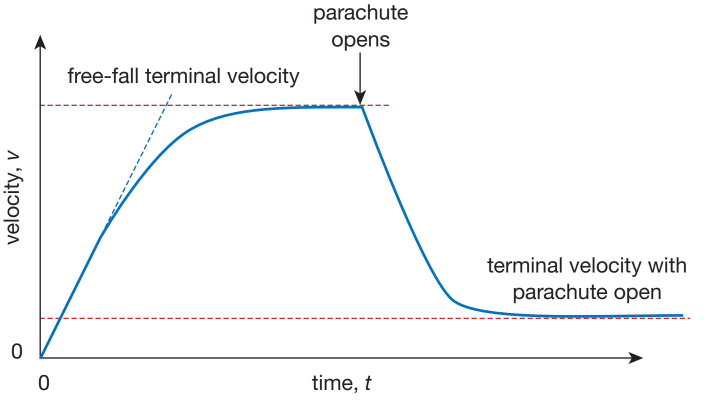

Figure 3.17 Velocity–time graph for a free-fall parachutist reaching terminal velocity, then opening the parachute

MODELLING TERMINAL VELOCITY

Objects have to accelerate to quite high speeds in air to reach terminal velocity. This makes demonstrating the effect in a laboratory difficult. However, objects falling through liquids also experience a drag force that increases with speed. The sizes of drag forces in liquids are much higher than in gases. This means that objects falling through liquids have a much lower terminal velocity than objects falling through air, and can be used to model terminal velocity. You can use a tall measuring cylinder filled with water and drop small-**diameter** (1–2 mm) glass balls into it. Alternatively, use a much thicker liquid like oil and use small-diameter balls. As well as demonstrating terminal velocity this presents plenty of opportunities for investigations. You could measure the terminal velocity using a light gate and a data logger.

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LOOKING AHEAD – WEIGHTLESSNESS

▲ Figure 3.18 Scientists in the International Space Station experience weightlessness

▲ Figure 3.19 Astronauts training for weightlessness in an aircraft

Figures 3.18 and 3.19 show astronauts in 'weightless' conditions in the International Space Station and training for weightlessness in an aircraft. In both cases the astronauts are still being pulled towards the Earth by gravity. They all experience the force we call weight, calculated using the equation *mg* that we met earlier in Chapter 3, yet they appear to float freely!

They are in a condition called free-fall. You may have noticed feeling very slightly 'lighter' when you are in a lift as it accelerates downwards. This effect is more noticeable if the lift accelerates at a greater rate. Further study of physics will explain all this.

Exploring the Solar System

Sir Isaac Newton worked out his laws of motion more than 300 years ago. Although Albert Einstein explained that these laws do not hold when objects are travelling at speeds close to the speed of light (3×10^8 m/s), Newton's laws give answers to calculations accurate enough for scientists to plan successful space missions like the Moon landing in 1969, the Phoenix lander to Mars in 2007 and the incredible achievement of landing the Philae lander (carried by the Rosetta spacecraft) on a **comet** in 2014.

If you look at Example 1 in Chapter 4 (based on the Saturn V rockets used in the Moon missions) the answer obtained using equation

$\text{force} = \dfrac{\text{increase in momentum}}{\text{time taken}}$ is not very accurate. There are a number of reasons for this: one is to do with air resistance, mentioned earlier in Chapter 3; another is to do with what is happening to the rocket as it uses up its fuel.

Understanding these allows physicists to apply the laws of motion more accurately.

CHAPTER QUESTIONS

More questions on force and acceleration can be found at the end of Unit 1 on page 55.

SKILLS CRITICAL THINKING 5

1 Explain what is meant by an unbalanced force? Illustrate your answer with an example.

SKILLS REASONING 7

2 Rockets burn fuel to give them the thrust needed to accelerate. As the fuel burns the mass of the rocket gets smaller. Assuming that the rocket motors provide a constant thrust force, explain what will happen to the acceleration of the rocket as it burns its fuel.

SKILLS PROBLEM SOLVING 9

3 a Calculate the force required to make an object of mass 500 g accelerate at 4 m/s^2. (Take care with the units!)

b An object accelerates at 0.8 m/s^2 when a resultant force of 200 N acts upon it. Calculate the mass of the object.

c What acceleration is produced by a force of 250 N acting on a mass of 25 kg?

SKILLS CRITICAL THINKING 5

4 Explain the meaning of the following terms used to describe stopping vehicles in an emergency:

a thinking distance

b braking distance

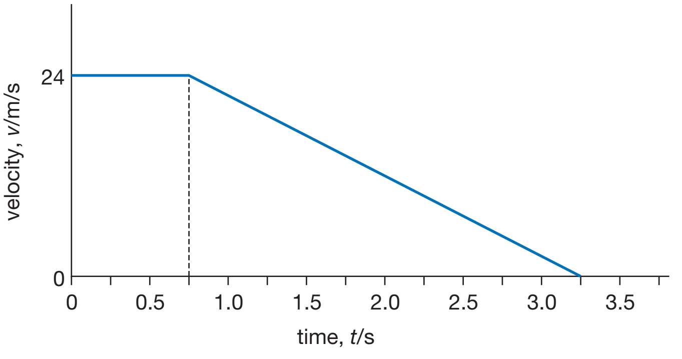
c overall stopping distance.

6

5 What factors affect the braking distance of a vehicle?

SKILLS ANALYSIS

6 The diagram below shows the velocity–time graph for a car travelling from the moment that the driver sees an object blocking the road ahead.



Use the graph to find out:

7 a how long the driver takes to react to seeing the obstacle (reaction time)

8 b how far the car travels in this reaction time

7 c how long it takes to bring the car to a halt once the driver starts braking

9 d the total distance the car travels before stopping.

SKILLS PROBLEM SOLVING 6

7 Calculate the weight of an apple of mass 100 grams:

a on the Earth (g = 10 N/kg)

b on the Moon (g = 1.6 N/kg).

SKILLS CRITICAL THINKING 5

8 What factors affect the drag force that acts on a high-speed train?

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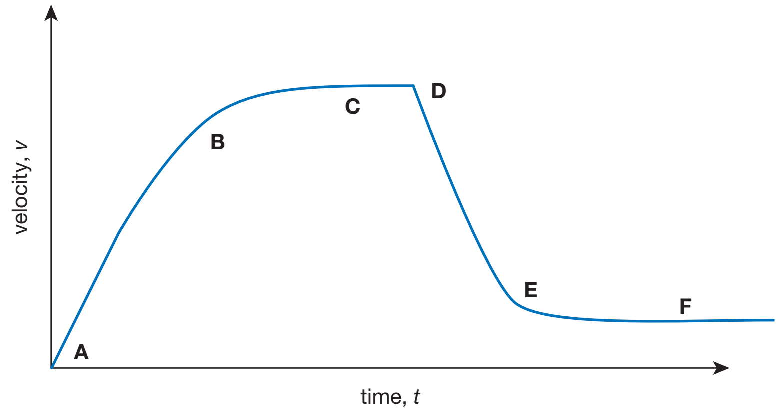
SKILLS DECISION MAKING 7

9 Describe an experiment to demonstrate terminal velocity. Say what measurements you need to take in your experiment to show that a falling object has reached terminal speed.

SKILLS ANALYSIS 9

10 Look at the velocity–time graph for a free-fall parachutist shown below.



State and explain the direction and relative size of the unbalanced force acting on the parachutist at each of the points A–F labelled on the graph.

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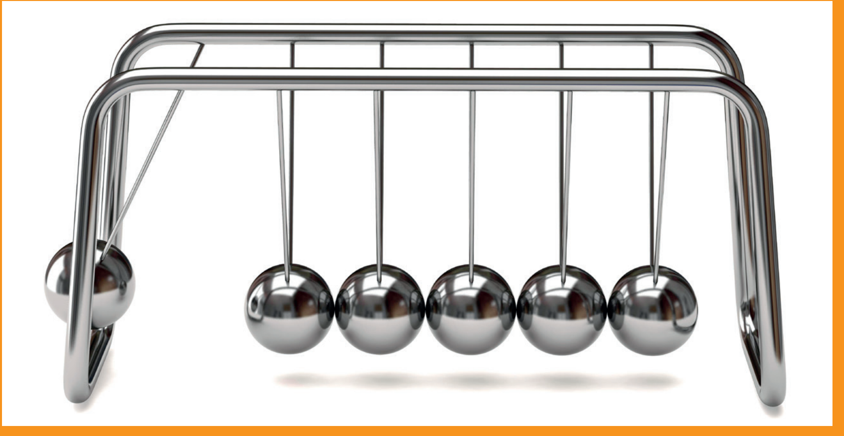
PHYSICS ONLY

4 MOMENTUM

Momentum is possessed by masses in motion – it is calculated by multiplying the mass of an object by its velocity. In this chapter you will learn that, when objects speed up or slow down, the rate of change of momentum is proportional to the force causing the change. You will also see that momentum is conserved in collisions and explosions.



▲ Figure 4.1 Newton's cradle

LEARNING OBJECTIVES

- Know and use the relationship between momentum, mass and velocity:

  momentum = mass × velocity

  $p = m \times v$

- Use the idea of momentum to explain safety features
- Use the conservation of momentum to calculate the mass, velocity or momentum of objects
- Use the relationship between force, change in momentum and time taken:

  $$\text{force} = \frac{\text{change in momentum}}{\text{time taken}}$$

  $$F = \frac{(mv - mu)}{t}$$

- Demonstrate an understanding of Newton's third law

KEY POINT

Do not confuse momentum, a property of moving masses, with moment, the turning effect of a force.

Newton's cradle is an entertaining toy but it also demonstrates a physics conservation law. When one of the balls is drawn back a short way and released, it swings and collides with the remaining group of balls. After the impact the ball at the opposite end springs away and swings out as far as the first ball was drawn back to start with. If two balls are drawn back and released then two balls will move away at the opposite end as the **collision** occurs. The moving ball has momentum, and momentum is conserved in collisions. This chapter is about momentum and what is meant by conservation of momentum.

MOMENTUM

We talk about objects 'gaining momentum' in everyday speech. When we say this we are usually trying to get across an idea of something becoming more

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difficult to stop. Sometimes we use the word in a way that is very close to the way it is defined in physics – for example, if a car starts rolling down a hill we might say that the car is 'gaining momentum' as it speeds up.

In physics, momentum is a quantity possessed by masses in motion. Momentum is a measure of how difficult it is to stop something that is moving. We calculate the momentum of a moving object using the equation:

momentum, p (kg m/s) = mass, m (kg) × velocity, v (m/s)

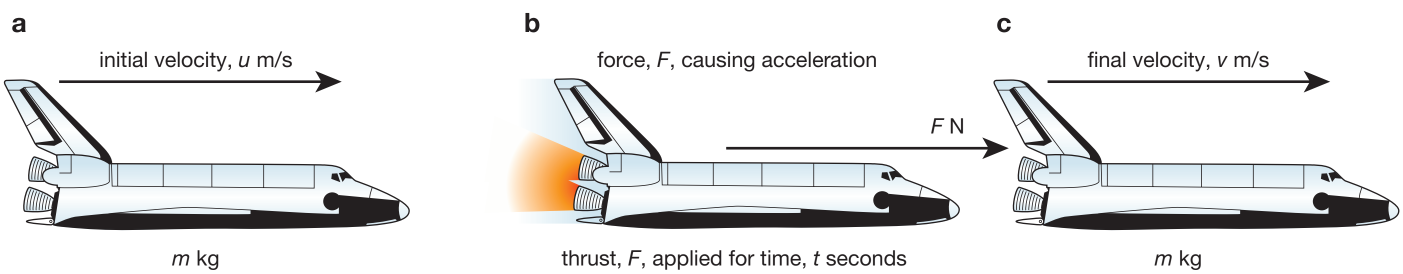
$$p = m \times v$$

Momentum is a vector quantity and is measured in kilogram metres per second (kg m/s) – provided that mass in the above equation is measured in kg and velocity in m/s.

You can see from the equation that the more mass an object has, the more momentum it will have when moving. The momentum of a moving object also increases with its speed.

MOMENTUM AND ACCELERATION

We have already discussed the relationship $F = m \times a$ (see page 30). This relationship was first discussed by Sir Isaac Newton (1642–1727). A more precise statement of Newton's discovery would be that when an unbalanced force acts on an object it causes a change in the momentum of the object in the direction of the unbalanced force. Newton discovered that the rate of change of momentum of an object is proportional to the force applied to that object. This means that if you double the force acting on an object its momentum will change twice as quickly. Figure 4.2 shows the effect of the thrust force on the velocity of a space shuttle, and, therefore, on its momentum.



▲ Figure 4.2 The thrust of the rocket motor makes the velocity and, therefore, the momentum of the shuttle increase.

initial momentum of object = mu

final momentum of object = mv

therefore, increase in momentum = $mv - mu$

so, rate of increase of momentum = $\dfrac{(mv - mu)}{t}$

As stated above, Newton identified a proportional relationship between the rate of increase of momentum and the force applied, but with the system of units we use the relationship appears as shown:

$$\text{force, } F = \frac{\text{change in momentum } (mv - mu)}{\text{time taken, } t}$$

$$F = \frac{mv - mu}{t}$$

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If you look at this equation you will notice it can be rearranged to give the more familiar equation $F = ma$:

$$F = \frac{mv - mu}{t}$$

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

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

then $F = ma$

The rearrangement is possible because we have assumed that the mass of the object involved is constant. This will not always be the case in real situations – for example, when a space shuttle is launched the mass of the rocket changes continuously as fuel is burned and rocket stages are jettisoned. Rocket scientists also have to include air resistance in their calculations. However, you will not meet problems like this at International GCSE level.

EXAMPLE 1

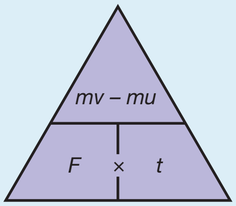
The first stage of the type of rocket used in Moon missions provides an unbalanced upward (away from the Earth) force of 30 MN and burns for 2.5 minutes.

a Calculate the increase in the rocket's momentum that results.

b If the rocket has a mass of 3000 tonnes what is the velocity of the rocket after the first stage has completed its 'burn'?

(Take care to convert units into N, kg and s. 1 MN = 10^6 N; 1 tonne = 1000 kg)

a The equation $F = \frac{(mv - mu)}{t}$ is another that can be rearranged using the triangle.



▲ Figure 4.3 Rearranging the change in momentum = $f \times t$ equation using the triangle method

We want the change in momentum (at the top of the triangle) so it is at the bottom of the triangle:

$$F \times t = (3 \times 10^7 \text{ N}) \times (2.5 \times 60 \text{ s})$$

increase in momentum is 4.5×10^9 kg m/s

b The rocket starts from rest, $u = 0$, therefore the initial momentum (mu) is 0. This means that the increase in momentum is $mv = 4.5 \times 10^9$ kg m/s. Divide this by mass, $m = 3 \times 10^6$ kg, to give:

$$v = \frac{4.5 \times 10^9 \text{ kg m/s}}{3 \times 10^6 \text{ kg}}$$

$$= 1.5 \times 10^3 \text{ m/s}$$

As we have seen above this has been calculated with the mass of the rocket staying the same. In a real launch fuel is used up so the mass of the rocket will decrease and the calculation would be harder.

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MOMENTUM AND COLLISIONS

The total momentum of objects that collide remains the same:

momentum before the collision = momentum after the collision

You will need to use this to work out what happens to objects that collide when they are moving along the same straight line.

EXTENSION WORK

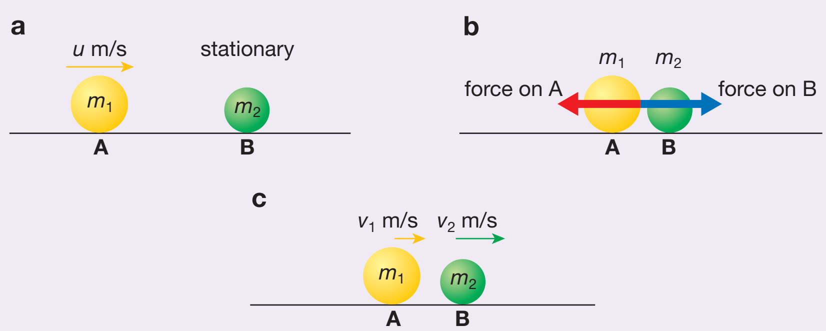
You will not need to learn the following explanation for the exam, but you do need to understand Newton's third law. You will see this again later in this chapter.

We can express the above equation in terms of momentum change, as follows:

force × time = increase in momentum

This simply says that a bigger force applied to an object for a longer time will result in a greater change in the momentum of the object.

Consider what happens when two balls collide, as shown in Figure 4.4.



▲ Figure 4.4 **a** Moving ball A, mass m_1, rolls towards stationary ball B, mass m_2; **b** During the impact each ball exerts a force on the other – equal in size and opposite in direction; **c** The balls after the collision.

EXTENSION WORK

During the time the two balls are in contact each exerts a force on the other (Newton's third law about action and reaction, see page 46). The forces act in opposite directions and obviously act for the same amount of time. This means that $F \times t$ for each is the same size, but opposite in direction.

KEY POINT

The term impulse is used for the product (force × time).

The increase in momentum of ball B is exactly balanced by the decrease in momentum of ball A, so the total momentum of the two balls is unchanged before and after the collision – momentum is conserved.

EXTENSION WORK

In any system, momentum is always conserved provided no external forces act on the system. This means that when two snooker balls collide the momentum of the balls is conserved if no friction forces act on them. The presence of friction means that the balls will eventually slow down and stop, thus ending up with no momentum. Although the balls have 'lost' momentum something else will, inevitably, have gained an equal amount of momentum! As the balls are slowed by the friction of the snooker table they, in turn, cause a friction force to act on the table. The table gains some momentum. However, the large mass of the table means that the effect is unnoticeable.

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EXAMPLE 2

A railway truck with a mass of 5000 kg rolling at 3 m/s collides with a stationary truck of mass 10 000 kg. The trucks join together. At what speed do they move after the collision?

We shall assume that friction forces are small enough to ignore, so we can apply the law of conservation of momentum:

momentum before the collision = momentum after the collision

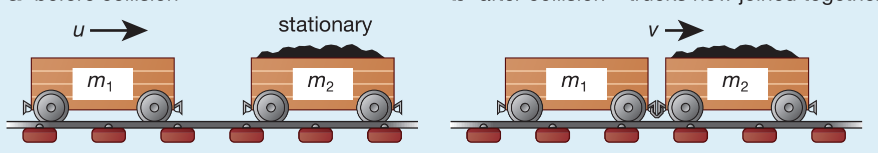

Figure 4.5 Railway trucks in collision

so, momentum of A before collision + momentum of B before collision = momentum of A and B moving together after collision

$$(m_1 \times u) + (m_2 \times 0 \text{ m/s}) = (m_1 + m_2) \times v$$

where m_1 is the mass of truck A, u is its velocity before the collision, m_2 is the mass of truck B (at rest before the collision so its velocity is 0 m/s), and v is the velocity of the two trucks after the collision.

Substituting these values gives:

(5000 kg × 3 m/s) + (10 000 kg × 0 m/s) = (5000 kg + 10 000 kg) × v

so $$v = \frac{15\,000 \text{ kg m/s}}{15\,000 \text{ kg}} = 1 \text{ m/s}$$

After the collision the trucks move with a velocity of 1 m/s in the same direction that the original truck was travelling.

EXPLOSIONS

Figure 4.6 A shuttle launch

The conservation of momentum principle can be applied to explosions. An explosion involves a release of energy causing things to fly apart. The momentum before and after the explosion is unchanged, though there will be a huge increase in movement energy. A simple demonstration of a safe 'explosion' is shown in Figure 4.6. You might think that the rocket in this photo is taking off because the rocket motor is pushing against the ground, but rockets work in space where there is nothing to push against.

Rocket motors use the principle of conservation of momentum to propel spacecraft through space. They produce a continuous, controlled explosion that forces large amounts of fast-moving gases (produced by the fuel burning) out of the back of the rocket. The spacecraft gains an equal amount of momentum in the opposite direction to that of the moving exhaust gases.

You can see the same effect if you blow up a balloon and release it without tying up the end!

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CAR SAFETY

In Example 1 on page 31 you saw that the force on a person in a car crash can be very large. In that example, the force was worked out from the deceleration in a crash. You can also work out the force in a crash using the equation for momentum.

Steep roads often have escape lanes filled with deep, soft sand. The soft sand slows heavy lorries that are out of control slowly – by making time, *t*, for the lorry to stop longer, the force, *F*, slowing the lorry is smaller and the driver is less likely to suffer serious injury,

EXAMPLE 3

A car travelling at 20 m/s collides with a stationary lorry and is brought to rest in just 0.02 s. A woman in the car has a mass of 50 kg. She experiences the same deceleration when she comes into contact with a hard surface in the car (such as the dashboard or the windscreen). What force does the person experience?

$$\text{force} = \frac{\text{change in momentum}}{\text{time}}$$

$$= \frac{(50\text{ kg} \times 20\text{ m/s}) - (50\text{ kg} \times 0\text{ m/s})}{0.02\text{ s}}$$

$$= 50\,000\text{ N}$$

Figure 4.7 Parts of cars are designed to crumple.

Cars are now designed with various safety features that increase the time over which the car's momentum changes in an accident. Figure 4.7 shows the safety features of a car being tested. The car has a rigid passenger cell or compartment with crumple zones in front and behind. The crumple zones, as the name suggests, collapse during a collision and increase the time during which the car is decelerating. For instance, if the deceleration time in Example 3 above is increased from 0.02 s to 1 s, then the impact causes a much smaller force of just 1000 N to act on the passenger, greatly increasing their chances of survival.

Crumple zones are just one of the safety features now used in modern cars to protect the passengers in an accident. They only work if the passengers are wearing seat belts so that the reduced deceleration applies to their bodies too. Without seat belts, the passengers will continue moving forward until they come into contact with some part of the car or with a passenger in front. If they hit something that does not crumple they will be brought to rest in a very short time, which, as we have seen in Example 3, means a large deceleration and, therefore, a large force acting on them.

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NEWTON'S LAWS OF MOTION

EXTENSION WORK

Scientists use the word 'law' very cautiously. Only when a hypothesis (idea) has been tested many times independently by careful experiment is it raised to the status of a 'law'. Einstein showed that in special situations Newton's laws break down, but they are still accurate enough to predict the way objects respond to forces with a high degree of accuracy.

EXTENSION WORK

Sir Isaac Newton lived from 1642 to 1727. He made many famous discoveries and some important observations about how forces affect the way objects move. The first observation, called Newton's first law, was:

Things don't speed up, slow down or change direction unless you push (or pull) them.

Newton didn't put it quite like that, of course! He said that a body would continue to move in a straight line at a steady speed unless a resultant (unbalanced) force was acting on the body. If the forces acting on an object are balanced then a stationary object stays in one place, and a moving object continues to move in just the same way as it did before the forces were applied. You have already met this idea in Chapter 3.

Newton then asked another obvious question: how does the acceleration of an object depend on the force that you apply to it? Again Newton's formal statement of the answer (Newton's second law) sounds complicated, but the basic findings are quite simple:

The bigger the force acting on an object, the faster the object will speed up.

Objects with greater mass require bigger forces than those with smaller mass to make them speed up (accelerate) at the same rate.

The force referred to is the resultant force acting on the object. This idea is also covered in Chapter 3. The relationship $F = m \times a$ is a consequence of Newton's second law.

The only law you you need to learn by name is Newton's third law.

NEWTON'S THIRD LAW: ACTION AND REACTION

In simple language Newton's third law might be stated:

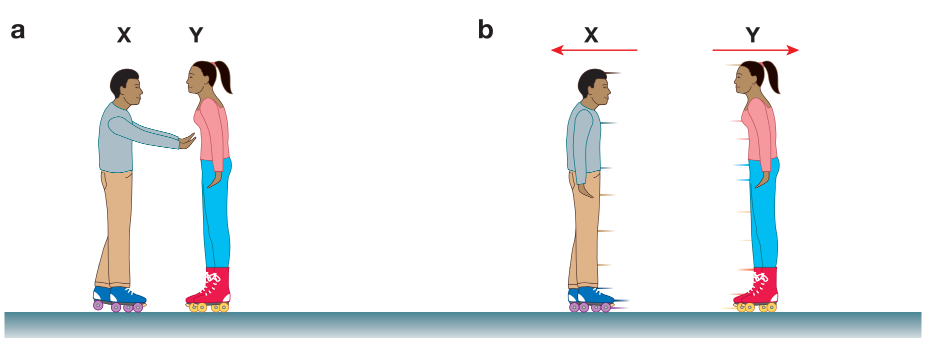
When you push something it pushes you back just as hard, but in the opposite direction.

It is usually stated as:

For every action there is an equal and opposite reaction.

When you sit down, your weight pushes down on the seat. The seat pushes back on you with an equal, but upward, force. An experiment to give you the idea of what this law means is shown in Figure 4.8.

In Figure 4.8, person X is clearly pushing person Y but it is not obvious that Y is pushing X back. When both X and Y move it is clear that X has been affected by a force pushing him to the left. The force felt by X is the reaction force.



▲ Figure 4.8 For every action there is an equal and opposite reaction.

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Look back at Figure 2.3 on page 19. The weight of the car is pushing down on the ground. Although the weight is shown coming from the centre of gravity of the car, it acts through the wheels pressing down on the ground. The total reaction force from the ground acting upwards on the wheels is the same as the weight of the car. It is this reaction force that stops the car sinking into the ground.

It can sometimes be difficult to sort out action and reaction forces from balanced forces. Balanced forces act in opposite directions on the same object. Action and reaction forces also act in opposite directions, but are always acting on different objects.

CHAPTER QUESTIONS

More questions on momentum can be found at the end of Unit 1 on page 55.

SKILLS PROBLEM SOLVING 9

1 Work out, giving your answers in kg m/s, the momentum of the following moving objects:

a a bowling ball of mass 6 kg travelling at 8 m/s

b a ship of mass 50 000 kg travelling at 3 m/s

c a tennis ball of mass 60 g travelling at 180 km/h.

2 An air rifle pellet of mass 2 g is fired into a block of modelling clay mounted on a model railway truck. The truck and modelling clay have a mass of 0.1 kg. The truck moves off after the pellet hits the modelling clay with an initial velocity of 0.8 m/s.

a Calculate the momentum of the modelling clay and truck just after the collision.

8 b State the momentum of the pellet just before it hits the modelling clay.

10 c Use your answers to a and b to calculate the velocity of the pellet just before it hits the modelling clay.

SKILLS REASONING 8

d State any assumptions you made in this calculation.

SKILLS PROBLEM SOLVING

3 A rocket of mass 1200 kg is travelling at 2000 m/s. It fires its engine for 1 minute. The forward thrust provided by the rocket engines is 10 kN (10 000 N).

9 a Use increase in momentum = $F \times t$ to calculate the increase in momentum of the rocket.

10 b Use your answer to a to calculate the increase in velocity of the rocket and its new velocity after firing the engines.

SKILLS CRITICAL THINKING

4 Air bags are a safety feature fitted to all modern cars. In the event of sudden braking an air bag is rapidly inflated with gas in front of the driver or passenger.

7 a Does the air bag remain inflated?

SKILLS REASONING 8

b Explain how the air bag protects the driver from more serious injury.

END OF PHYSICS ONLY

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PHYSICS ONLY

5 THE TURNING EFFECT OF FORCES

A force can have a turning effect – it can make an object turn around a fixed pivot point. When the anticlockwise turning effects of forces are balanced by turning forces in the clockwise direction, the object will not turn – it is in balance.

a

b

▲ Figure 5.1 Turning effects are used in many places, such as in **a** the see-saw, and **b** the cranes.

LEARNING OBJECTIVES

- Know and use the relationship between the moment of a force and its perpendicular distance from the pivot:

  moment = force × perpendicular distance from the pivot
- Know that the weight of a body acts through its centre of gravity
- Use the principle of moments for a simple system of parallel forces acting in one plane
- Understand how the upward forces on a light beam, supported at its ends, vary with the position of a heavy object placed on the beam

Unbalanced forces acting on objects can make them accelerate or decelerate. In the examples in Figure 5.1, the forces acting are having a turning effect. They are making the objects, like the see-saw, turn around a fixed point called a **pivot** or fulcrum. The turning effect in cranes is explained in Figure 5.6 on page 51. We use this turning effect of forces all the time. In our bodies the forces of our muscles make parts of our bodies turn around joints like our elbows or knees. When you turn a door handle, open a door or remove the lid off a tin of paint with a knife you are using the turning effect of forces. Understanding the turning effect of forces is important. Sometimes we want things to turn or rotate – the see-saw wouldn't be much fun if it didn't. However, sometimes we want the turning effects to balance so that things don't turn – it would be terrible if the crane did not balance!

OPENING A DOOR

Challenge a partner (perhaps one who thinks that he or she is strong!) to try to hold a door closed while you try to open it – then explain the rules! They can apply a pushing force but no further than 20 cm from the hinge (the part of the door that fastens it to the wall), while you try to pull the door open by pulling on the handle. You will be able to open the door quite easily.

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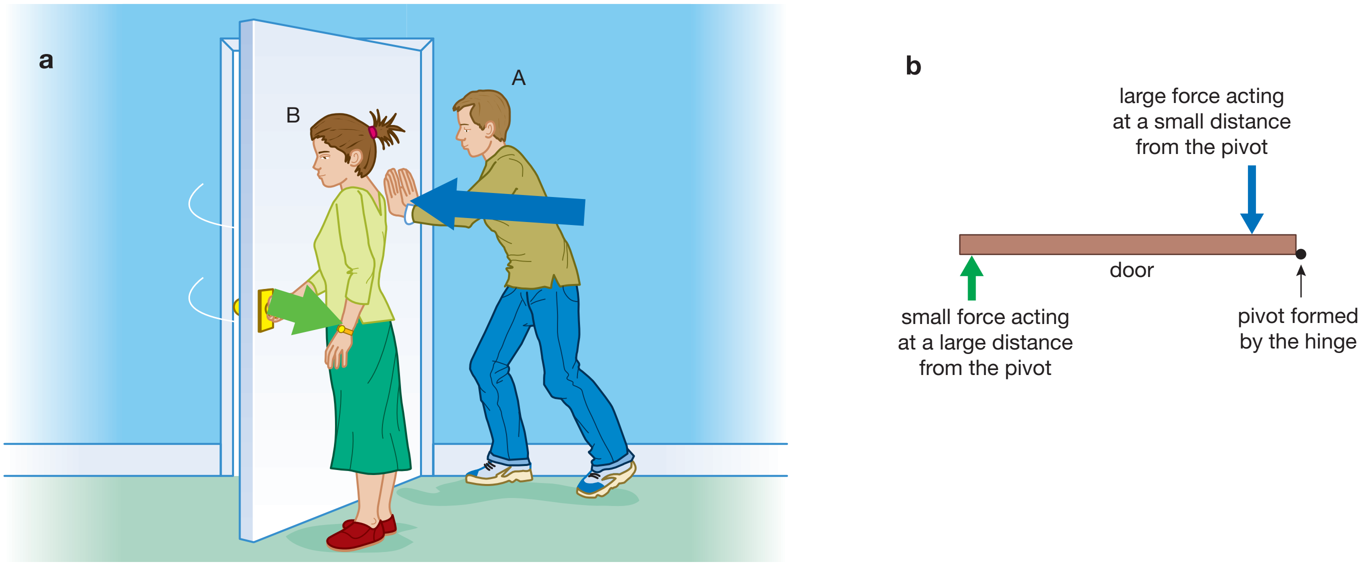


▲ Figure 5.2 The distance of the force from the pivot is crucial.

You will realise that you have an advantage because the turning effect of your force doesn't just depend on the size of the force you apply but also on the distance from the hinge or pivot at which you apply it. You have the advantage of greater leverage (Figure 5.2).

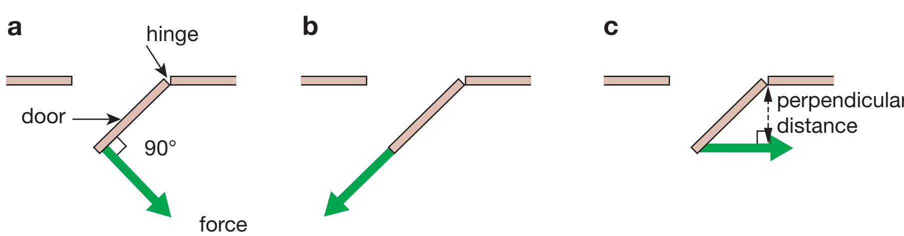
THE MOMENT OF A FORCE

The turning effect of a force about a hinge or pivot is called its moment. The moment of a force is defined like this:

moment of a force (Nm) = force, F (N) × perpendicular distance from pivot, d (m)

moment = $F \times d$

The moment of a force is measured in newton metres (Nm) because force is measured in newtons and the distance to the pivot is in metres. We need to be precise about what distance we measure when calculating the moment of a force. Look at the diagrams in Figure 5.3.



▲ Figure 5.3 For a force to have its biggest effect it should be at 90º to the lever.

If you think about the simple door opening 'competition' we discussed earlier you will realise that for a force to have the biggest turning effect it should be applied as in Figure 5.3a – that is, its line of action should be perpendicular (at 90°) to the door.

In Figure 5.3b the force has no turning effect at all because the line along which the force is acting passes through the pivot.

Figure 5.3c shows how the distance to the pivot must be measured to get the correct value for the moment. The distance is the perpendicular distance from the line of action of the force to the pivot.

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IN BALANCE

An object will be in balance (that is, it will not try to turn about a pivot point) if:

sum of anticlockwise moments = sum of clockwise moments

For example, Figure 5.4 shows two children sitting on a see-saw.

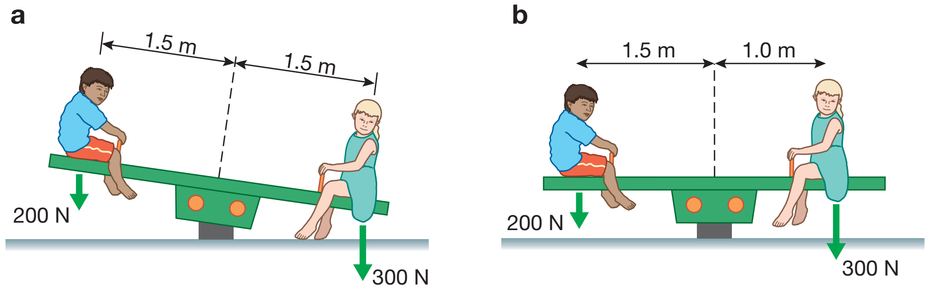

Figure 5.4 The moment of the heavier child is reduced when she sits closer to the pivot, so that it balances the moment of the lighter child.

In Figure 5.4a:

the anticlockwise moment = 200 N × 1.5 m = 300 Nm

the clockwise moment = 300 N × 1.5 m = 450 Nm

So the see-saw is not balanced and leans down to the right as it rotates clockwise about the pivot.

The calculations for Figure 5.4a are approximate because the forces are not acting perpendicularly to the see-saw.

In Figure 5.4b:

the anticlockwise moment = 200 N × 1.5 m = 300 Nm

the clockwise moment = 300 N × 1.0 m = 300 Nm

So the see-saw is now balanced.

EXAMPLE 1

Look again at Figure 5.2. Person A pushes the door with a force of 200 N at a distance of 20 cm from the hinge (the pivot in this example). Person B opens the door by pulling the door handle which is 80 cm from the hinge.

What is the minimum pulling force that person B must use to open the door?

Here is a simplified sketch of the problem:

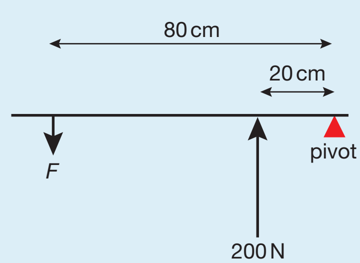

Figure 5.5 A labelled sketch of the problem

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The door will be in balance (on the point of opening) if:

sum of anticlockwise moments = sum of clockwise moments

$$F \times 80\text{ cm} = 200\text{ N} \times 20\text{ cm}$$

$$F = \frac{200\text{ N} \times 20\text{ cm}}{80\text{ cm}}$$

$$= 50\text{ N}$$

But this means the turning effects are balanced and we want person B to apply a big enough force to make the anticlockwise moment bigger than the clockwise moment.

The answer is that person B must apply a force greater than 50 N ($F > 50$ N).

Look back at Figure 5.1 and look at Figure 5.6. The load arm is long so that the crane can reach across a construction site and move loads backwards and forwards along the length of the arm. The weight of the long load arm and the load must be counterbalanced by the large concrete blocks at the end of the short arm that projects out behind the crane controller's cabin. The counterbalance weights must be large because they are positioned closer to the pivot point, where the crane tower supports the crosspiece of the crane. Without careful balance the turning forces on the support tower could cause it to bend and collapse.

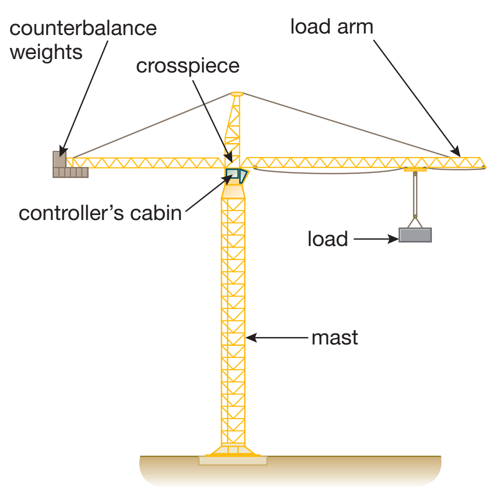

Figure 5.6 The clockwise and anticlockwise moments on the crane must be balanced.

CENTRE OF GRAVITY

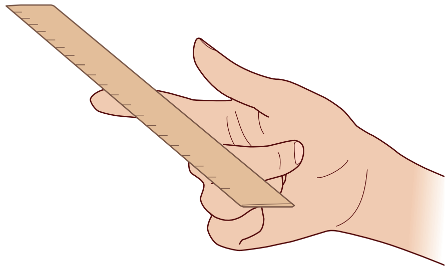

Figure 5.7 Can you find the point at which the ruler balances?

Try balancing a ruler on your finger, as shown in Figure 5.7.

When the ruler is balanced, the anticlockwise moment is equal to the clockwise moment, but there are no downward forces acting in this situation other than the weight of the ruler itself. We know that the weight of the ruler is due to the pull of the Earth's gravity on the mass of the ruler. The mass of the ruler is equally spread throughout its length. It is not, therefore, surprising to find that the ruler balances at its centre point.

We say that the centre of gravity of the ruler is at this point. The weight force of the ruler acts through the centre of gravity – it is the point where the whole of the weight of the ruler appears to act. If we support the ruler at this point there is no turning moment in any direction about the point, and it balances. The centre of gravity is sometimes called the centre of mass.

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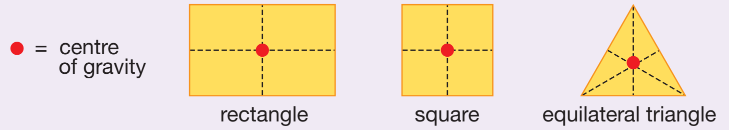
EXTENSION WORK

Finding the centre of gravity of a sheet of card

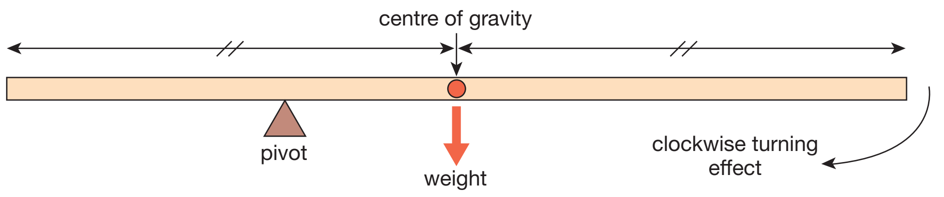
If you have a sheet of card or any other uniform material then finding its centre of gravity is quite straightforward – it will be located where the axes of symmetry cross, as shown in Figure 5.8.



▲ Figure 5.8 The centre of gravity for these three regular shapes is where the axes of symmetry cross. An axis of symmetry can be found using a plane mirror. If you place a plane mirror along one of the dotted lines in any of the above shapes, the reflection in the mirror looks exactly like the original.

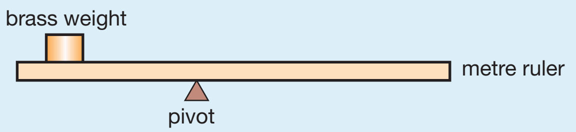
OBJECTS NOT PIVOTED AT THE CENTRE OF GRAVITY

A simple see-saw is a uniform beam (plank) pivoted in the middle. The centre of gravity of a uniform beam is in the middle, so the see-saw is pivoted through its centre of gravity. When an object is not pivoted through its centre of gravity the weight of the object will produce a turning effect. This is shown in Figure 5.9.



▲ Figure 5.9 The weight of the beam causes a clockwise turning effect about the pivot.

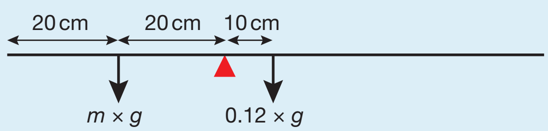
EXAMPLE 2



▲ Figure 5.10 In balance – not tipping in either direction

This sketch diagram shows a uniform wooden metre ruler with a mass of 0.12 kg. A pivot at the 40 cm mark supports the rule. When a brass weight is placed at the 20 cm mark the ruler just balances in the horizontal position. Take moments about the pivot to calculate the mass of the brass weight.

The weight of the ruler acts vertically through the centre of gravity of the rule. As the ruler is uniform the centre of gravity is at the 50 cm mark.



▲ Figure 5.11 A labelled sketch of the problem

For balance:

anticlockwise moments = clockwise moments

$$(m \times g) \times 20 \text{ cm} = (0.12 \text{ kg} \times g) \times 10 \text{ cm}$$

The mass of the brass weight is 0.06 kg.

Here g is the gravitational field strength in N/kg but, as you can see, it cancels. You can leave the distances in centimetres because you are using the same length units on both sides of the equation.

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EXTENSION WORK

Centre of gravity and stability

The position of the centre of gravity of an object will affect its stability. A stable object is one that is difficult to push over – when pushed and then released it will tend to return to its original position.

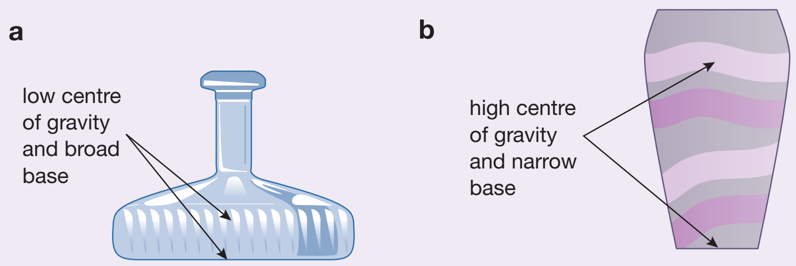


Figure 5.12 Stable and **unstable** objects

The shape in Figure 5.12a is typical for a ship's decanter (bottle). Bottles used on ships need to be difficult to knock over for obvious reasons! It is stable because, when knocked, its low centre of gravity and wide base result in a turning moment that tries to pull it back to its original position. The object in Figure 5.12b has a higher centre of gravity and smaller base, so it is much less stable. Only a small displacement is needed to make it fall over.

FORCES ON A BEAM

Figure 5.13a shows a boy standing on a beam across a stream. The beam is not moving, so the upward and downward forces must be balanced. As the boy is standing in the middle of the beam, the upward forces on the ends of the beam are the same as each other. The forces are shown in Figure 5.13b – to keep things simple, we are ignoring the weight of the beam.

If he moves to one end of the beam, as shown in Figure 5.13c, then the upward force will all be at that end of the beam. As he moves along the beam, the upward forces at the ends of the beam change. In Figure 5.13d, he is one-quarter along the beam. The upward force on the support nearest to him is three-quarters of his weight, and the upward force on the end furthest away from him is only one-quarter of his weight.

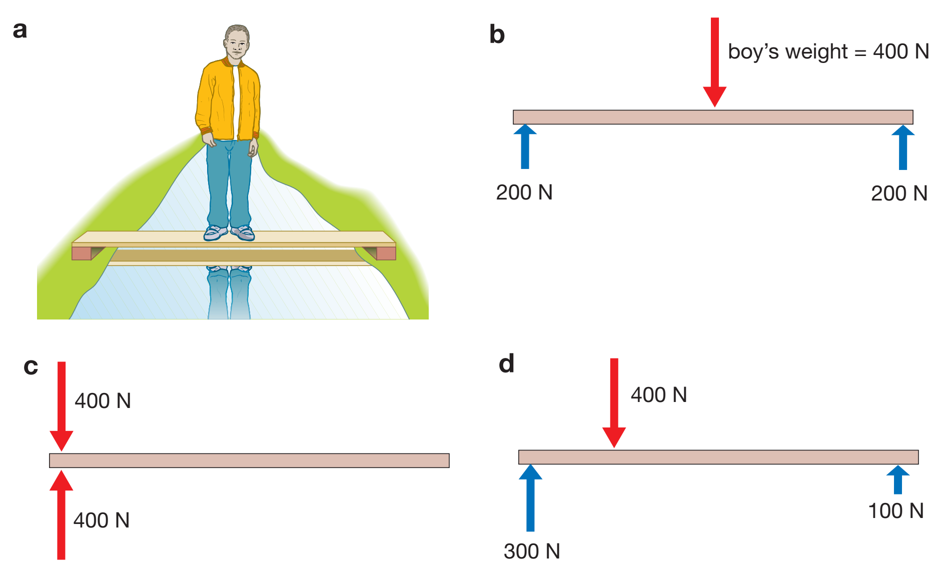


Figure 5.13 The forces at the ends of a beam depend on where the load is applied.

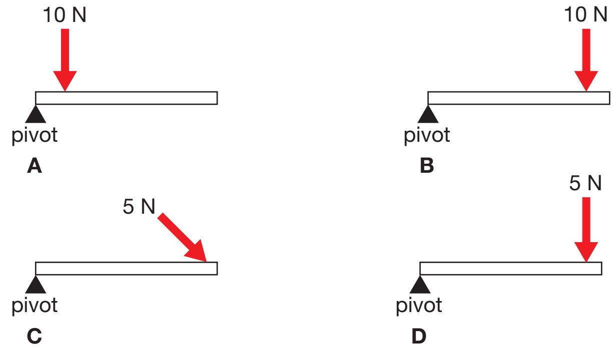
CHAPTER QUESTIONS

More questions on the turning effect of forces can be found at the end of Unit 1 on page 55.

SKILLS ANALYSIS

8

1 Look at the diagram below. It shows various forces acting on objects about pivots.

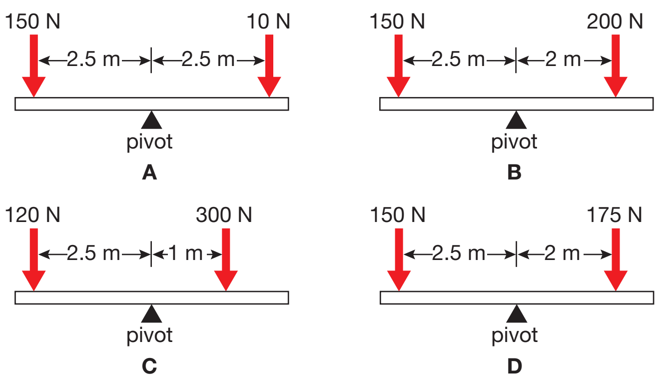


Write down the letter of the diagram that:

a shows the greatest turning moment about the pivot

b shows a turning moment of zero.

2 Look at the four see-saw diagrams below.



Write down the letter(s) of the diagram(s) that agree with the following statements, or write 'none' if no diagram agrees with the statement.

7 **a** The see-saw is balanced.

8 **b** The see-saw will rotate clockwise (dip down to the right).

c The see-saw will rotate anti-clockwise (dip down to the left).

SKILLS INTERPRETATION

3 A bookshelf is 2 m long, with supports at its ends (P and Q). Do not consider the weight of the bookshelf when you are answering these questions.

4 **a** Draw a sketch of the shelf, showing the supports.

SKILLS PROBLEM SOLVING

7 **b** A book weighing 10 N is placed in the middle of the shelf. What are the upward forces at P and Q?

8 **c** The book is moved so that it is 50 cm from Q. Use moments to calculate the forces at P and Q.

9 **d** The bookshelf weighs 10 N. Repeat parts **b** and **c** taking into account the weight of the shelf as well as the weight of the book.

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UNIT QUESTIONS

SKILLS CRITICAL THINKING 6

1

a Which of the following quantities is not a vector quantity?

A force

B area

C displacement

D velocity

(1)

b Which of the following quantities is not a scalar quantity?

A speed

B your age

C volume

D acceleration

(1)

c Which of the following statements about the motion of an object on which unbalanced forces act is false?

A The object could continue moving at constant speed in a straight line.

B The object could accelerate.

C The object could slow down.

D The object could change the direction in which it is moving.

(1)

d A ball is thrown vertically upwards in the air. Which of the following statements about the motion of the ball is false?

A The ball will be travelling as fast as it was when it gets back to the ground as it was when first thrown upwards.

B The ball will be stationary for an instant at the highest point in its flight.

C The direction of the force on the ball changes so the ball falls back to the ground.

D The direction of the acceleration is always downwards.

(1)

(Total for Question 1 = 4 marks)

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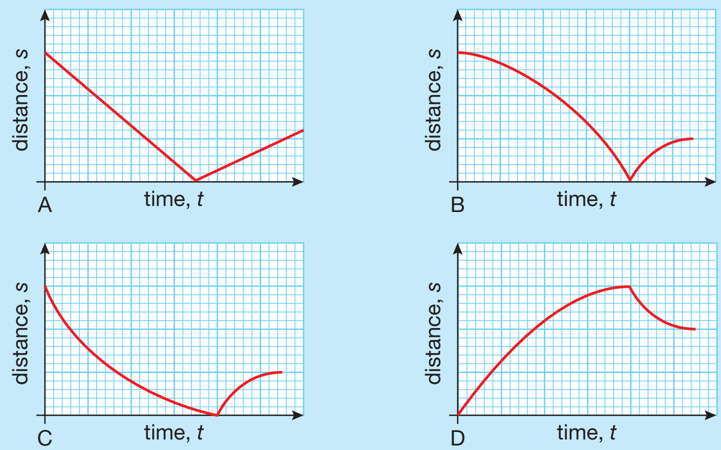
SKILLS ANALYSIS

2 A tennis ball is dropped from a height of 3 m and bounces back to a height of 1 m after hitting the ground ($s = 0$).

a Which of the following distance–time graphs shows this motion correctly? **(1)**



SKILLS CRITICAL THINKING

b **i** Explain the difference between the terms distance and displacement. **(2)**

SKILLS PROBLEM SOLVING

ii What is the displacement of the tennis ball at the end of the described motion? **(1)**

c **i** Use the equation $v^2 = u^2 + 2as$ to calculate the velocity of the tennis ball when it hits the ground. **(4)**

ii What is the average speed of the tennis ball while it is falling to the ground? **(2)**

iii Calculate how long it takes for the tennis ball to reach the ground. **(2)**

SKILLS CRITICAL THINKING

d How can the distance travelled by the tennis ball be found from a velocity–time graph of its motion? **(1)**

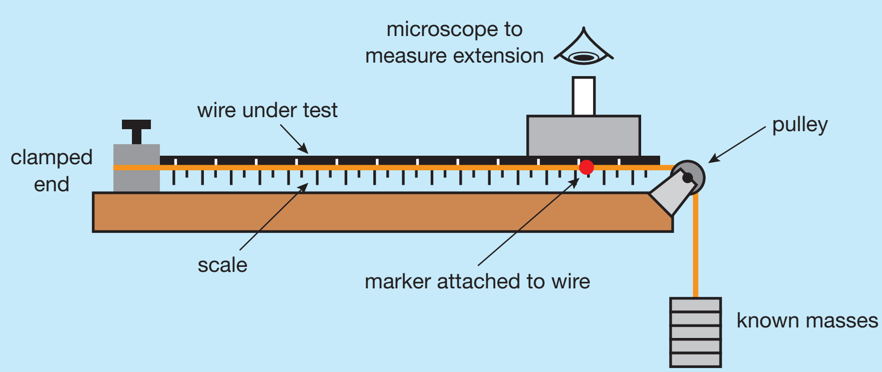
SKILLS INTERPRETATION

e Sketch a velocity–time graph for the tennis ball from the time that it is released to the time that it has rebounded to 1 m after the first bounce. Assume that the time that the ball is in contact with the ground is negligible (too short to show on your graph). Include as much numerical detail as you can without doing any further calculations. **(6)**

(Total for Question 2 = 19 marks)

SKILLS CRITICAL THINKING

3 A student uses the following piece of apparatus to investigate how the extension of a length of wire varies with the force applied to it.



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a **i** Name the independent variable in this investigation. **(1)**

ii Name the dependent variable in this investigation. **(1)**

iii Name one control variable in this investigation. **(1)**

SKILLS DECISION MAKING

b How is the force being applied to the wire calculated? **(1)**

SKILLS EXECUTIVE FUNCTION

c Explain how the student should use the apparatus to determine if the wire obeys Hooke's law. **(5)**

d The student also wants to know if the sample behaves elastically. Explain how the student can improve the investigation and discover whether or not the wire behaves elastically. **(3)**

(Total for Question 3 = 12 marks)

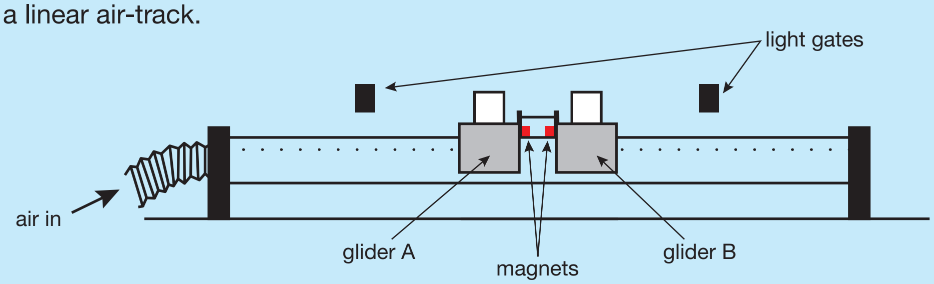
PHYSICS ONLY

SKILLS CRITICAL THINKING

4 This question is about momentum.

a State whether momentum is a scalar or a vector quantity and explain your answer. **(3)**

The following apparatus is used to investigate the momentum of two gliders on a linear air-track.



The gliders are fitted with magnets with like poles facing each other, so that they repel each other, and tied together with a cotton thread. This cotton thread will be burnt using a flame later in the investigation. 5 cm square cards are attached to both gliders – these will pass through the light gates. Digital timers time how long each card takes to pass through the light gates. The gliders are initially at rest.

SKILLS PROBLEM SOLVING

b State the initial momentum of the gliders. **(1)**

SKILLS INTERPRETATION

c **i** Draw a labelled diagram showing the forces acting on glider A before the thread is burnt. **(4)**

SKILLS CRITICAL THINKING

ii State Newton's third law and explain how it applies to the horizontal forces on the gliders when the thread is cut with the flame. **(3)**

SKILLS REASONING

iii Describe what happens to the two gliders when the thread is cut. **(1)**

SKILLS PROBLEM SOLVING

d After the thread is cut the card on glider A passes the light gate in 1.25 s.

i Calculate the speed of glider A as it passes through the light gate. **(2)**

ii Glider A has a mass of 500 g and glider B has a mass of 800 g. Calculate how fast glider B will be moving, explaining your method and any assumptions you make. **(5)**

SKILLS REASONING

e The experiment is repeated but the two gliders are tied closer together with a shorter cotton thread. Explain what difference this would make to the result of cutting the thread, if any. **(3)**

(Total for Question 4 = 22 marks)

HINT
Think about magnetic forces.

END OF PHYSICS ONLY