5 Forces

WHAT ARE FORCES?

A force is a push or a pull. The way that an object behaves depends on all of the forces acting on it. A force may come from the pull of a chain or rope, the push of a jet engine, the push of a pillar holding up a ceiling, and, as we have already seen, the pull of the gravitational field around the Earth.

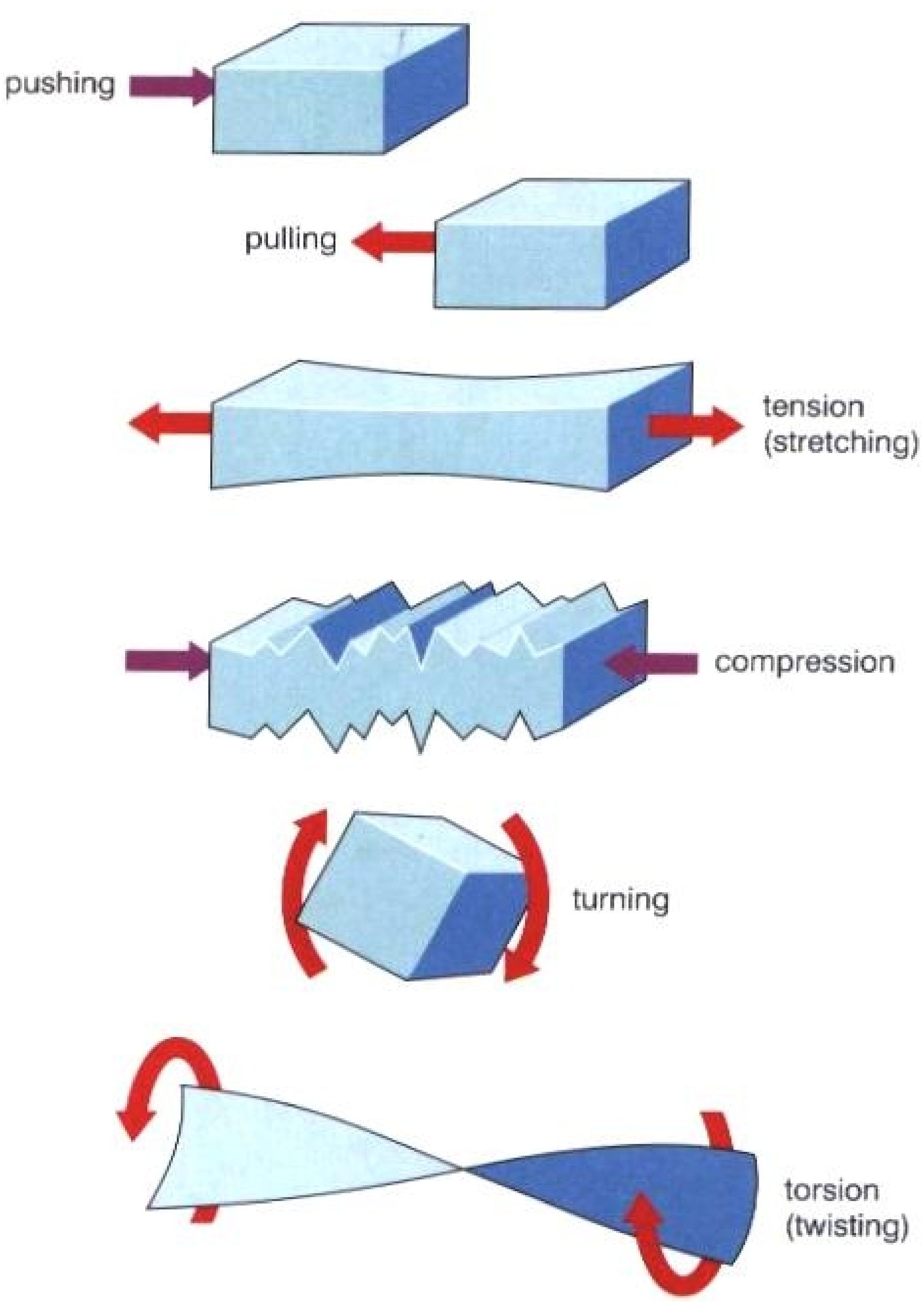
Effects of forces

It is unusual for a single force to be acting on an object. Usually there will be two or more. The size and direction of these forces determine whether the object will move and the direction it will move in.

Forces are measured in **newtons**. They take many forms and have many effects including pushing, pulling, bending, stretching, squeezing and tearing. Forces can:

- **change the speed** of an object
- **change the direction** of movement of an object
- **change the shape** of an object.

Combinations of forces can have all kinds of effects.



To describe a force fully, you must state the size of the force and also the direction in which it is trying to move the object. The direction can be described in many different ways such as 'left to right', 'upwards' or 'north'. Sometimes it is useful to describe all of the forces in one direction as positive, and all of the forces in the other direction as negative. For two forces to be equal they must have the same size and the same direction.

WHAT IS FRICTION?

Friction is a very common force. It is the force that tries to stop movement between touching surfaces. Friction is caused by the roughness of the two surfaces, which produces resistance to movement.

In many situations friction can be a disadvantage, e.g. friction in the bearings of a bicycle wheel. In other situations, friction can be an advantage, e.g. between brake pads and a bicycle wheel.

Friction can stop any movement occurring at all, and it is friction that stops a nail coming out of a piece of wood.

ADDING FORCES

If two or more forces are pulling or pushing an object in the same direction, then the effect of the forces will add up; if they are pulling it in opposite directions, then the backwards forces can be subtracted.

Six husky dogs are pulling a sledge similar to the one in the picture. The sledge is travelling to the right and each dog is pulling with a force of 50 N. There is a friction force of 250 N that is trying to slow the sledge, and therefore must be pointing to the left.

The total force to the right is (6 × 50) N.
The total force to the left is 250 N.
The **resultant** force (the total added-up force) = 300 – 250 N to the right
= 50 N to the right.

Note that you must give the direction of the resultant force.

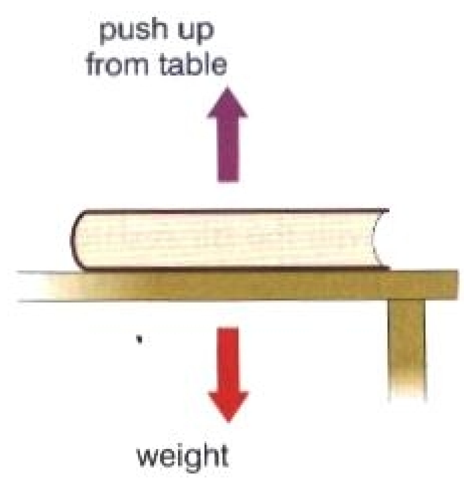
The sledge will behave as if this one force was acting on it, and therefore it will be accelerating to the right.

The husky dogs are able to pull this sledge due to the low level of friction between the sledge and the snow.

BALANCED FORCES

Usually there are at least two forces acting on an object. If these two forces are **balanced** then the object will either be stationary or moving at a constant speed.

A spacecraft in deep space will have no forces acting on it – no air resistance (no air), no force of gravity – and because there is no need to produce a forward force from its rockets, it will travel at a constant speed.



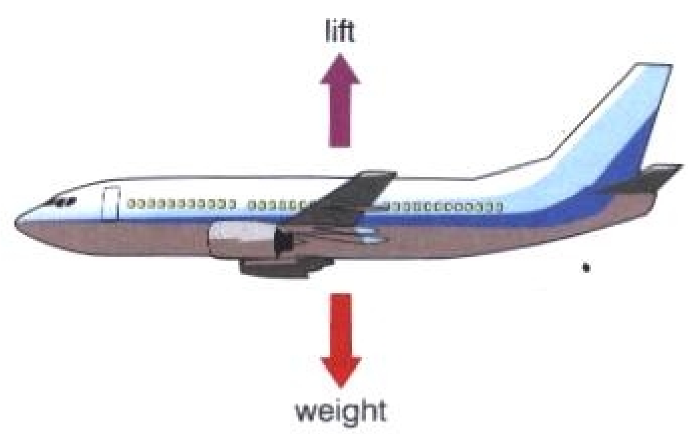
The book is stationary because the push upwards from the table is equal to the weight downwards. If the table stopped pushing upwards, the book would fall.

UNBALANCED FORCES

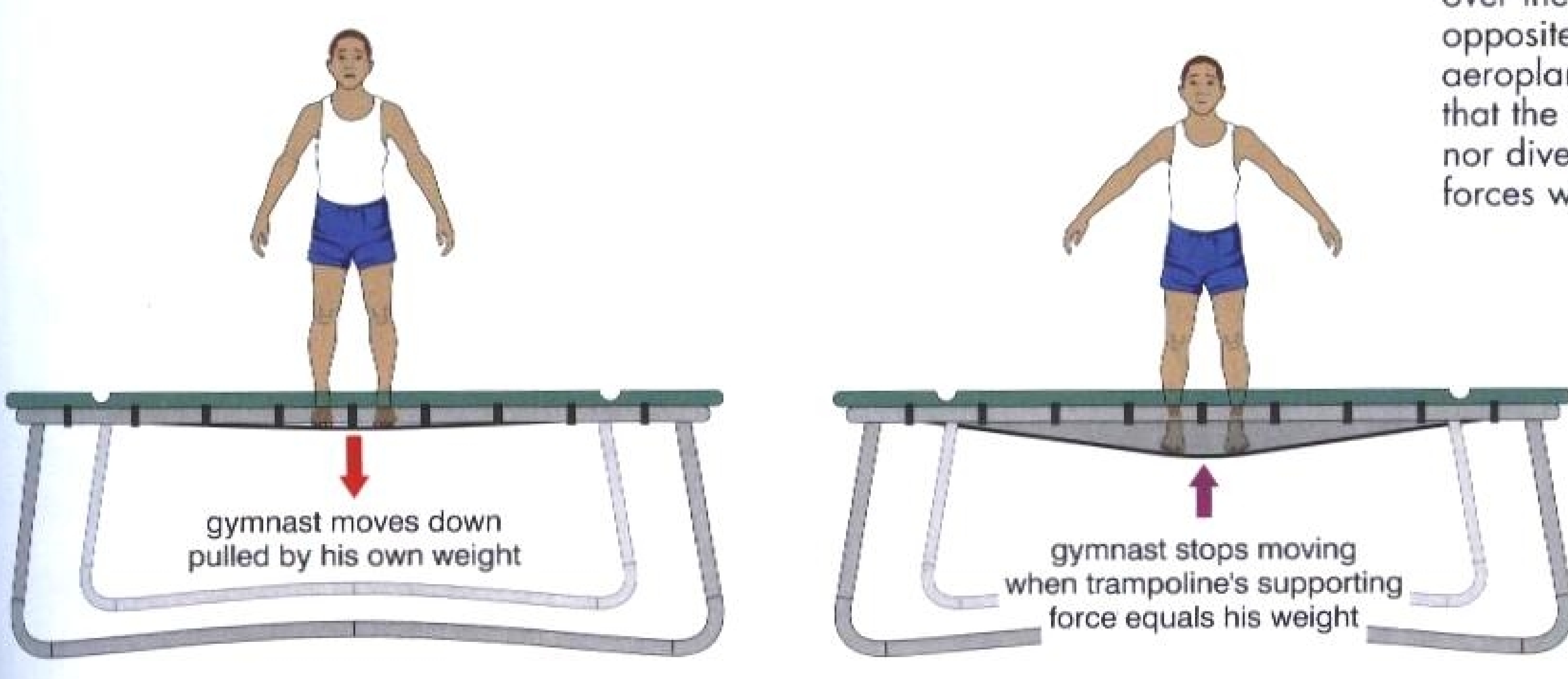
If the forces acting on an object are **unbalanced**, then it will change its speed or direction of movement – it will accelerate.

As a gymnast first steps on to a trampoline, his weight is much greater than the opposing supporting force of the trampoline, so he moves downwards, stretching the trampoline. As the trampoline stretches, its supporting force increases until the supporting force is equal to the gymnast's weight. When the two forces are balanced, the trampoline stops stretching. If an elephant stood on the trampoline, it would break because it could never produce a supporting force equal to the elephant's weight.

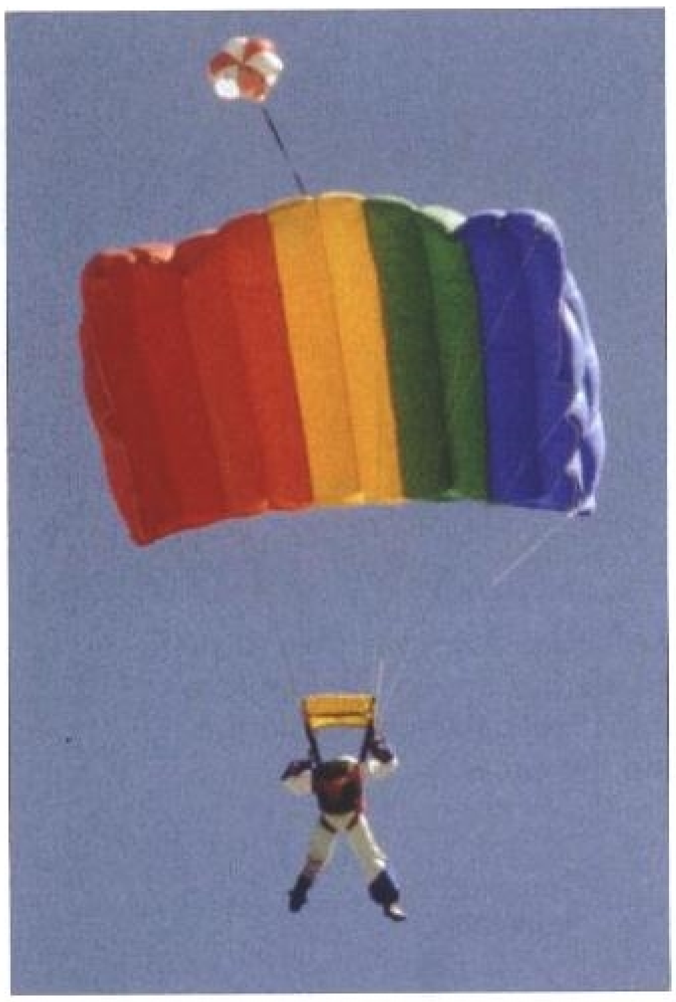
You see the same effect if you stand on snow or soft ground. If you stand on quicksand, then the supporting force will not equal your weight, and you will continue to sink.



This aeroplane is flying 'straight and level' because the lift generated by the air flowing over the wings is equal and opposite to the weight of the aeroplane. This diagram shows that the plane will neither climb nor dive, as it would if the forces were not equal.



A trampoline stretches until it supports the weight on it.



The parachutist descends slowly, with the air resistance on the parachute causing it to pull upwards with a force exactly equalling the parachutist's weight.

As a skydiver jumps from a plane, the weight will be much greater than the opposing force caused by air resistance. Initially she will accelerate downwards at 10 m/s^2, just the same as the coconut on page 13.

The skydiver's speed will increase rapidly – and the force caused by the air resistance increases as the skydiver's speed increases. Eventually it will exactly match the weight, the forces will be balanced and the speed of the skydiver will remain constant. This speed is known as the **terminal speed**, typically 180 km/h.

If the skydiver makes herself streamlined by going headfirst, with her arms by her side, then she will cut through the air more easily, and the air resistance will be less. She will then accelerate again, until the force of air resistance increases again to equal her weight. She will now be going at almost 300 km/h.

A parachute has a very large surface area, and produces a very large resistive force, so the terminal speed of a parachutist is quite low. This means that he or she can land relatively safely.

HOW ARE MASS, FORCE AND ACCELERATION RELATED?

The acceleration of an object depends on its **mass** and the **force** that is applied to it. The relationship between these factors is given by the formula:

force = mass × acceleration	F = force in newtons
$F = m\ a$	m = mass in kg
	a = acceleration in m/s^2

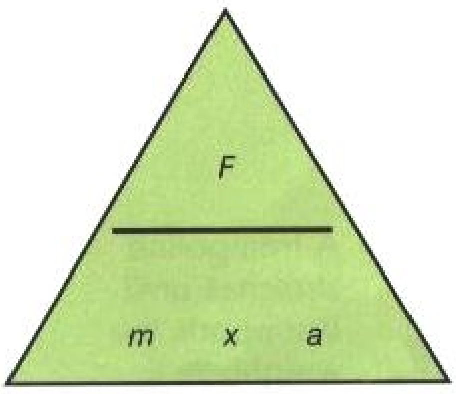
This equation explains the definition of the newton. 'A newton is the force that will accelerate a mass of 1 kg at 1 m/s^2.'

The equation is perhaps easier to understand if we rearrange it into the form $a = \frac{F}{m}$. This shows that if you use a big force you will get a larger acceleration, but if the object has more mass, then you get a smaller acceleration.

So a light object with a large force applied to it will have a large acceleration. (Think of an athlete with a racing bicycle.) But a massive object with a small force applied to it will have a small acceleration. (Think of a small child trying to pedal a large bicycle rickshaw.)

A* EXTRA

- The equation $F = m\ a$ shows that the acceleration of an object is directly proportional to the force acting on it (if its mass is constant) and is inversely proportional to its mass (if the force is constant).



WORKED EXAMPLES

1 What force would be required to give a mass of 5 kg an acceleration of 10 m/s^2?

Write down the formula:	$F = m\ a$
Substitute the values for m and a:	$F = 5 \times 10$
Work out the answer and write down the units:	$F = 50$ N

2 A car has a resultant driving force of 6000 N and a mass of 1200 kg. Calculate the car's initial acceleration.

Write down the formula in terms of a:	$a = \frac{F}{m}$
Substitute the values for F and m:	$a = \frac{6000}{1200}$
Work out the answer and write down the units:	$a = 5\,m/s^2$

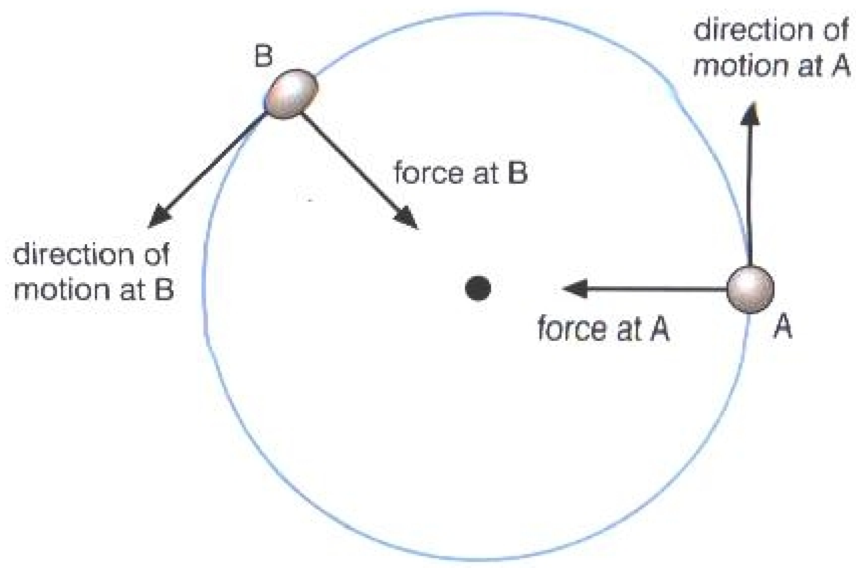
MOTION IN A CIRCLE

If a moving object has no forces acting on it, it will continue to move in a straight line at constant velocity.

So, if an object is moving in a circle, or along the arc of a circle, it follows that there must be a force acting on it, to change its direction. Moving in a circle means that the direction of motion is constantly changing, so this in turn means that the direction of the force is constantly changing.

In order for the object to move on a circular path, the force must *always be acting towards the centre of the circle.*

This force, which always acts towards the centre of the circle, is given the name of **centripetal force**. You will also see that the centripetal force also acts perpendicularly to the direction of motion of the object at any instant.



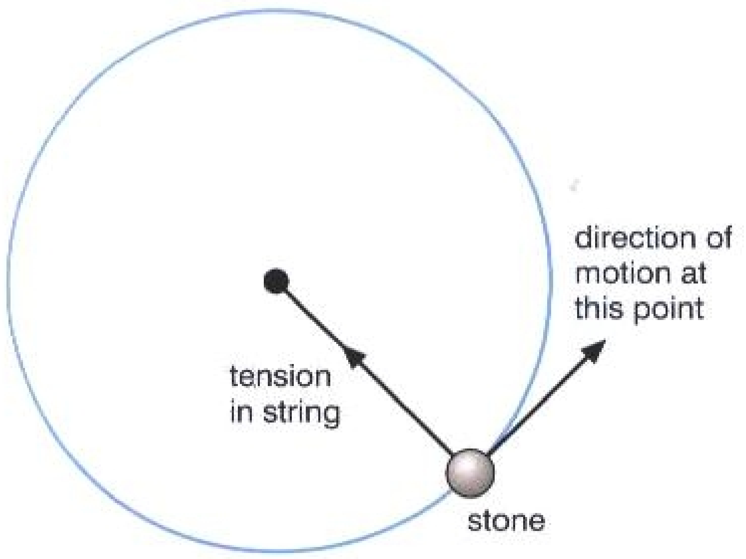
The centripetal force is not a new and different force from any you have come across before, but is one or more of the forces already acting on the object which is moving in the circle.

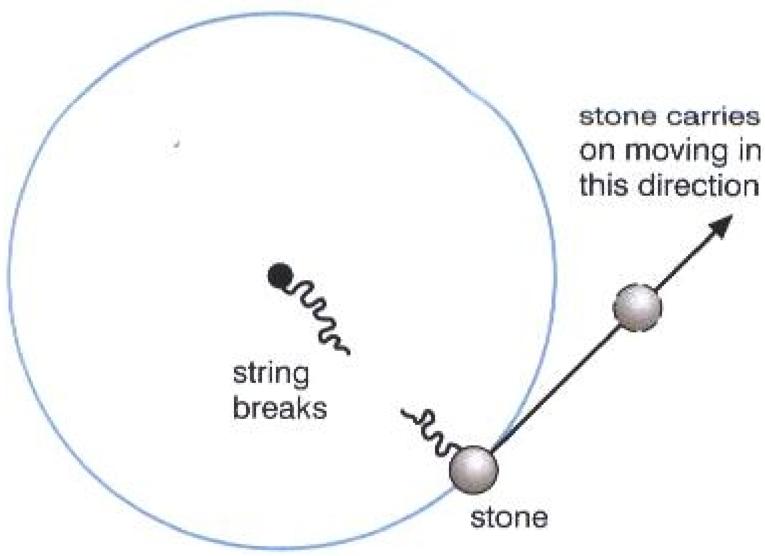
The table below gives some examples.

Example	How is the centripetal force supplied?
1. a stone on the end of a string, being whirled in a horizontal circle	by the tension force in the string
2. the Moon, orbiting the Earth	by the gravitational force of the Earth on the Moon
3. a car turning a corner	by the sideways friction force of the road on the tyres
4. a train going round a bend	by the sideways force of the rails on the wheels
5. a person standing on the Earth, which is spinning rapidly	by the gravitational force of the Earth on the person

See if you can think of other examples of things moving around arcs of circles, and work out what force is providing the centripetal force. Remember that the centripetal force is always towards the centre of the arc and perpendicular to the direction in which the object is travelling at that instant.

Consider a stone being whirled in a circle on the end of a string.





What happens if the string breaks?

In this case, the centripetal force is suddenly removed. There is now no force acting on the stone, so it continues to move in a straight line in whatever direction it had when the string broke (i.e. along the tangent to the circle at that point).

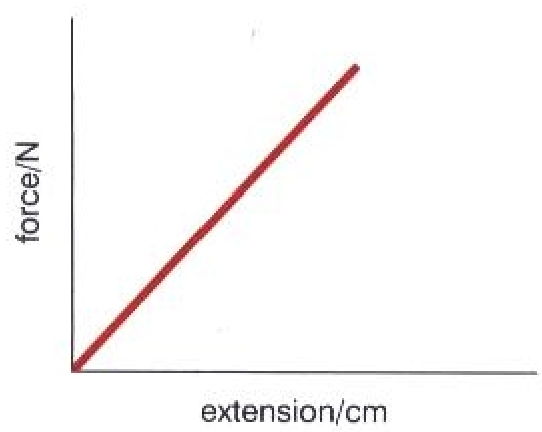
Of course, once it is free of the string, the effects of gravity start to change the motion, but initially the stone flies off along a tangent. It is important to note that the stone does NOT fly out along a radius. [A common mistake some people make is to say that there is a centrifugal (note: not centripetal) force pulling the stone outwards, which leads to the conclusion that when the string breaks, the stone flies out along a radius. This idea is incorrect.]

See if you can work out what would happen:
(a) to the Moon if gravity suddenly ceased,
(b) to a car turning a corner when the road was very slippery,
(c) to a person on Earth if gravity suddenly ceased.

HOOKE'S LAW

When a spring stretches, the extension of the spring is proportional to the force stretching it, provided the elastic limit of the spring is not exceeded. This is **Hooke's law** and is shown by a straight line on a graph.

The gradient of the line is a measure of the stiffness of the spring.



Elastic behaviour in a spring is shown by a straight line.

An experiment to measure Hooke's law

1 Assemble the apparatus shown on the left, but with only the mass hanger hooked on to the spring. The slotted masses are added later. For accurate readings, the mass hanger needs to be close to the rule, but not touching it.

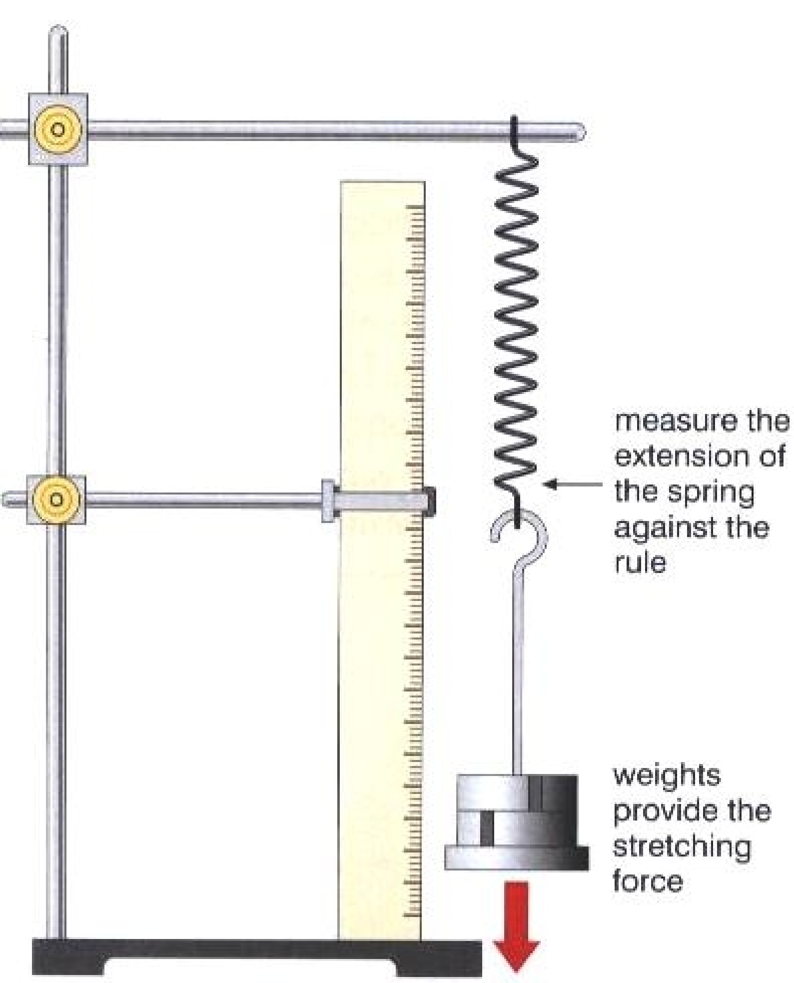
2 Note and record the reading on the scale of the rule, next to the bottom of the mass hanger.

3 Add one slotted mass to the mass carrier. Slotted masses commonly used by schools are typically 100 g (weight 1 N) or 50 g (weight 0.5 N). Note and record the new scale reading of the bottom of the mass hanger.

4 Repeat step 3, adding masses one at a time and recording the corresponding scale readings. Add the masses carefully so that the spring stretches slowly.

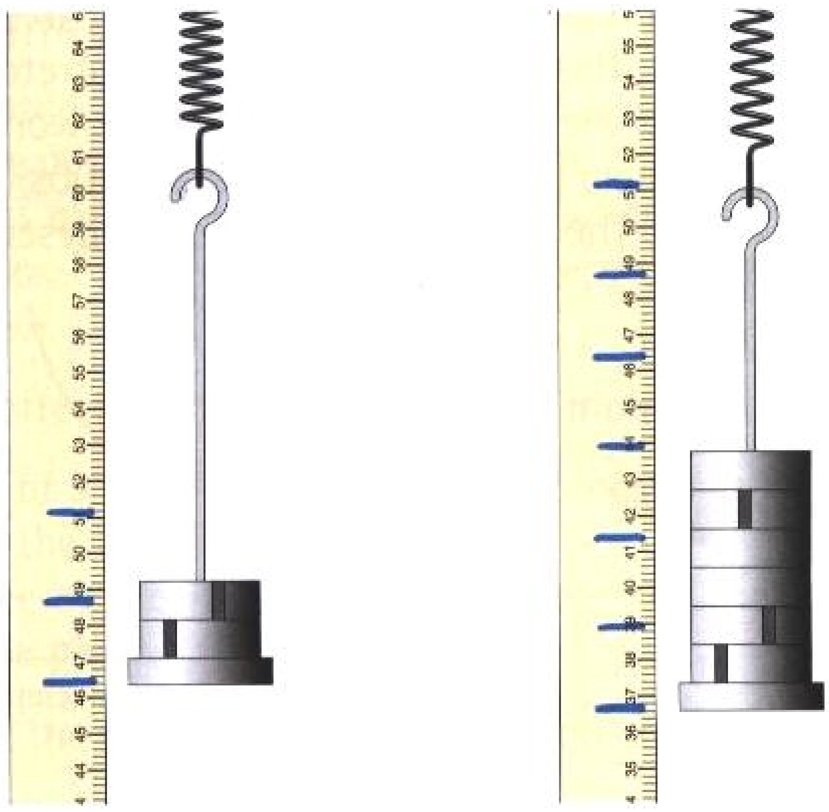
5 You may want to reverse the experiment to see what happens as the masses are removed.

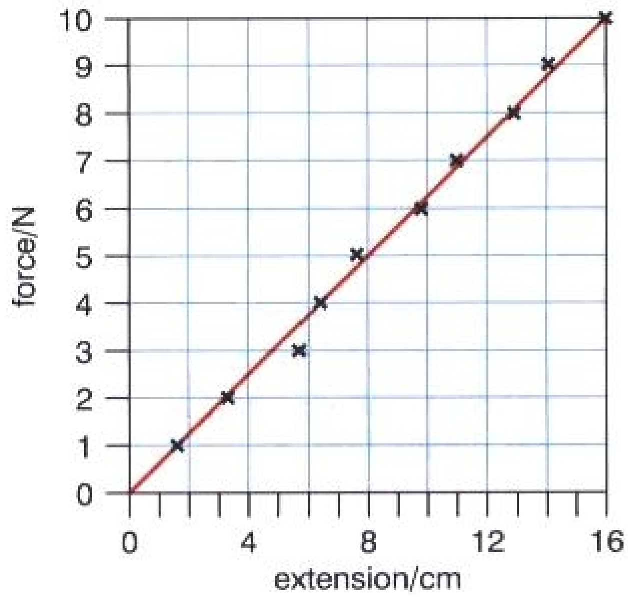
6 Calculate the extension of the spring caused each time by the load on the hanger.



The table below gives the results of one such experiment.

Mass/g	Force/N	Reading/cm	Calculate the extension/cm	Extension/cm
0	0	15.2	–	–
100	1.0	16.8	16.8 – 15.2	1.6
200	2.0	18.5	18.5 – 15.2	3.3
300	3.0	19.9	19.9 – 15.2	4.7
400	4.0	21.6	21.6 – 15.2	6.4
etc.	etc.			





If any two quantities are proportional, when they are plotted against each other on a graph, the graph will have two characteristics:

(a) It will be a straight line,
(b) It will pass through the origin.

Because the graph of Force against Extension is a straight line which passes through the origin, this experiment verifies Hooke's law.

If you do stage 5 in the experiment above, you will also note that the spring, as well as showing proportional behaviour, also shows elastic behaviour – when the force is removed, the spring returns to its original length.

LIMIT OF PROPORTIONALITY

If you stretch the spring too far, the line is no longer straight, and Hooke's law is no longer true. This point at the end of the straight line is know as the 'limit of proportionality'.

The spring may (if you do not stretch it too far) be elastic and go back to its original length.

But as you stretch the material beyond the limit of proportionality, different materials can behave in widely different ways.

HOW ARE OTHER MATERIALS AFFECTED BY STRETCHING?

A music wire string, such as a guitar string, will behave as shown in the graph for wire (see page 30), but will break shortly after the limit of proportionality is reached.

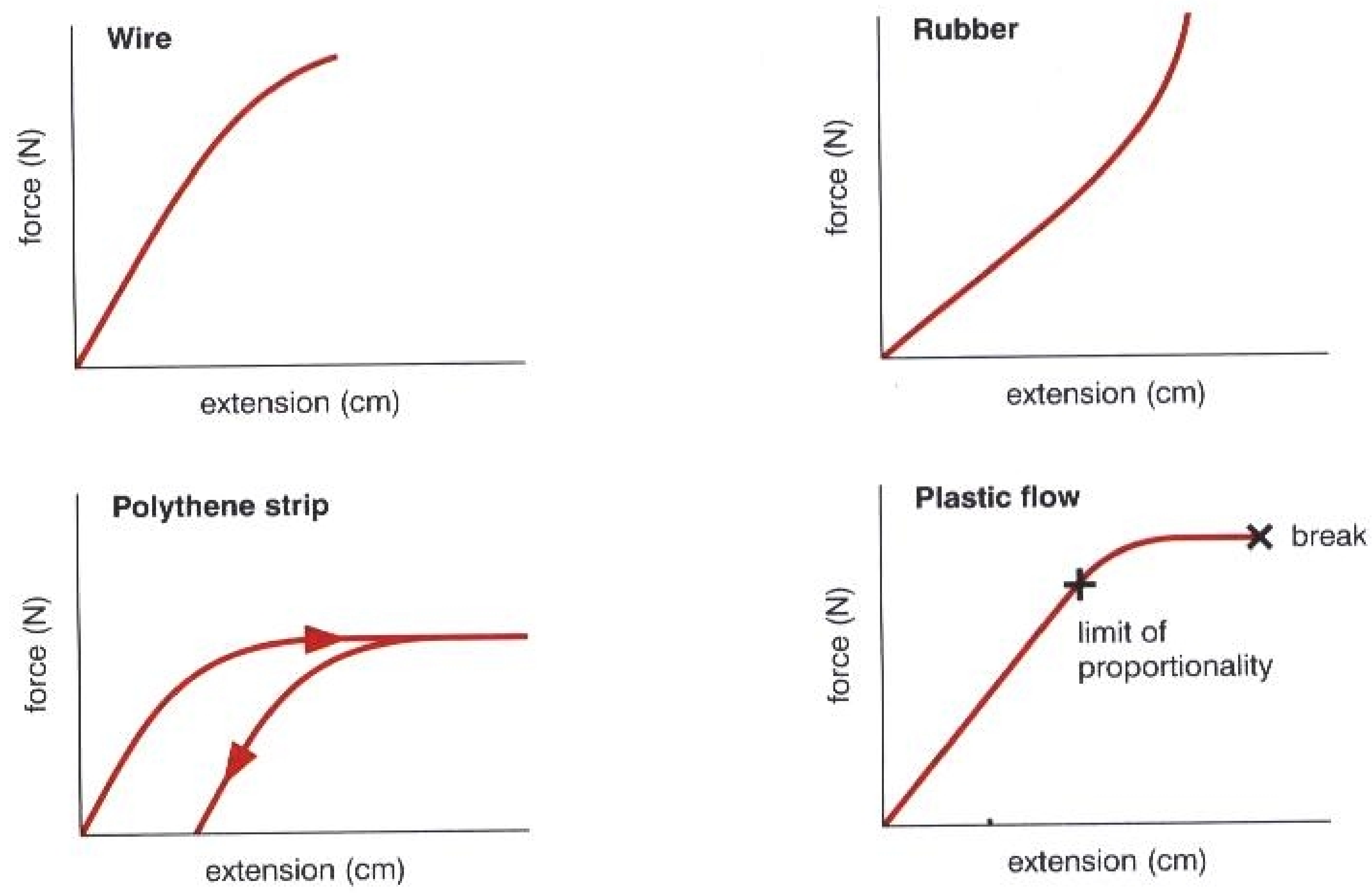
A piece of rubber stretches quite a lot for small forces. The long polymer molecules are being 'straightened out'. Once this is done it becomes much stiffer and harder to extend further. However, unless it breaks, its behaviour is elastic.

A copper wire has a large plastic section on the graph. As it stretches, the wire becomes thinner and thinner until it finally breaks. This stretching is irreversible, and the extension is caused by 'plastic flow'.

A* EXTRA

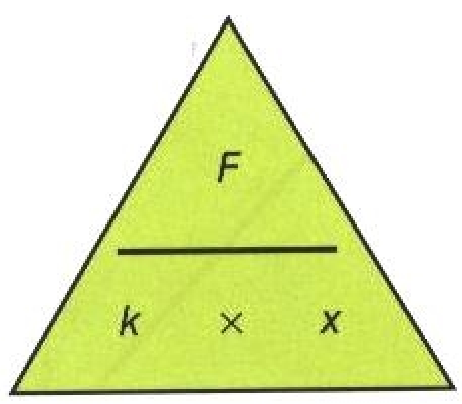
- During elastic behaviour, the particles in the material are pulled apart a little. During plastic behaviour the particles slide past each other, and the structure of the material is changed permanently.

A strip of polythene will stretch relatively easily, but it will scarcely shorten at all when the load is removed. This means that polythene stretches almost entirely by plastic flow. This was the original meaning of the word 'plastic'. When people started to invent new materials in the early 1900s, many of them stretched in a plastic way. The word was then used to describe them.



Force–extension graphs for a metal wire, for rubber, for a polythene strip, and to show plastic flow.

The equation for Hooke's law is:



force = stiffness of spring × extension of spring	F = force in newtons
$F = k \times x$	k = stiffness of the spring in N/m
	x = extension of the spring in m

Note that it is acceptable to use a stiffness in N/cm or N/mm, so long as the extension is measured in the same units.

This equation works for springs that are being stretched or compressed. The value of k will be the same for both, but note that some springs cannot be compressed (if, for example, the turns of the spring are already in contact).

WORKED EXAMPLE

A motorbike has a single compression spring on the rear wheels. When the cyclist sits on the bike, she pushes on the rear wheel with 60 per cent of her weight. If her mass is 50 kg, and the stiffness of the spring is 60 N/cm, how much does the spring compress when she sits on the bike?

Write down the formula for the weight of the cyclist: $W = m \times g$
Substitute the values for m and g: $W = 50 \times 10$
Work out the answer and write down the units: $W = 500$ N

The force on the rear spring = 60 per cent of 500 N
= 0.6×500 N
= 300 N

Write down the formula for the compression of the spring: $x = \frac{F}{k}$

Substitute the values for F and k: $x = \frac{300}{60}$

Work out the answer and write down the units: $x = 5$ cm

The spring compresses by 5 cm

Turning effect

If you have used a spanner to tighten a nut, or you have turned the handle of a rotary beater, you have used a force to turn something. But turning applies to less obvious examples, such as when you push the door handle to close a door, or when a child sits on the end of a see-saw to push her end of it down.

The turning effect of a force is called the **moment** of the force.

The moment of a force depends on two things:
- the size of the force
- the distance between the line of the force and the turning point, which is called the **pivot**.

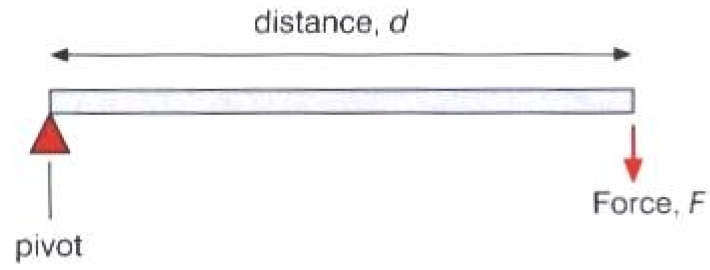
We calculate the moment of force using this formula:

moment of a force = force × distance from pivot

$$\text{moment} = F\,d$$

Moment is measured in newton metres (Nm).

F = force in newtons (N)
d = distance in metres (m)



WORKED EXAMPLE

A girl pushes open a door with a force of 20 N. The door handle is at a distance of 0.80 m from the hinges.

Write down the formula:	moment = force × distance from pivot
Substitute the values for F and d:	moment = 20 N × 0.8 m
Work out the answer and write down the units:	moment = 16 Nm

WHEN MOMENTS BALANCE

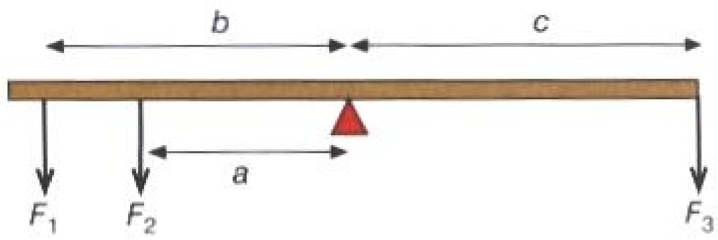
The Principle of Moments says that if a system of forces is not turning, then the sum of the clockwise moments equals the sum of the anticlockwise moments about any point.

So, for example, if the following system of forces is balanced then:

sum of clockwise moments = sum of anticlockwise moments

moment of F_3 = moment of F_1 + moment of F_2

$$(F_3 \times c) = (F_1 \times b) + (F_2 \times a)$$



An experiment to verify the Principle of Moments

1 Drill a hole at the 50 cm mark of a metre rule.

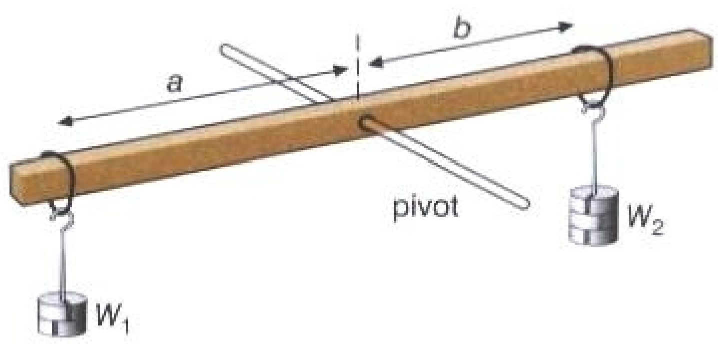
2 Support the rule on a pivot through the drilled hole.

3 Using two loops of thread and two mass hangers and some slotted masses, suspend different weights, W_1 and W_2, at different distances, a and b, from the pivot. Carefully adjust the distances a and b until the rule balances horizontally.

4 Record the values of W_1, W_2, a and b.

5 Repeat stages 3 and 4 several times, with different values of W_1, W_2, a and b.

6 For each set of results, calculate $(W_1 \times a)$ and $(W_2 \times b)$.

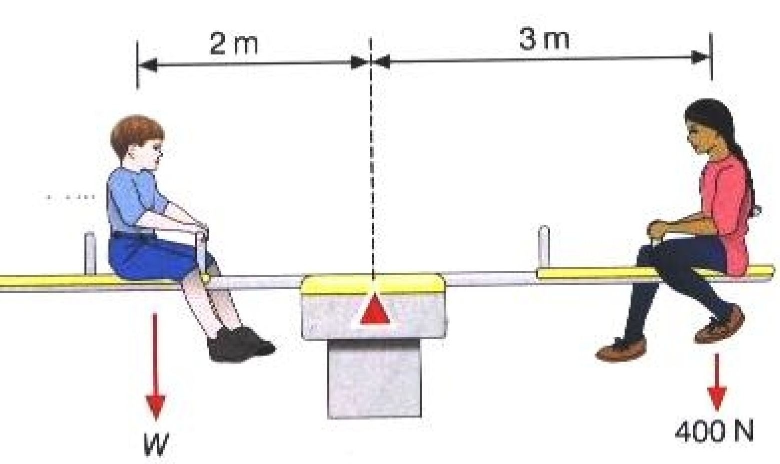


You will find that, within the limits of experimental accuracy, $(W_2 \times a)$ and $(W_2 \times b)$ will be equal for each set of readings.

	W_1/N	W_2/N	a/cm	b/cm	$(W_1 \times a)$/Ncm	$(W_2 \times b)$/Ncm
(a)	0.5	1.0	41.6	20.4	20.8	20.4
(b)	1.5	1.0	25.7	38.8	38.6	38.8
(c)	1.5	0.5	15.8	47.8	23.7	23.9
(d)	2.0	2.5	44.4	35.4	88.8	88.5

You will see that for each set of readings, the last two columns are equal, within the limits of the accuracy of the experiment. Thus the results verify the Principle of Moments.

The name we use in Physics to describe a set of balanced forces is **equilibrium**. When the system of forces is in equilibrium then the sum of the anticlockwise moments are balanced by the sum of the clockwise moments. In other words, there is no net moment on a body in equilibrium.



Forces on the see-saw

WORKED EXAMPLE

Two children are sitting on a see-saw. The see-saw is balanced on a pivot. Work out the boy's weight.

The girl is causing the clockwise moment of 400 N × 3 m.

The boy is causing the anticlockwise moment of W × 2 m.

The see-saw is balanced, so

the sum of the clockwise moments = the sum of the anticlockwise moments

$$400 \times 3 = W \times 2$$

$$W = 600 \text{ N}$$

A* EXTRA

- Questions involving balancing can look quite difficult. Work out each moment in turn and add together the moments that turn in the same direction.

WORKED EXAMPLE

A mechanic with a racing car team knows that a bolt on the engine is to be tightened to 60 Nm. If she is using a spanner that is 0.2 m long, with what force and in what direction should she push the end of the spanner?

Moment = force × distance from pivot

Rearrange the equation: $\text{force} = \dfrac{\text{moment}}{\text{distance from pivot}}$

Substitute the values for moment and distance: $\text{force} = \dfrac{60 \text{ Nm}}{0.2 \text{ m}}$

Work out the answer and write down the units: force = 300 N

This force should be applied at right angles to the end of the spanner.

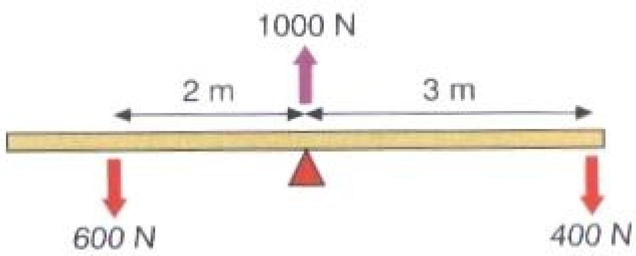
Conditions for equilibrium

We use the word 'system' to describe a collection of objects working together. So in the example of the see-saw above, the two children and the see-saw form a system. We say that a system is in equilibrium if it is not moving in any direction and it is *not* rotating. We already know that for a system not to be moving, the forces on it must be equal and

So:

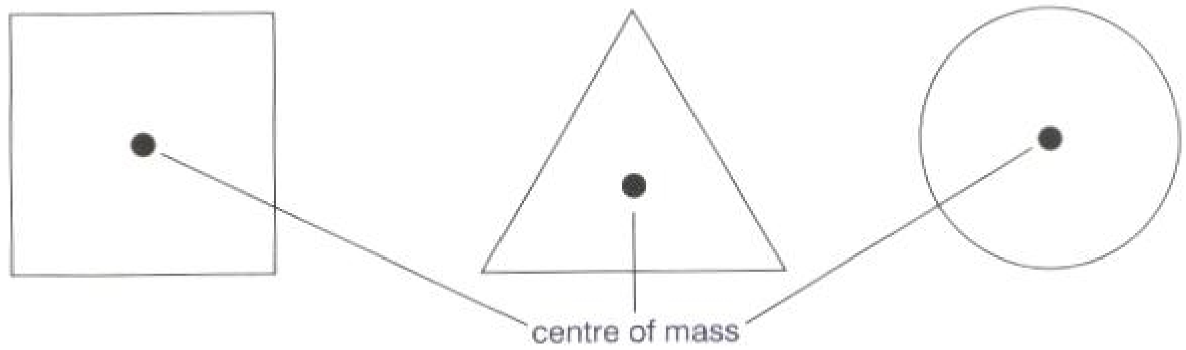
For a system to be in equilibrium, there must be no resultant force and no resultant turning effect.

opposite.



In the case of the balanced see-saw, we have already shown that there is no resultant turning effect on the see-saw because the clockwise and anticlockwise turning effects are equal and opposite. In addition, the downward weight of the two children on the see-saw is 1000 N, and the upward force on the see-saw from the pivot must also be 1000 N.

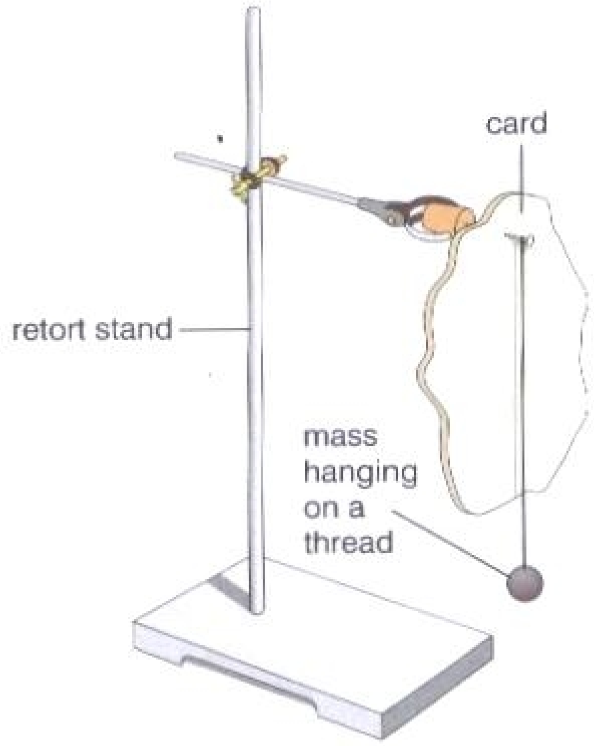
Centre of mass



The centre of mass is the point where we can assume *all* the mass of the object is concentrated. This is a useful simplification because we can pretend **gravity** only acts at a **single point** in the object, so a single arrow on a diagram can represent the **weight** of an object.

The centre of mass for objects with a regular shape is in the centre.

WHAT ABOUT IRREGULAR SHAPES?

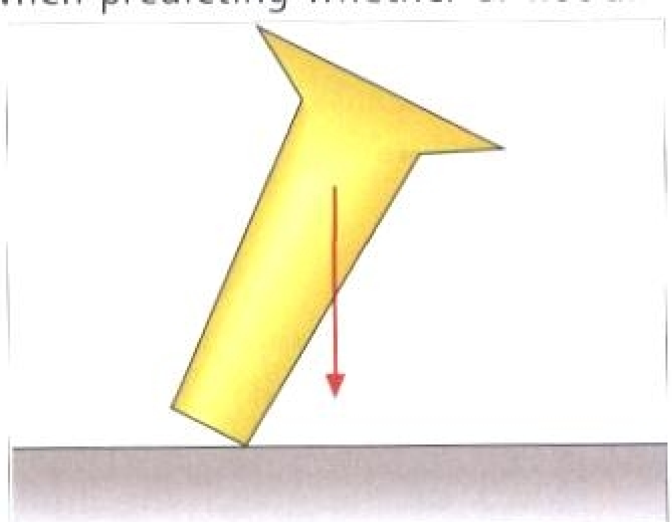


To find the centre of mass of simple objects, such as a piece of card, follow these steps:

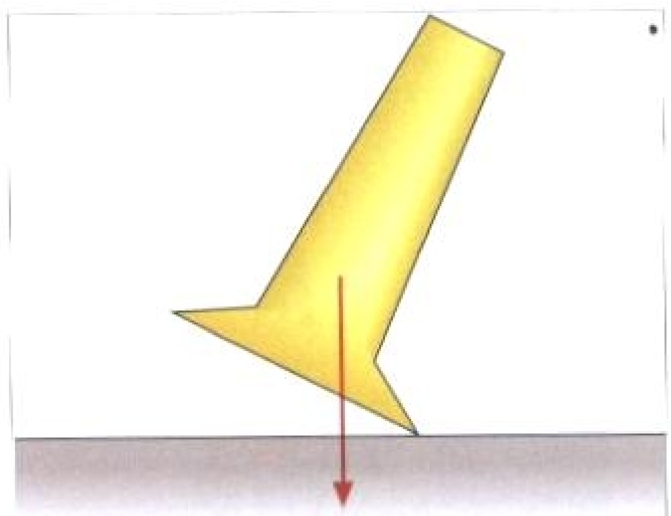
1. Hang up the object.
2. Suspend a mass from the same place.
3. Mark the position of the thread.
4. The centre of mass is somewhere along the line of the thread.
5. Repeat steps 1 to 3 with the object suspended from a different place.
6. The centre of mass is where the two lines cross.

CENTRE OF MASS LINKS TO STABILITY

The idea of centre of mass is useful when predicting whether or not an



This object will topple over – a vertical line from the centre of mass falls outside the base of the object so the weight of the object tips it over the rest of the way. The moment of the force turns the object over. An object that is easy to topple is said to be in unstable equilibrium.



This object will fall back into place – a vertical line from the centre of mass falls inside the base of the object so the weight of the object pulls it back onto its base. The moment of the force returns the object to its base. An object that is difficult to topple is said to be in stable equilibrium.

Scalars and vectors

Force, velocity and acceleration are examples of **vector** quantities. A vector has a specific direction as well as a size, with a unit. We will meet many more later in this book: pressure, electrical current and even the flow of heat are all vectors.

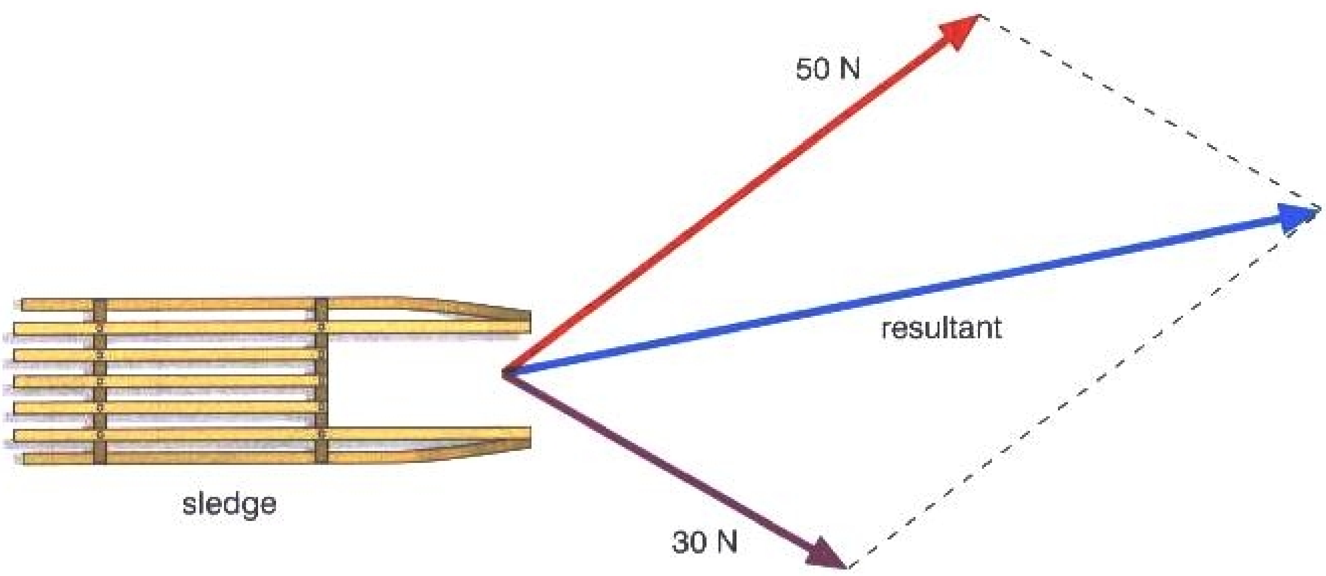
Speed and mass are examples of a **scalar** quantity. A scalar quantity has size only, with a unit. There are many more scalar quantities to be met: temperature, work, power and electrical resistance are all scalars.

GRAPH TO FIND RESULTANT

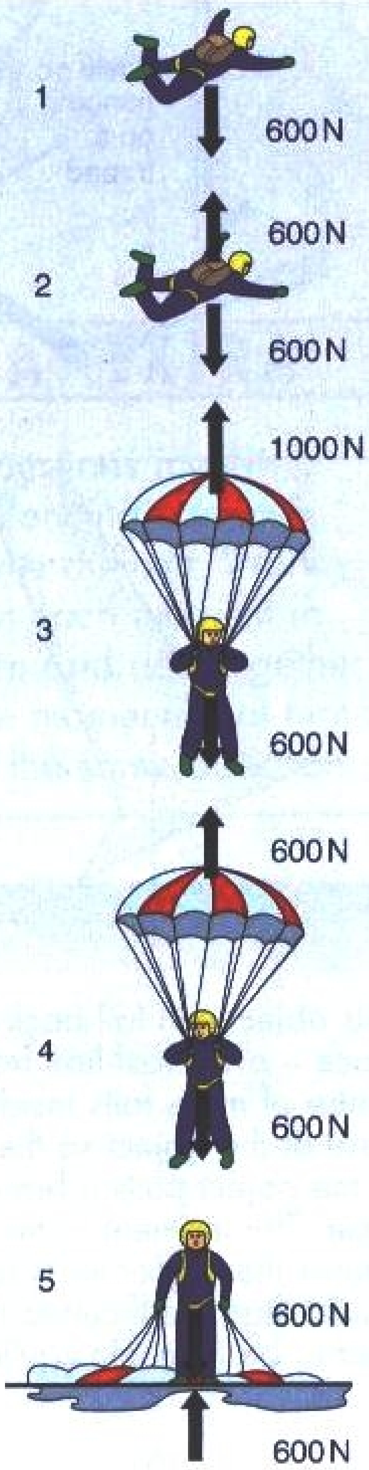
If two husky dogs are pulling a sledge in different directions, it is clear that the sledge will move in a direction that is some sort of average of these directions. To find out exactly what will happen, we replace the two forces with a single force (the resultant) that will have just the same effect.

To calculate this single force we draw the two forces in the correct direction and to a scale length that is suitable. In the case of the husky dogs, a suitable scale might be 1 cm per 10 N, or perhaps 1 cm per 5 N.

We then find the resultant by completing a parallelogram. The resultant is then the diagonal line across the parallelogram between the two forces. This gives us the direction of the resultant force. We can calculate the magnitude of the resultant force by measuring its length, and using the scale that we chose to begin with.



In this case one of the dogs is not working very hard, and the sledge will start to go in the direction in which the stronger dog is pulling.



REVIEW QUESTIONS

Q1 The diagram shows the stages in the descent of a skydiver.

a Describe and explain the motion of the skydiver in each stage.

b In stage 5 explain why the parachutist does not sink into the ground.

Q2 The skydiver performed an experiment stretching a spring. She loaded masses onto the spring and measured its extension. Here are her results.

Extension/cm	0	4	8	12	16	20	24
Load/N	0	2.0	4.0	6.0	7.5	8.3	8.6

a On graph paper, plot a graph of Load (*y*-axis) against Extension (*x*-axis).
Draw a suitable line through your points.

b Mark on the graph the limit of proportionality, and indicate the region where proportional behaviour occurs and the region where the behaviour is probably plastic.

c How does the skydiver check whether the spring, after being loaded with 8.6 N has shown plastic behaviour or purely elastic behaviour?

d Calculate the spring constant (stiffness) of the spring in the region of proportional behaviour. Note that you must give the units as well as the value.

Q3 The manufacturer of a car gave the following information:
Mass of car 1000 kg. The car will accelerate from 0 to 30 m/s in 12 seconds.

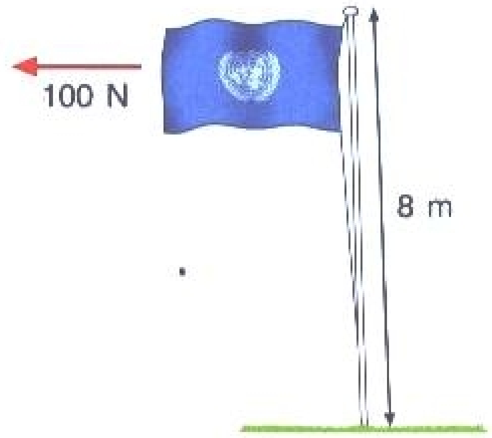
a Calculate the average acceleration of the car during the 12 seconds.

b Calculate the force needed to produce this acceleration.

Q4 Two tug boats have ropes attached to a ship and are about to start moving it very carefully. One tug is north of the ship and is pulling with a force of 3000 N, and the other tug is east of the ship and is pulling with a force of 4000 N.

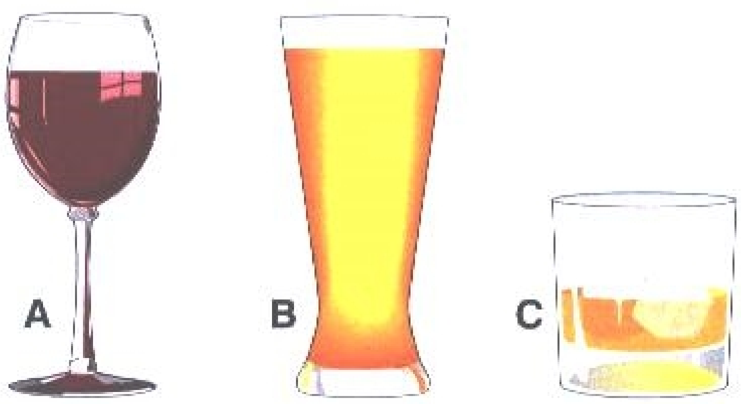
a By means of a diagram calculate the total force with which the ship will be pulled, and show the direction in which it will be pulled.

b If the ship has a mass of 500 tonnes (1 tonne = 1000 kg) how fast will it be moving 10 s after it starts?



Q5 A flag is being blown by the wind. The force on the flag is 100 N and the flagpole is 8 m tall.
Calculate the moment of the force about the base of the flagpole.

Q6 Which of these glasses is the most stable? Explain your answer.



Examination questions are on page 50.

More questions on the CD ROM