1.5 Forces

1.5.1 Effects of forces

FOCUS POINTS

★ Understand that the size and shape of objects can be altered by forces.
★ Become familiar with load–extension graphs for an elastic solid and describe an experiment to show how a spring behaves when it is stretched.
★ Understand that when several forces act simultaneously on an object that a resultant can be determined.
★ Know that, unless acted upon by a resultant force, an object will remain at rest or will continue moving with a constant speed in a straight line.
★ Understand that solid friction acts to slow an object and produce heat.
★ Explain the terms 'drag' and 'air resistance' in terms of friction acting on objects.

★ Define the spring constant and the limit of proportionality on a load–extension graph.
★ Apply the equation $F = ma$ to calculate force and acceleration.
★ Describe motion in a circular path and understand the effect on force if speed, radius or mass change.

A gravitational force causes a freely falling object to accelerate and keeps a satellite moving in a circular path. Clearly a force can change the speed or direction of travel of an object. A force can also change the shape or size of an object. If you stand on an empty paper carton it will change its shape and if you pull on a spiral spring it will stretch. Several forces may act on an object at once and it is useful to calculate a resultant force to predict their combined effect; both the size and direction of the forces are needed for this. Friction between a moving object and its surroundings is also important as it acts to reduce the speed of the object and produce heat. You have already learnt how to quantify some of these changes and in this topic you will encounter more ways to do so.

Force

A **force** is a push or a pull. It can cause an object at rest to move, or if the body is already moving it can change its speed or direction of motion.

A force can also change a body's shape or size. For example, a spring (or wire) will stretch when loaded with a weight.

▲ **Figure 1.5.1** A weightlifter in action exerts first a pull and then a push.

Practical work

Stretching a spring

For safe experiments/demonstrations related to this topic, please refer to the *Cambridge IGCSE Physics Practical Skills Workbook* that is also part of this series.

Safety

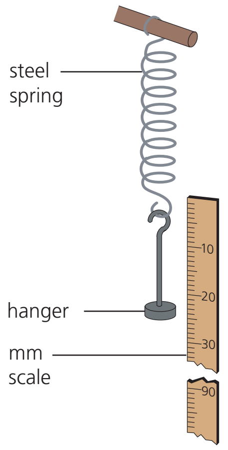
- Eye protection must be worn (in case the spring snaps).

Arrange a steel spring as in Figure 1.5.2. Read the scale opposite the bottom of the hanger. Add 100 g loads one at a time (thereby increasing the **stretching force** by steps of 1 N) and take readings from the scale after each one. Enter the readings in a table for loads up to 500 g.

Note that at the head of columns (or rows) in data tables it is usual to give the name of the quantity or its symbol followed by / and the unit.

Stretching force/N	Scale reading/mm	Total extension/mm

Sometimes it is easier to discover laws by displaying the results on a graph. Do this on graph paper by plotting total **extension** readings along the *x*-axis (horizontal axis) and **stretching force** readings along the *y*-axis (vertical axis) in a load–extension graph. Every pair of readings will give a point; mark them by small crosses and draw a smooth line through them.



▲ **Figure 1.5.2**

1. What is the shape of the graph you plotted?
2. Do the results suggest any rule about how the spring behaves when it is stretched?
3. What precautions could you take to improve the accuracy of the results of this experiment?
4. How could you test if the extension of the spring is proportional to the stretching force?

Extension in springs

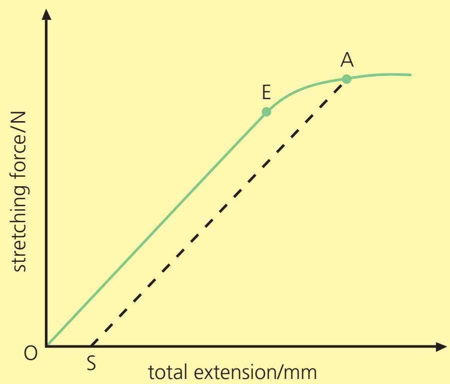
Springs were investigated by Robert Hooke just over 350 years ago. He found that the extension was proportional to the stretching force provided the spring was not permanently stretched. This means that doubling the force doubles the extension, trebling the force trebles the extension, and so on. Using the sign for proportionality, $\propto$, we can write

extension $\propto$ stretching force

It is true only if the **limit of proportionality** of the spring is not exceeded.

> **Key definition**
> **Limit of proportionality** the point at which the load-extension graph becomes non-linear

The graph of Figure 1.5.3 is for a spring stretched beyond its limit of proportionality, E. OE is a straight line passing through the origin O and is graphical proof that the extension is proportional to the stretching force over this **range**. If the force for point A on the graph is applied to the spring, the proportionality limit is passed and on removing the force some of the extension (OS) remains.



▲ **Figure 1.5.3**

Test yourself

1 In Figure 1.5.3, over which part of the graph does a spring balance work?

Spring constant

The **spring constant**, k, is defined as force per unit extension. It is the force which must be applied to a spring to cause an extension of 1 m.

If a force F produces extension x then

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

Rearranging the equation gives

$$F = kx$$

Key definition

Spring constant force per unit extension

Proportionality also holds when a force is applied to an elastic solid such as a straight metal wire, provided it is not permanently stretched.

Load–extension graphs similar to Figure 1.5.3 are obtained. You should label each axis of your graph with the name of the quantity or its symbol followed by / and the unit, as shown in Figure 1.5.3.

The limit of proportionality can be defined as the point at which the load–extension graph becomes non-linear because the extension is no longer proportional to the stretching force.

? Worked example

A spring is stretched 10 mm (0.01 m) by a weight of 2.0 N. Calculate

a the spring constant k

b the weight W of an object that causes an extension of 80 mm (0.08 m).

a $k = \frac{F}{x} = \frac{2.0\,\text{N}}{0.01\,\text{m}} = 200\,\text{N/m}$

b W = stretching force F

$= k \times x$

$= 200\,\text{N/m} \times 0.08\,\text{m}$

$= 16\,\text{N}$

Now put this into practice

1 Calculate the spring constant of a spring which is stretched 2 mm by a force of 4 N.

2 A 2 N weight is applied to a spring which has a spring constant of 250 N/m. Calculate the extension of the spring in mm.

Test yourself

2 State two effects which a force may have on an object.

3 Make a sketch of a load–extension graph for a spring and indicate the region over which the extension is proportional to the stretching force.

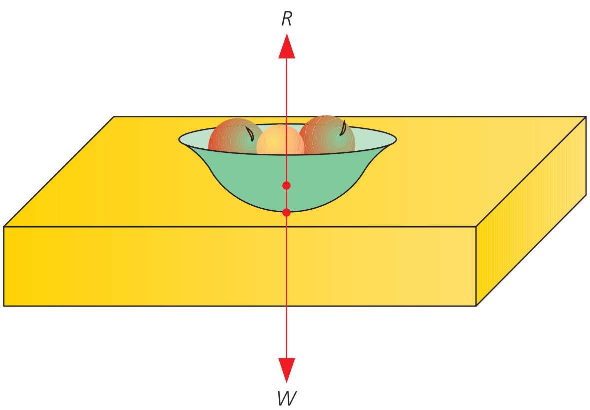
4 Calculate the spring constant of a spring which is stretched 4 cm by a mass of 200 g.

5 Define the limit of proportionality for a stretched spring.

Forces and resultants

Force has both magnitude (size) and direction. It is represented in diagrams by a straight line with an arrow to show its direction of action.

Usually more than one force acts on an object. As a simple example, an object resting on a table is pulled downwards by its weight W and pushed upwards by a force R due to the table supporting it (Figure 1.5.4). Since the object is at rest, the forces must balance, i.e. $R = W$.

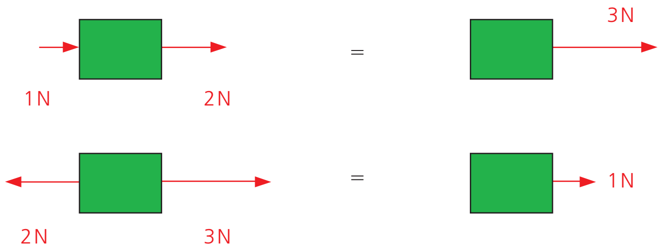


▲ **Figure 1.5.4**

In structures such as a giant oil platform (Figure 1.5.5), two or more forces may act at the same point. It is then often useful for the design

▲ **Figure 1.5.5** The design of an offshore oil platform requires an understanding of the combination of many forces.

engineer to know the value of the single force, i.e. the resultant force, which has exactly the same effect as these forces, If the forces act in the same straight line, the resultant is found by simple addition or subtraction as shown in Figure 1.5.6; if they do not they are added by using the **parallelogram law.**



▲ **Figure 1.5.6** The resultant of forces acting in the same straight line is found by addition or subtraction.

Practical work

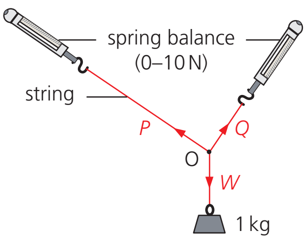
Parallelogram law

Safety

- Take care when using the mass in case it drops.

Arrange the apparatus as in Figure 1.5.7a with a sheet of paper behind it on a vertical board. We have to find the resultant of forces P and Q.

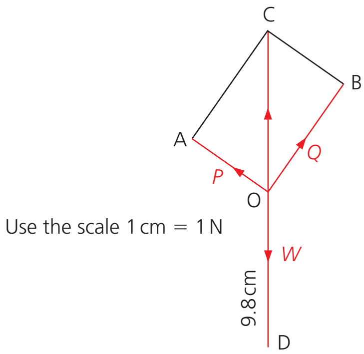
Read the values of P and Q from the spring balances. Mark on the paper the directions of P, Q and W as shown by the strings. Remove the paper and, using a scale of 1 cm to represent 1 N, draw OA, OB and OD to represent the three forces P, Q and W which act at O, as in Figure 1.5.7b. (W = weight of the 1 kg mass = 9.8 N; therefore OD = 9.8 cm.)



▲ **Figure 1.5.7a**

P and Q together are balanced by W and so their resultant must be a force equal and opposite to W.

Complete the parallelogram OACB. Measure the diagonal OC; if it is equal in size (i.e. 9.8 cm) and opposite in direction to W then it represents the resultant of P and Q.



▲ **Figure 1.5.7b** Finding a resultant by the parallelogram law

The parallelogram law for adding two forces is:

> If two forces acting at a point are represented in size and direction by the sides of a parallelogram drawn from the point, their resultant is represented in size and direction by the diagonal of the parallelogram drawn from the point.

5 List the equipment you would need for this experiment.

6 What quantity would you vary to test the law under different conditions?

Test yourself

6 Jo, Daniel and Helen are pulling a metal ring. Jo pulls with a force of 100 N in one direction and Daniel with a force of 140 N in the opposite direction. If the ring does not move, what force does Helen exert if she pulls in the same direction as Jo?

7 A boy drags a suitcase along the ground with a force of 100 N. If the frictional force opposing the motion of the suitcase is 50 N, what is the resultant forward force on the suitcase?

8 A picture is supported by two vertical strings. If the weight of the picture is 50 N, what is the force exerted by each string?

9 Using a scale of 1 cm to represent 10 N, find the size and direction of the resultant of forces of 30 N and 40 N acting at right angles to each other.

Newton's first law

Friction and air resistance cause a car to come to rest when the engine is switched off. If these forces were absent, we believe that an object, once set in motion, would go on moving forever with a constant speed in a straight line. That is, force is not needed to keep a body moving with **uniform velocity** provided that no opposing forces act on it.

This idea was proposed by Galileo and is summed up in **Isaac Newton's first law of motion**:

> An object stays at rest, or continues to move in a straight line at constant speed, unless acted on by a **resultant force**.

It seems that the question we should ask about a moving body is not what keeps it moving but what changes or stops its motion.

The smaller the external forces opposing a moving body, the smaller is the force needed to keep it moving with constant velocity. A hover scooter, which is supported by a cushion of air (Figure 1.5.8), can skim across the ground with little frictional opposition, so that relatively little power is needed to maintain motion.

A resultant force may change the velocity of an object by changing its direction of motion or speed.

Key definitions

Resultant force may change the velocity of an object by changing its direction of motion or its speed

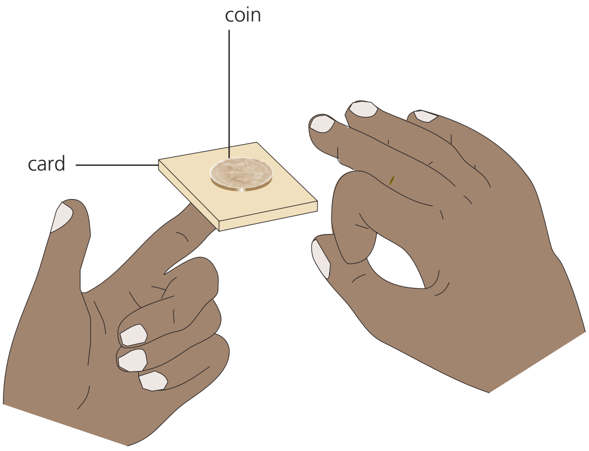
▲ **Figure 1.5.8** Friction is much reduced for a hover scooter.

Going further

Mass and inertia

Newton's first law is another way of saying that all matter has a built-in opposition to being moved if it is at rest or, if it is moving, to having its motion changed. This property of matter is called inertia (from the Latin word for laziness).

Its effect is evident on the occupants of a car that stops suddenly: they lurch forwards in an attempt to continue moving, and this is why seat belts are needed. The reluctance of a stationary object to move can be shown by placing a large coin on a piece of card on your finger (Figure 1.5.9). If the card is flicked *sharply* the coin stays where it is while the card flies off.



▲ **Figure 1.5.9** Flick the card sharply

The larger the mass of a body, the greater is its inertia, i.e. the more difficult it is to move it when at rest and to stop it when in motion. Because of this we consider that *the mass of a body measures its inertia*. This is a better definition of mass than the one given earlier (Topic 1.3) in which it was stated to be the amount of matter in a body.

Practical work

Effect of force and mass on acceleration

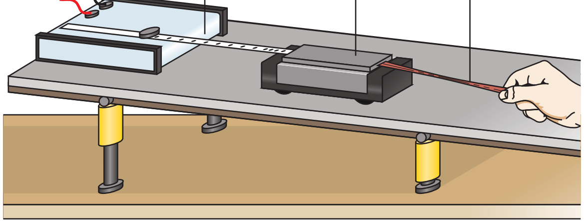
For safe experiments/demonstrations related to this topic, please refer to the *Cambridge IGCSE Physics Practical Skills Workbook* that is also part of this series.

Safety

- Take care when rolling the trolley down the ramp. Ensure it is clear at the bottom of the ramp and use a side barrier to prevent the trolley from falling onto the floor.

The apparatus consists of a trolley to which a force is applied by a stretched length of elastic (Figure 1.5.10). The velocity of the trolley is found from a tickertape timer or a motion sensor, datalogger and computer.

First compensate the runway for friction: raise one end until the trolley runs down with constant velocity when given a push. The dots on the tickertape should be equally spaced, or a horizontal trace obtained on a speed–time graph. There is now no resultant force on the trolley and any acceleration produced later will be due only to the force caused by the stretched elastic.



▲ **Figure 1.5.10**

(a) Force and acceleration (mass constant)

Fix one end of a short length of elastic to the rod at the back of the trolley and stretch it until the other end is level with the front of the trolley. Practise pulling the trolley down the runway, keeping the same stretch on the elastic. After a few trials you should be able to produce a steady accelerating force.

Repeat using first two and then three *identical* pieces of elastic, stretched side by side by the same amount, to give two and three units of force.

If you are using tickertape, make a tape chart for each force and use it to find the acceleration produced in cm/ten-tick^2. Ignore the start of the tape (where the dots are too close) and the end (where the force may not be steady). If you use a motion sensor and computer to plot a speed–time graph, the acceleration can be obtained in m/s^2 from the slope of the graph (Topic 1.2).

Put the results in a table.

Force (F)/(no. of pieces of elastic)	1	2	3
Acceleration (a)/cm/ten-tick^2 or m/s^2			

(b) Mass and acceleration (force constant)

Do the experiment as in part (a) using two pieces of elastic (i.e. constant F) to accelerate first one trolley, then two (stacked one above the other) and finally three. Check the friction compensation of the runway each time.

Find the accelerations from the tape charts or computer plots and tabulate the results.

Mass (m)/(no. of trolleys)	1	2	3
Acceleration (a)/cm/ten-tick^2 or m/s^2			

7 For part (a), does a steady force cause a steady acceleration?

8 Do your results in part (a) suggest any relationship between acceleration a and force F?

9 Do your results for part (b) suggest any relationship between a and m?

10 Name the two independent variable quantities in experiments (a) and (b).

11 How could you use the results to verify the equation $F = ma$?

Newton's second law

The previous experiment should show roughly that the acceleration a is

i directly proportional to the applied force F for a fixed mass, i.e. $a \propto F$, and

ii **inversely proportional** to the mass m for a fixed force, i.e. $a \propto 1/m$.

Combining the results into one equation, we get

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

or

$$F \propto ma$$

Therefore

$$F = kma$$

where k is the **constant of proportionality**.

One newton is defined as the force which gives a mass of 1 kg an acceleration of 1 m/s^2, i.e. 1 N = 1 kg m/s^2, so if m = 1 kg and a = 1 m/s^2, then F = 1 N.

Substituting in $F = kma$, we get $k = 1$ and so we can write

$$F = ma$$

This is **Newton's second law of motion**. When using it, two points should be noted. First, F is the resultant (or unbalanced) force causing the acceleration a in the same direction as F. Second, F must be in newtons, m in kilograms and a in metres per second squared, otherwise k is not 1. The law shows that a will be largest when F is large and m small.

You should now appreciate that when the forces acting on a body do not balance there is a net (resultant) force which causes a change of motion, i.e. the body accelerates or decelerates. The force and the acceleration are in the same direction. If the forces balance, there is no change in the motion of the body. However, there may be a change of shape, in which case internal forces in the body (i.e. forces between neighbouring atoms) balance the external forces.

Worked example

A block of mass 2 kg has a constant velocity when it is pushed along a table by a force of 5 N. When the push is increased to 9 N what is

a the resultant force

b the acceleration?

When the block moves with constant velocity the forces acting on it are balanced. The force of friction opposing its motion must therefore be 5 N.

a When the push is increased to 9 N the resultant (unbalanced) force F on the block is (9 – 5) N = 4 N (since the frictional force is still 5 N).

b The acceleration a is obtained from $F = ma$ where F = 4 N and m = 2 kg.

$$a = \frac{F}{m} = \frac{4\,\text{N}}{2\,\text{kg}} = \frac{4\,\text{kg m/s}^2}{2\,\text{kg}} = 2\,\text{m/s}^2$$

Now put this into practice

1 A box of mass 5 kg has a constant velocity when it is pushed along a table by a force of 8 N. When the push is increased to 10 N calculate

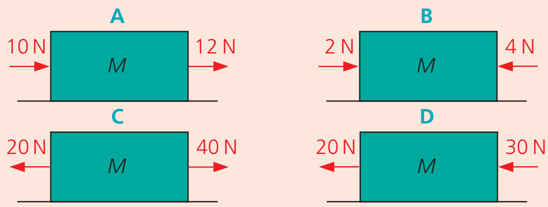
a the resultant force

b the acceleration.

2 A force F produces a constant acceleration in a straight line of 0.5 m/s^2 on a block of mass 7 kg. Calculate the value of F.

Test yourself

10 Which one of the diagrams in Figure 1.5.11 shows the arrangement of forces that gives the block of mass M the greatest acceleration?



▲ **Figure 1.5.11**

11 In Figure 1.5.12 if P is a force of 20 N and the object moves with constant velocity, what is the value of the opposing force F?

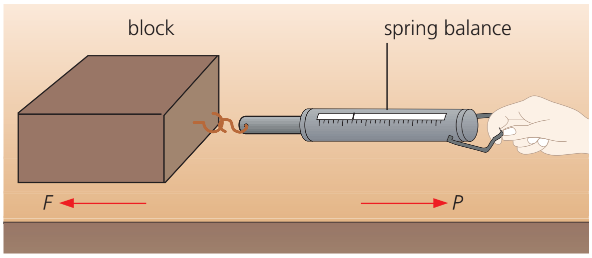
▲ **Figure 1.5.12**

12 a What resultant force produces an acceleration of 5 m/s^2 in a car of mass 1000 kg?
b What acceleration is produced in a mass of 2 kg by a resultant force of 30 N?

13 A block of mass 500 g is pulled from rest on a horizontal frictionless bench by a steady force F and reaches a speed of 8 m/s in 2 s. Calculate
a the acceleration
b the value of F.

Friction

Friction is the force that opposes one surface moving, or trying to move, over another. It can be a help or a hindrance. We could not walk if there was no friction between the soles of our shoes and the ground. Our feet would slip backwards, as they tend to when we walk on ice. On the other hand, engineers try to reduce friction to a minimum in the moving parts of machinery by using lubricating oils and ball-bearings.



▲ **Figure 1.5.13** Friction opposes motion between surfaces in contact.

When a gradually increasing force P is applied through a spring balance to a block on a table (Figure 1.5.13), the block does not move at first. This is because an equally increasing but opposing frictional force F acts where the block and table touch. At any instant P and F are equal and opposite.

If P is increased further, the block eventually moves; as it does so F has its maximum value, called **starting** or **static friction**. When the block is moving at a steady speed, the balance reading is slightly less than that for starting friction. **Sliding** or **dynamic friction** is therefore less than starting or static friction.

Placing a mass on the block increases the force pressing the surfaces together and increases friction.

When work is done against friction, the temperatures of the bodies in contact rise (as you can test by rubbing your hands together); kinetic energy is transferred to thermal energy by mechanical working (see Topic 1.7).

Solid friction can be described as the force between two surfaces that may impede motion and produce heating.

Friction (drag) acts on an object moving through gas (air resistance), such as a vehicle or falling leaf, which opposes the motion of the object. Similarly, friction (drag) acts on an object moving through a liquid. Drag increases as the speed of the object increases, and acts to reduce acceleration and slow the object down.

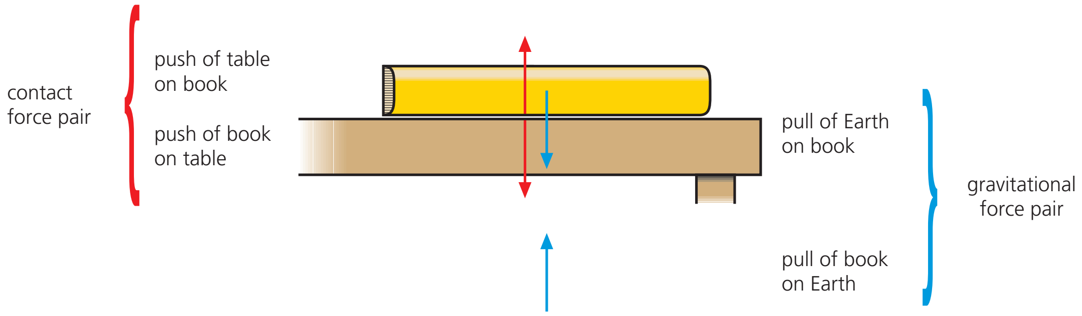
Going further

Newton's third law

If a body A exerts a force on body B, then body B exerts an equal but opposite force on body A.

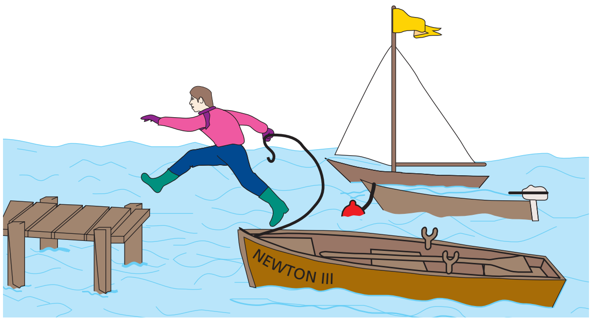
This is Newton's third law of motion and states that forces never occur singly but always in pairs as a result of the action between two bodies. For example, when you step forwards from rest your foot pushes backwards on the Earth, and the Earth exerts an equal and opposite force forward on you. Two bodies and two forces are involved. The small force you exert on the large mass of the Earth gives no noticeable acceleration to the Earth but the equal force it exerts on your very much smaller mass causes you to accelerate.

Note that the pair of equal and opposite forces *do not act on the same body*; if they did, there could never be any resultant forces and acceleration would be impossible. For a book resting on a table, the book exerts a downward force on the table and the table exerts an equal and opposite upward force on the book; this pair of forces act on different objects and are represented by the red arrows in Figure 1.5.14. The weight of the book (blue arrow) does not form a pair with the upward force on the book (although they are equal numerically) as these two forces act on the same body.



▲ **Figure 1.5.14** Forces between book and table

An appreciation of the third law and the effect of friction is desirable when stepping from a rowing boat (Figure 1.5.15). You push backwards on the boat and, although the boat pushes you forwards with an equal force, it is itself now moving backwards (because friction with the water is slight). This reduces your forwards motion by the same amount – so you may fall in!



▲ **Figure 1.5.15** The boat moves backwards when you step forwards!

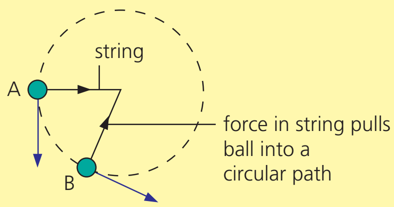
Circular motion

There are many examples of bodies moving in circular paths – rides at a funfair, clothes being spun dry in a washing machine, the planets going round the Sun and the Moon circling the Earth. When a car turns a corner, it may follow an arc of a circle. 'Throwing the hammer' is a sport practised at Highland Games in Scotland (Figure 1.5.16), in which the hammer is whirled round and round before it is released.

▲ **Figure 1.5.16** 'Throwing the hammer'

Centripetal force

In Figure 1.5.17 a ball attached to a string is being whirled round in a horizontal circle. Its direction of motion is constantly changing. At A, it is along the tangent at A; shortly afterwards, at B, it is along the tangent at B; and so on. It can be seen that motion in a circular path is due to a force perpendicular to the motion.



▲ **Figure 1.5.17**

Velocity has both size and direction; speed has only size. Velocity is speed in a stated direction and if the direction of a moving body changes, even if its speed does not, then its velocity has changed. A change of velocity is an acceleration, and so during its whirling motion the ball is accelerating.

It follows from Newton's first law of motion that if we consider a body moving in a circle to be accelerating, then there must be a force acting on it to cause the acceleration. In the case of the whirling ball it is reasonable to say the force is provided by the string pulling inwards on the ball. Like the acceleration, the force acts towards the centre of the circle and keeps the body at a fixed distance from the centre.

A larger force is needed if

- the speed v of the ball is increased, with mass and radius constant
- the radius r of the circle is decreased, with mass and speed constant
- the mass m of the ball is increased, with speed and radius constant.

This force, which acts *towards the centre* and keeps a body moving in a circular path, is called the **centripetal force** (centre-seeking force).

Should the force be greater than the string can bear, the string breaks and the ball flies off with steady speed in a straight line *along the tangent*, i.e. in the direction of travel when the string broke (as Newton's first law of motion predicts). It is not thrown outwards.

Whenever an object moves in a circle (or circular arc) there must be a centripetal force acting on it. In throwing the hammer it is the pull of the athlete's arms acting on the hammer towards the centre of the whirling path. When a car rounds a bend, a frictional force is exerted inwards by the road on the car's tyres.

Satellites

For a satellite of mass m orbiting the Earth at radius r with orbital speed v, the centripetal force, F, is the Earth's gravitational force on the mass.

To put an artificial satellite in orbit at a certain height above the Earth it must enter the orbit at the correct speed. If it does not, the force of gravity, which decreases as height above the Earth increases, will not be equal to the centripetal force needed for the orbit.

Communication satellites

Communication satellites circle the Earth in orbits above the equator. Geostationary satellites have an orbit high above the equator (36 000 km); they travel with the same speed as the Earth rotates, so appear to be stationary at a particular point above the Earth's surface – their orbital period is 24 hours. They are used for transmitting television, intercontinental telephone and data signals. Geostationary satellites need to be well separated so that they do not interfere with each other; there is room for about 400.

Mobile phone networks use many satellites in much lower equatorial orbits; they are slowed by the Earth's atmosphere and their orbit has to be regularly adjusted by firing a rocket engine. Eventually they run out of fuel and burn up in the atmosphere as they fall to Earth.

Monitoring satellites

Monitoring satellites circle the Earth rapidly in low **polar** orbits, i.e. passing over both poles; at a height of 850 km the orbital period is only 100 minutes. The Earth rotates below them so they scan the whole surface at short range in a 24-hour period and can be used to map or monitor regions of the Earth's surface which may be inaccessible by other means. They are widely used in weather forecasting as they continuously transmit infrared pictures of cloud patterns down to Earth (Figure 1.5.18), which are picked up in turn by receiving stations around the world.

▲ **Figure 1.5.18** Satellite image of cloud over Europe