# 8.3 Newton's laws of motion

Forces are pushes, pulls or twists. A force can make an object start moving, speed up, slow down, stop moving, change direction or even change its shape. Sometimes it is hard to tell that forces are acting because they are balanced and an object does not change its motion. Other times, such as in a car accident, the effect of forces is obvious. The great English scientist Isaac Newton formulated three laws of motion in 1687. These three laws explain why everything around you moves the way it does.

INQUIRY science 4 fun

## Loose change

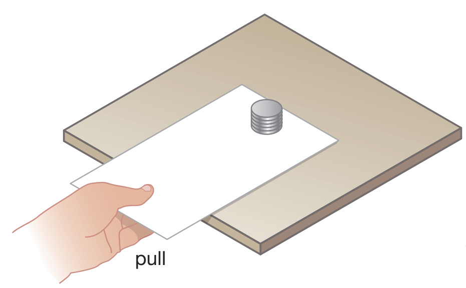
What can you do to a pile of coins without them falling over?

**SAFETY**

Do not flick objects at or near people.

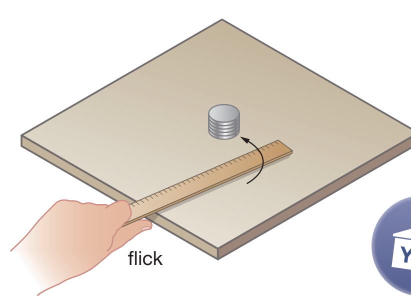
### Collect this …

- 5 × 20-cent pieces
- ruler
- piece of paper




### Do this …

1. Rest the piece of paper on a bench so that a little of it overhangs the edge.
2. Put the pile of 20-cent pieces on the other end of the paper
3. Quickly pull the sheet of paper out and note what happens to the coins.
4. Put a pile of coins on a bench, and flick a ruler towards them to try to knock out the bottom coin. (Place a rolled-up towel near the pile to stop the coins from hitting anything.)




### Record this …

**Describe** what happened.
**Explain** why you think this happened.

# Newton's first law

If you give a pencil case a light push, it moves a small distance across the desk and stops. For thousands of years, people believed that such an object stopped because the force you gave the pencil case stops working. Galileo (1564–1642) realised that these objects stop because friction acts in the opposite direction to their motion. He reasoned that if there was no friction, then a single push would be enough to keep it moving. The object would only be stopped by some other force. Galileo was right. Once launched, an unmanned spacecraft such as *Voyager 1* (Figure 8.3.1) continues to travel through space, long after its fuel has gone.

Figure 8.3.1 *Voyager 1* was launched in 1977 and is still travelling at high speeds through deep space. It is currently reaching the limits of the solar system.

Isaac Newton developed Galileo's ideas further and developed three laws of motion. **Newton's first law of motion** states that:

- An object at rest will remain this way unless it is acted upon by a force.
- An object that is moving will continue to move at the same speed and in the same direction unless an unbalanced force acts upon it.

In other words, this law states that a force is needed to get something moving. A force is also required to change the speed or direction of something that is already moving. This tendency to resist any change in motion is called an object's **inertia**. The larger the mass of an object, the greater its inertia, and the harder it is to change its motion. This explains why it is easier to stop an empty runaway shopping trolley than one that is full. It also explains why it takes much more fuel for a heavy truck to start moving than for a small car.

**SciFile**

### Isaac Newton

Born in England, Isaac Newton (1642–1727) made enormous contributions to scientific knowledge. He discovered that white light consists of many colours and that gravity is a force that affects all objects on Earth. In using mathematics to explain motion, Newton changed the way that people understood the world.

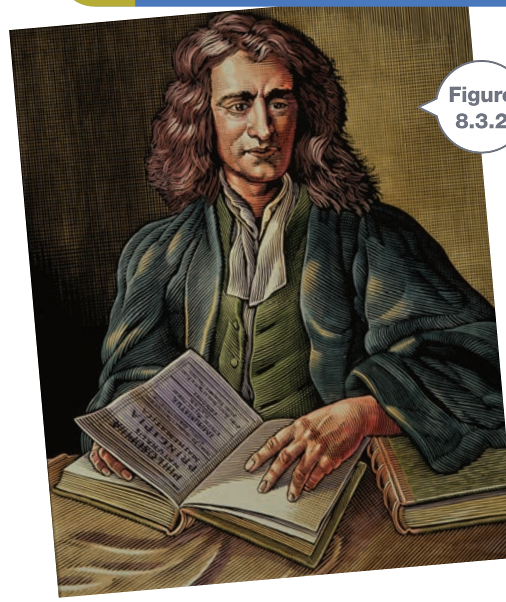


Figure 8.3.2 Sir Isaac Newton

## Examples of Newton's first law

You feel the effects of inertia whenever you are in a train (Figure 8.3.3) that suddenly accelerates, stops or turns.

When a train begins to move, your feet move forwards but your body tends to remain stationary—it appears to 'fall backwards' as you try to stay stationary. Once you are moving in the train, the brakes that slow the train act on the train, but not on you. As the train slows, your feet slow down but your body continues its motion, and you can fall forwards.

Figure 8.3.3 Your inertia is obvious when travelling in a train. It causes you to lurch about as the train accelerates and decelerates.


**Figure 8.3.4** This high-speed photograph shows crash-test dummies in a car hitting a wall at 56 km/h. The dummies continue to travel at this speed, colliding with objects in the car, other passengers and the car itself.

Consider what happens in a car accident. If you are travelling in a car at 60 km/h that is suddenly brought to a stop, then your body continues to travel forwards at 60 km/h. Figure 8.3.4 shows this situation using crash-test dummies. Seatbelts restrain your body so that you come to a stop with the car. An airbag in a car will inflate when the car collides with a solid object at speeds above 18 km/h. The airbag reduces the force on a passenger in a collision and prevents their head hitting the steering wheel or side of the car.

8.4

## Newton's second law

**Newton's second law of motion** states that:

An object will accelerate in the direction of an unbalanced force acting upon it. The size of this acceleration depends upon the mass of the object and the size of the force acting.

This can be expressed as:

$$F_{net} = m \times a$$

where $F_{net}$ is the total force acting on an object measured in newtons (N), $m$ is the mass of the object (kg) and $a$ is the acceleration of the object (m/s$^2$).

This formula can be rearranged to express acceleration as:

$$a = \frac{F_{net}}{m}$$

According to Newton's second law, a larger force is needed to accelerate a heavy load (such as the one shown in Figure 8.3.5) than a lighter load.

Figure 8.3.6 shows a way of working out which formula you need to use.

**Figure 8.3.5** The more massive an object, the more force is required for it to accelerate.

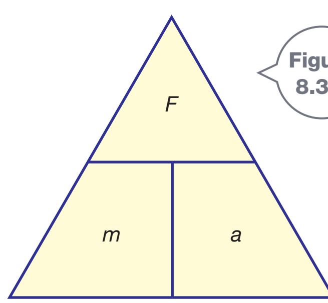



**Figure 8.3.6** To calculate force, place your finger over '$F$'. This gives the formula $m \times a$.

To calculate acceleration, place your finger over '$a$'. The formula is $\frac{F}{m}$.

To calculate mass, place your finger over '$m$'. The formula is $\frac{F}{a}$.

**SciFile**

**No pain, more gain!**

Catching a cricket ball with a rigid grip will hurt more than if you increase the time of your catch by following through the motion of the ball with your hand. Similarly, a car airbag increases the time interval of a collision and reduces the force of impact.

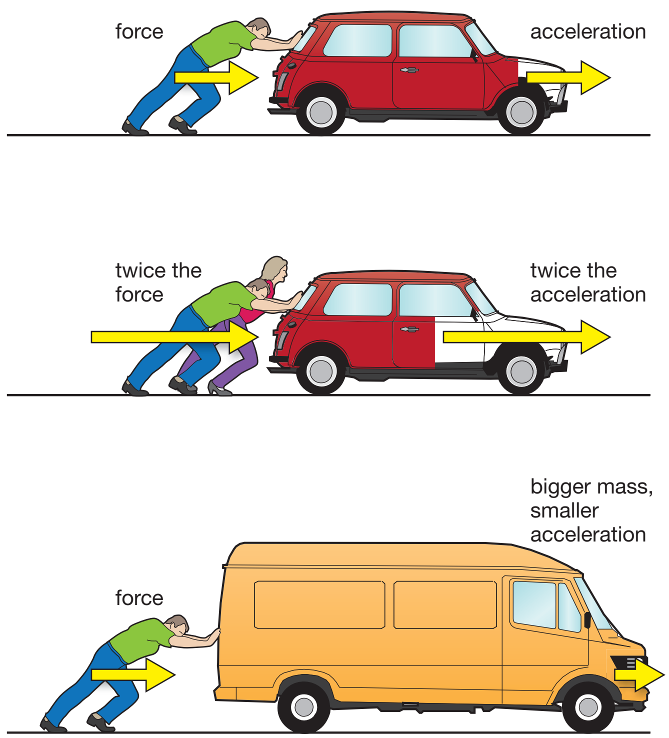



Figure 8.3.7 Acceleration depends upon the size of the force acting and the mass of the object.

Figure 8.3.7 shows what Newton's second law means in practice. Figure 8.3.8 shows what happens if all forces on an object are balanced. In this case, the overall, or net, force acting on the car is zero. If the car was stationary (at rest), then it would stay at rest. Since the car is moving, it will travel at constant speed.

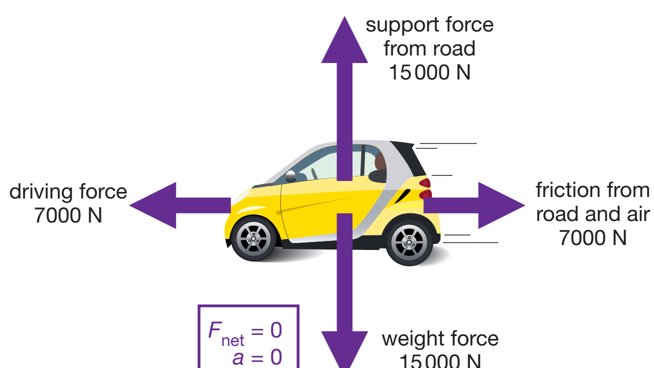



Figure 8.3.8 The vertical and horizontal forces acting on this car are balanced, so the net force acting on the car is zero.

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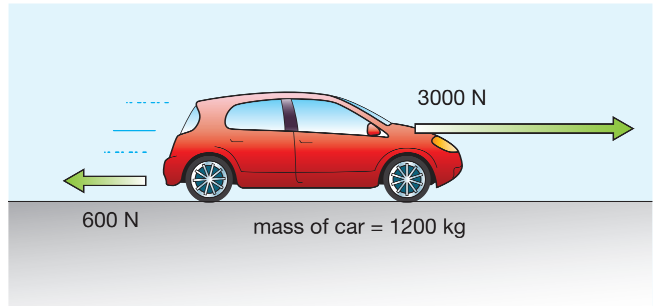
8.5

## WORKED EXAMPLE
## Force and acceleration

Calculate the acceleration of each object shown.

### Problem 1




### Solution

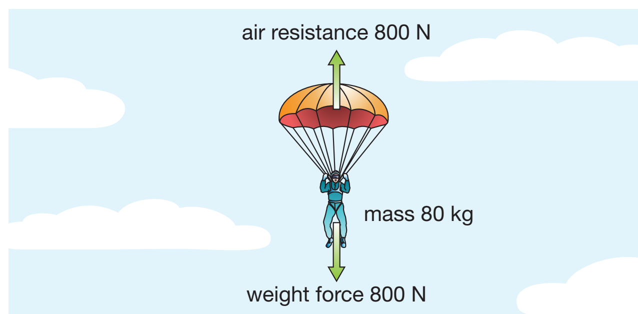
The net horizontal force acting on the car is:

3000 – 600 = 2400 N to the right

So, the car will travel with acceleration:

$a = \frac{F_{net}}{m} = \frac{2400}{1200} = 2\ \text{m/s}^2$ to the right

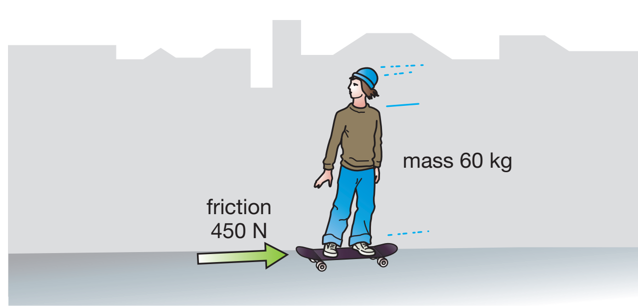
### Problem 2




### Solution

The net force acting on the parachute is zero. Its acceleration is zero and it falls with a constant velocity.

### Problem 3




### Solution

The net horizontal force acting on the boy is the force of friction, 450 N to the right. His acceleration is:

$a = \frac{F_{net}}{m} = \frac{450}{60} = 7.5\ \text{m/s}^2$ to the right

He is slowing down with a deceleration of 7.5 m/s$^2$.

INQUIRY
science 4 fun

## Heavy reading

A book rests on a table. Does the book exert a force on the table? Does the table exert a force on the book?

Yes

### Collect this …


- some heavy books
- stopwatch

### Do this …

1. Ask a volunteer to extend an arm at right angles to their body with palm facing up.
2. Place three books on their palm and ask the volunteer to keep their arm straight.
3. Time them for a minute, then ask how they are feeling and remove the books.

### Record this …

**Describe** what happened.

**Explain** why you think this happened.

# Newton's third law

Isaac Newton realised that forces always occur in pairs. If a tennis ball is hit by a racquet, the racquet applies a force on the ball, and the ball accelerates forwards. This is called an action force. However, the ball also exerts a force back onto the racquet. You can feel this force as you hit the ball. It is called a reaction force.

**Newton's third law of motion** states that:

For every action force there is an equal and opposite reaction force.

A few pairs of action and reaction forces are shown in Table 8.3.1.

**Table 8.3.1 Some pairs of action and reaction forces**

| Action force | Reaction force |
|---|---|
| A nail is hit by a hammer. | The nail exerts an equal force back on the hammer. |
| A sprinter pushes back on the starting blocks as a race begins. | The starting blocks push forward on the sprinter. |
| A book resting on a table exerts its weight force onto the table. | The table exerts an equal support force upwards on the book. |
| An octopus squirts water out as jets through a tube just below its head. | These water jets push back on the octopus, propelling it in the opposite direction. |
| You stand on a skateboard and push against a wall. | The wall pushes back on you with equal force, and you move away. |

Recalling Newton's second law, the acceleration that an object experiences due to a force depends upon its mass. Although the size of action and reaction forces is the same, an object of low mass will travel with much greater acceleration than a more massive object. Figure 8.3.9 shows the different effects of the action–reaction forces from a cannon.

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Figure 8.3.10 shows how a rocket relies upon action–reaction forces.

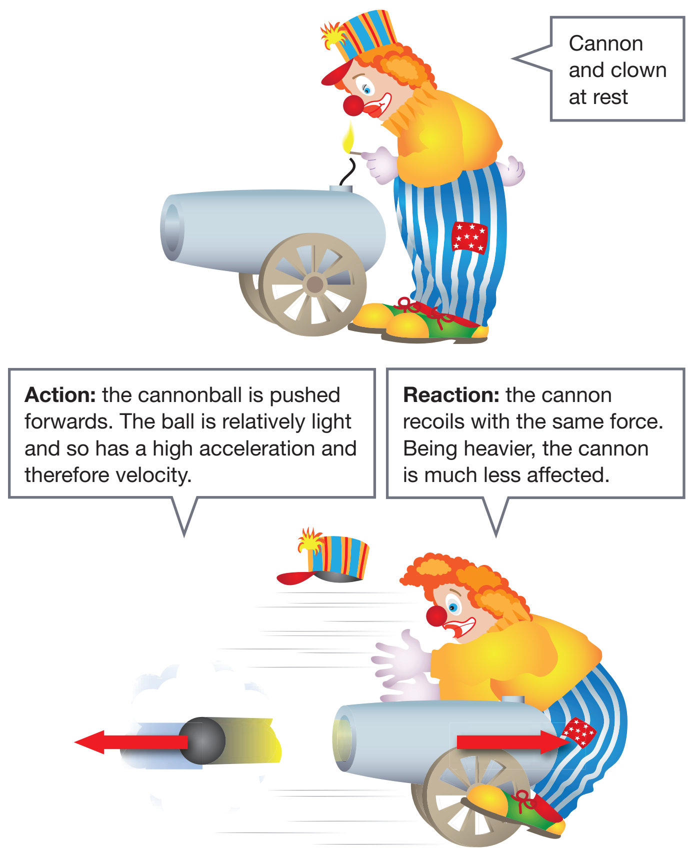



**Figure 8.3.9** The action and reaction forces on the cannon and cannonball are the same, but the cannonball has greater acceleration because it has a lower mass.

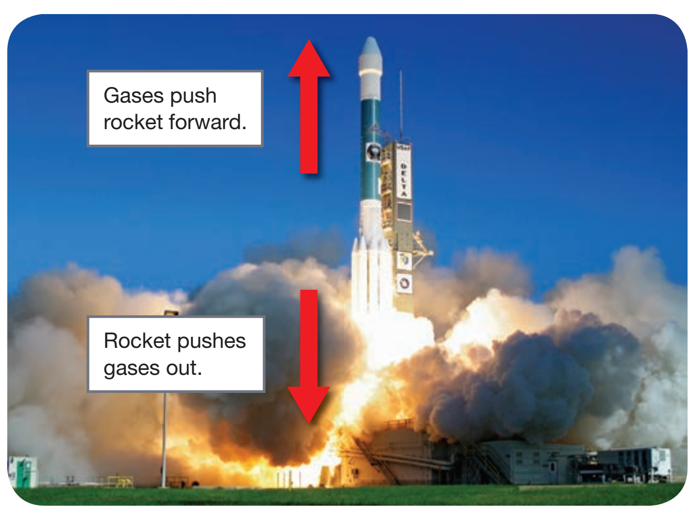



**Figure 8.3.10** Explosive exhaust gases expelled from the base of a rocket exert an opposite reaction force to launch the rocket into space.

# SCIENCE AS A HUMAN ENDEAVOUR

## Nature and development of science

### The forces of boomerang flight

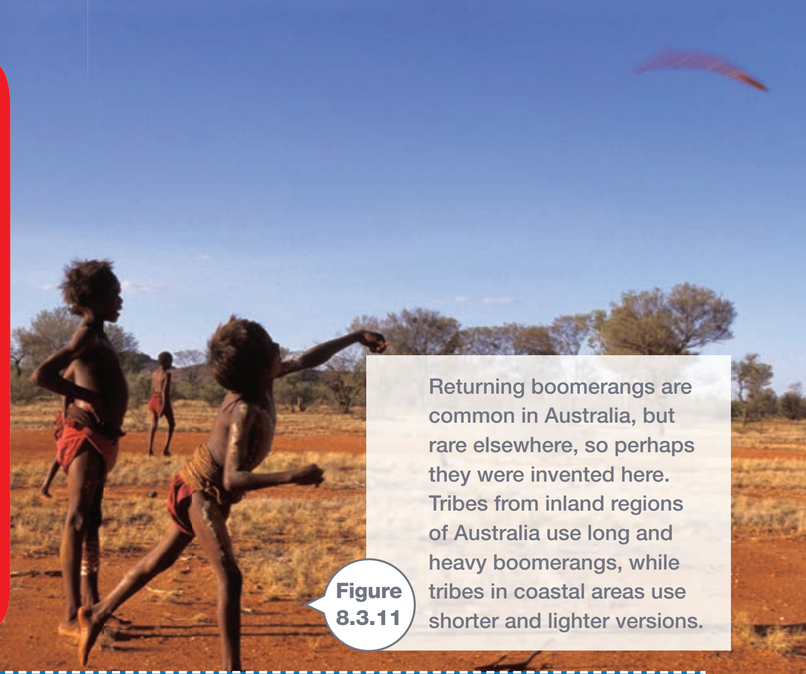


Figure 8.3.11 Returning boomerangs are common in Australia, but rare elsewhere, so perhaps they were invented here. Tribes from inland regions of Australia use long and heavy boomerangs, while tribes in coastal areas use shorter and lighter versions.

**Boomerangs have been used by Indigenous Australians for thousands of years. The original inventors probably tried changing the shape of the wood and throwing it to see what it would do. When the wooden shapes began returning from a throw, they had successfully invented the first boomerang.**

Scientists now use the concept of force to understand how a returning boomerang works. To explain the flight path of a boomerang, you need to consider its shape (Figure 8.3.12) and its spin.

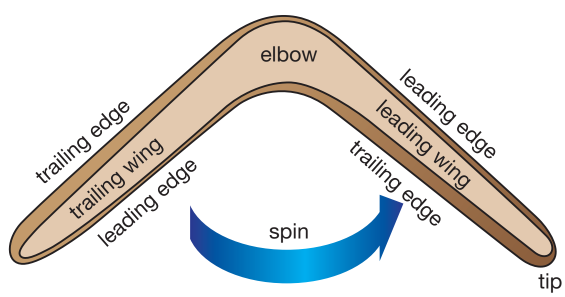
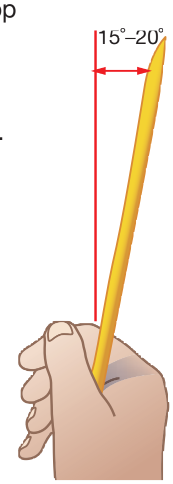



Figure 8.3.12 A boomerang consists of two wings joined at the centre. This diagram shows the design for a right-handed thrower.

## Shape

The base of a boomerang is flat, while the top surface is curved. The shape is known as an airfoil and is like an aircraft wing. Air flows more rapidly over this curved upper surface, creating a lift force which pushes it upwards. The airfoil on the wings of a helicopter or aircraft faces upwards and the lift force acts upwards. A boomerang is thrown at a slight angle (15–20°) to the vertical, as shown in Figure 8.3.13, so the lift force created points to the centre of the boomerang's flight path, as shown in Figure 8.3.14.




A boomerang is thrown at an angle of around 15–20° to the vertical. If it is windy, the boomerang is thrown closer to the vertical. Figure 8.3.13

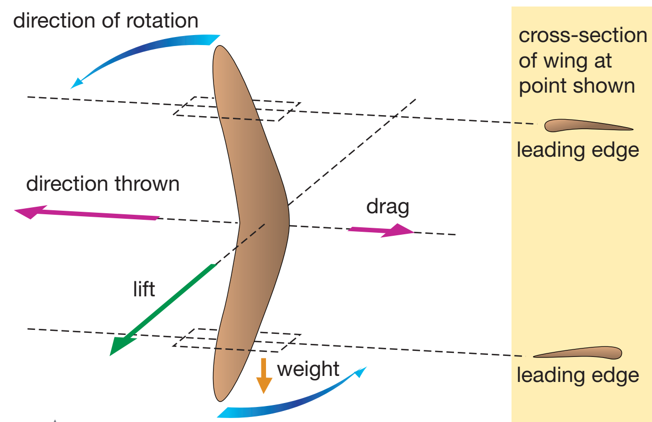
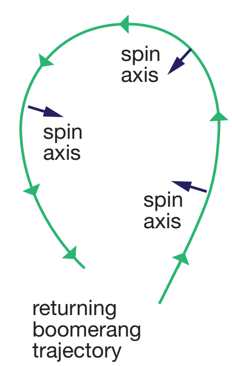



Figure 8.3.14 The boomerang is thrown and its two wings cut through the air with their leading edges. The shape of the wings creates the lift force shown.

## Spin

The spin of a boomerang depends upon its wing length, the materials from which it is constructed and the angle that separates the wings. Air rushes more quickly over the wing rotating in the direction of the boomerang's flight than the wing rotating in the opposite direction. This uneven lift sets up complex forces that allow the boomerang to return to its thrower, as shown in Figure 8.3.15.




The boomerang returns due to forces acting at right angles to the plane of its motion. Figure 8.3.15

# 8.3 Unit review

## Remembering

**1** **State** Newton's first law of motion.

**2** **a** **State** the formula for Newton's second law that is used to calculate force.

**b** **State** this law expressed in terms of acceleration.

## Understanding

**3** **Explain** why Voyager 1 (Figure 8.3.1 on page 270) is still in motion, even though its fuel ran out a long time ago.

**4** In terms of Newton's first law, **explain** why having sharp objects on the dashboard of a car, or loose objects in the back, could cause injury or death in an accident.

**5** **Explain** how it is possible for the car shown in Figure 8.3.8 on page 272 to be in motion, even though the net force acting on it is zero.

**6** **Explain** what an airfoil is and **describe** how this produces a lift force on an aircraft wing and on a boomerang.

## Applying

**7** **Use** Figure 8.3.16 to **explain** how hitting the ball with a tennis racquet involves action and reaction forces.

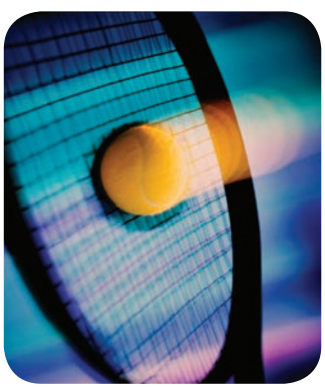


Figure 8.3.16

**8** **Identify** which has greater inertia—a suitcase packed for a holiday or the same suitcase after its contents have been packed away.

**9** Copy the following table and then **use** Newton's second law to **calculate** the missing values.

| Net force (N) | Mass (kg) | Acceleration ($m/s^2$) |
|---|---|---|
| 24.0 | 6.0 | |
| 13.5 | 3.0 | |
| | 58.0 | 1.5 |
| | 25.0 | 3.5 |
| 1160.0 | 80.0 | |
| 5.5 | | 1.1 |

**10** The mass of a Nissan GT-R is 1740 kg.

**a** **Calculate** the net force required for the car to travel with an acceleration of 3 $m/s^2$.

**b** If there was a 2000 N force of friction opposing the car's motion, **calculate** the size of the driving force that must be provided by the engine to maintain this acceleration.

**11** **Calculate** the net force and the acceleration of each object shown in Figure 8.3.16.

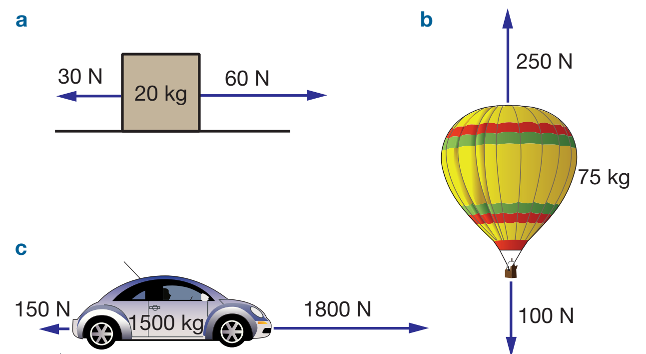



Figure 8.3.17

**12** **Identify** the direction of the lift force acting on a boomerang in flight.

**13** **Use** your understanding of Newton's third law to **identify** the reaction force that acts with each action force listed.

**a** Mylinh's foot pushes back on the footpath as she walks down the street.

**b** Ted applies a force to a cricket ball as he catches it.

**c** Sally pushes on the handle of a lawnmower.

**d** Alf pushes a punching bag.

**e** Jade pushes on pizza dough as she kneads it.

Questions 14–17 are all based on the same information.

**14** Phil, a motorcyclist, takes off from rest and reaches 17 m/s in 4 seconds.

**a** **Calculate** what 17 m/s is in km/h.

**b** **Calculate** Phil's acceleration in $m/s^2$.

**c** If the mass of Phil's bike plus Phil is 190 kg, **calculate** the force required to produce this acceleration.

**15** Phil's sister Yen also rides motorbikes. The mass of Yen's bike plus Yen is 150 kg. Yen can also reach 17 m/s from rest in 4 seconds. **Calculate** the force required to produce this acceleration.

# 8.3 Unit review

16 Yen's bike weighs the same as Phil's, but is less powerful. Yen takes Phil's bike and rides away on it.
- **a** **State** the combined mass of Yen and Phil's bike.
- **b** Given that the driving force acting on Phil's bike is the same as the force calculated in question 14, **calculate** the size of Yen's acceleration.
- **c** **Calculate** Yen's speed after 4 seconds.

17 As Yen has taken off with his bike, Phil is forced to use Yen's bike to try to catch up to her.
- **a** **State** the combined mass of Phil and Yen's bike.
- **b** Given that the driving force acting on Yen's motorbike is the same as that in question 15, **calculate** the size of Phil's acceleration.
- **c** **Calculate** Phil's speed after 4 seconds.

## Analysing

18 According to Newton's second law, the acceleration of a cart of mass $m$ being pushed with force $F$ is $a = \frac{F}{m}$.
Ignoring any friction, **compare** the acceleration of the same cart when:
- **a** pushed with a force $2F$
- **b** pushed with a force $\frac{1}{2}F$
- **c** pushed with force $F$ but loaded up so that its mass is now $2m$
- **d** pushed with force $2F$ and with a mass of $2m$.

## Inquiring

1 Design and construct a safety capsule to protect an egg from cracking when dropped from a metre above the ground. Investigate the maximum height that your safety capsule will still protect the egg.

2 Use plastic containers filled with sand and a video camera or mobile phone to re-enact the famous trick of pulling the tablecloth (shown in Figure 8.3.18). Test the effect of using different types of tablecloths. Do not try this with glass, crockery or anything breakable.

Figure 8.3.18

3 Select a car on the market in Australia. Search the ANCAP website and other related sources of information to construct a report that summarises:
- what ANCAP stands for and what its role is
- the safety features and crash-test rating of the model of the car you chose to investigate.

4
- **a** Compile a list of instructions that describe how to throw a boomerang correctly.
- **b** Investigate how the angle to the vertical that the boomerang is launched affects its flight. Write a report on your discoveries.

5 Describe the different directions that your body is pushed or pulled when playing on playground equipment such as roundabouts, see-saws, swings and slides. Explain each of these sensations in terms of inertia.

# 8.3 Practical activities

## 1 Newton's second law

### Purpose

To test whether an object moves with greater acceleration when the size of a pulling force is increased.

### Materials

- trolley
- piece of wood
- G-clamp
- string or fishing line
- electronic balance
- pulley and clamp
- 50 g slotted masses
- calculator
- stopwatch and ruler (to measure acceleration) (Alternatively, use light gates for data-logging or ticker timer and ticker tape and carbon disks.)

**SAFETY**

Keep your feet away from the falling masses. Put padding (such as books) on the floor under the falling masses.

### Procedure

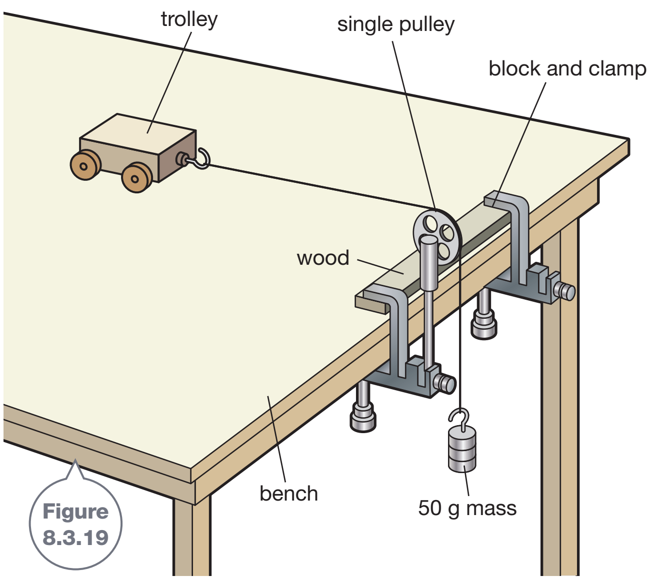



Figure 8.3.19

When setting up, make sure the masses do not reach the ground when the trolley reaches the pulley.

1. Copy the table from the results section on page 278 into your workbook or use a spreadsheet.
2. Measure the mass of a trolley and record this value.
3. Clamp a piece of wood and a single pulley to a bench top.
4. Set up the trolley and hanging masses as shown in Figure 8.3.19.
5. Pull the trolley back so that when released, it accelerates towards the edge of the bench.
6. Measure the distance from the starting point of the trolley to the pulley.
7. Release the trolley from its starting position and use a stopwatch or light gates to measure the time taken to reach the pulley.

   Alternatively, calculate acceleration using the ticker tape method shown in Unit 8.2 Practical activity 2 (page 268), but divide $mm/s^2$ by 1000 to obtain acceleration in $m/s^2$.
8. Record three trial measurements of time.
9. Repeat this task for increasing hanging masses as shown in the results table.

### Results

1. Calculate the average time taken by the trolley for each hanging mass tested.
2. As the trolley starts from a stationary position, its acceleration can be calculated:

   $a = \frac{2d}{t^2}$

   where $d$ is distance travelled (m) and $t$ is time taken (s).

   Calculate acceleration, $a = \frac{2d}{t^2}$, using the distance you measured (in metres) and the average time taken (in seconds).

Newton's second law continued on next page

## Newton's second law continued

| Hanging mass (g) | Force applied (N) (hanging mass × gravity) | Time for trolley to reach pulley | | | Average time (s) | Acceleration (m/s²) |
|---|---|---|---|---|---|---|
| | | Trial 1 (s) | Trial 2 (s) | Trial 3 (s) | | |
| 100 | 1 | | | | | |
| 200 | 2 | | | | | |
| 300 | 3 | | | | | |
| 400 | 4 | | | | | |
| 500 | 5 | | | | | |

3 Using a set of axes, plot a graph of force applied (N) on the vertical axis against acceleration ($m/s^2$) on the horizontal axis.

4 Draw a line through the points on your graph and calculate its gradient ($\frac{\text{rise}}{\text{run}}$)

### Discussion

1 **Describe** the effect of increasing force on the acceleration of the trolley.

2 According to Newton's second law, the gradient of your graph should be the mass of the trolley. **Compare** your result to this value.

3 **Propose** any sources of error that would affect the results you obtained in this experiment.

## 2 Balloon challenge

### Purpose

To design and conduct an experiment using a balloon to investigate Newton's third law of motion.

### Materials

Choose from a range of materials, such as:

- string or fishing line
- straw
- balloon
- masking tape
- piece of dowel
- pivot pin

### Procedure

1 Design a way of using a balloon releasing air to investigate Newton's third law.

2 Investigate how the reaction force is affected by more air being released by the balloon.

3 Balloons could move horizontally along a string or piece of fishing wire, or spin on an axis such as that shown in Figure 8.3.20.

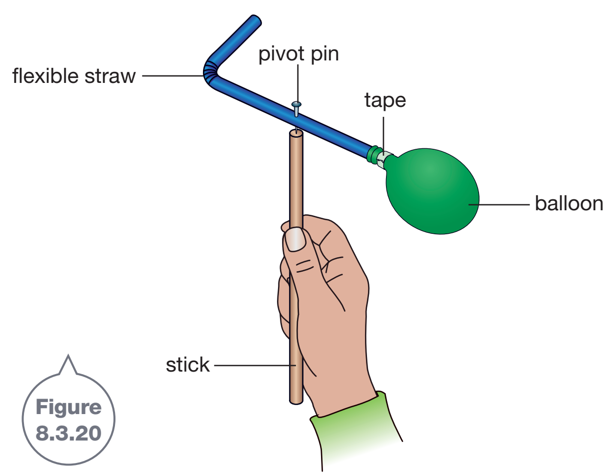



Figure 8.3.20

### Results

1 **Describe** your practical design, including a diagram in your response.

2 **Describe** what happened.

3 **Explain** your results in terms of Newton's third law.

4 **Propose** how you could make improvements to your practical activity.

# 8.4 Energy changes

This bullet hit the egg at a speed of about 100 m/s. The bullet has energy because of its movement. The force of the impact shatters the egg. The bullet exits the egg with slightly less energy than it had when it hit it, because some energy has been transferred to the egg. Whenever something happens around you, energy has been transferred or transformed.

## Energy and work

Whenever a force moves something, **work** is done. Work is a measure of the amount of energy used in moving the object. It is measured in joules (J):

Work can be calculated using the following equation:

$$\text{work done} = \text{force applied} \times \text{distance moved (in the direction of the force)}$$

or

$$W = F \times d$$

where $W$ is the work done (J), $F$ is the force applied (N) and $d$ is the distance moved (m).

In each situation shown in Figure 8.4.1, work is done as objects or people are moved a distance by a force. If a force acts but nothing moves, such as that shown in Figure 8.4.2 on page 280, then no work has been done. **Power** is the rate that work is done, or how fast energy is used. Power is measured in watts (W):

$$\text{power} = \frac{\text{work done}}{\text{time}}$$


Figure 8.4.1 Work is done as a force lifts a teabag, pulls you up a cliff or pulls along a sled.

**Figure 8.4.2** If an object doesn't move, then no work has been done.

## WORKED EXAMPLE
### Calculating work and power

#### Problem

Tom pulls Su on a sled for 10 seconds with a force of 120 N over a distance of 3 metres. Calculate:

**a** the work Tom has done on the sled

**b** Tom's power in pulling the sled.

#### Solution

**a** $F = 120\ \text{N}, d = 3\ \text{m}$

$W = F \times d$

$= 120 \times 3$

$= 360\ \text{J}$

**b** $\text{Power} = \dfrac{\text{work done}}{\text{time}}$

$= \dfrac{360}{10}$

$= 36\ \text{W}$

## Kinetic energy

An object that is moving has the ability to do work. A speeding bullet does work because it pushes things around in the collision. A car travelling at high speed will crumple on impact and break apart, or crush what is in its path. The energy of a moving object is called **kinetic energy**, $E_k$. It is calculated using the following equation:

$$E_k = \frac{1}{2}mv^2$$

where $m$ is the mass of the object (kg) and $v$ is its speed (m/s).

Compare the size of kinetic energy at different speeds for the small and large car calculated in the Worked Example on the next page. Doubling the mass of a moving object doubles its kinetic energy. However, doubling its speed increases its kinetic energy by a factor of four. The greater a vehicle's kinetic energy, the more work it can do. This is why even a small increase in speed rapidly increases the risk of death or injury when travelling in a car. This is shown in Table 8.4.1.

**Table 8.4.1 Speed and injury risk**

| Speed (km/h) | Risk of death or injury compared with travelling at 60 km/h |
|---|---|
| 65 | Double |
| 70 | 4 times |
| 75 | 11 times |
| 80 | 32 times |

Source: *Road Traffic Authority of NSW*

INQUIRY science 4 fun

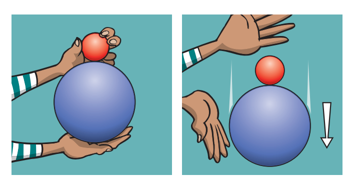
### Energy transfer

What happens when the kinetic energy of one ball is transferred to another ball?

Yes

#### Collect this …

- basketball
- tennis ball
- video camera (optional)



#### Do this …

1. Hold a basketball about a metre above a hard floor.
2. Hold a tennis ball just above the basketball.
3. Drop both balls at exactly the same time and record what happens.

#### Record this …

**Describe** what happened.

**Explain** why you think this happened.

Another reason why increased speed is more dangerous is that cars travelling at higher speed require longer distances to stop. This is shown in Figure 8.4.3.

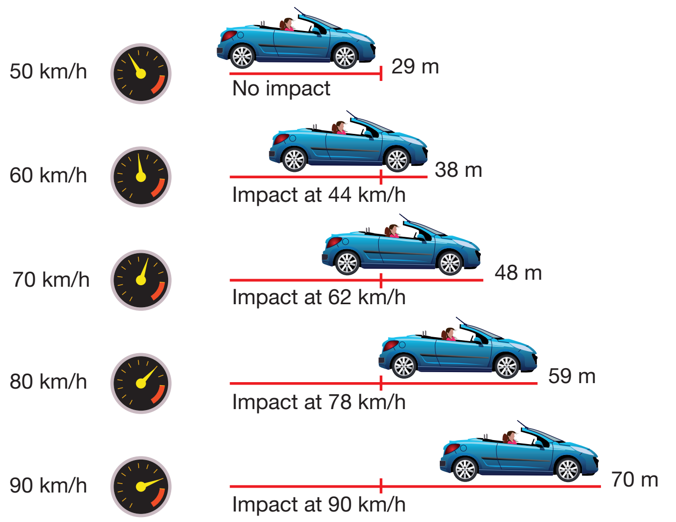



**Figure 8.4.3** This shows how the distance required for a car to stop increases for cars travelling at 50, 60, 70, 80 and 90 km/h.

**SciFile**

**Bonnet bags?**

Pedestrians hit by a car can suffer injuries or death due to contact of their head with a bonnet or windscreen. Where they hit is shown in Figure 8.4.4. Researchers in the UK have developed a system that releases a giant airbag from the bonnet and covers the windscreen when it detects that a pedestrian is about to be hit.

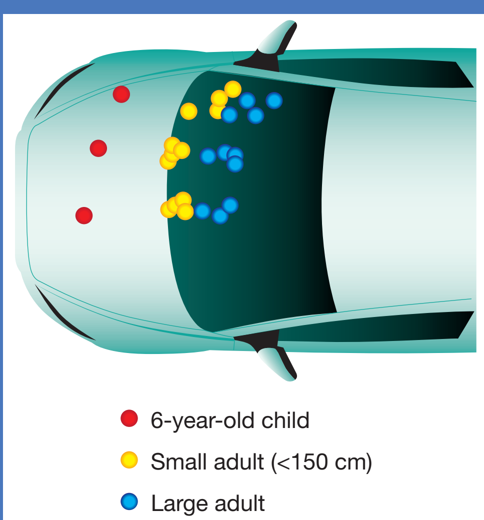



**Figure 8.4.4** This illustration shows where three different pedestrians will hit their head on a car.

## WORKED EXAMPLE
## Calculating kinetic energy

### Problem 1

Calculate the kinetic energy of this Ford Focus travelling at:


**a** 5 m/s (18 km/h)

**b** 16 m/s (57.6 km/h)

### Solution

**a** Ford Focus at 5 m/s

$E_k = \frac{1}{2}mv^2$

$= \frac{1}{2} \times 1300 \times 5^2$

$= 16\,250$ J or 16.25 kJ.

**b** Ford Focus at 16 m/s

$E_k = \frac{1}{2}mv^2$

$= \frac{1}{2} \times 1300 \times 16^2$

$= 166\,400$ J or 166.4 kJ

### Problem 2

Calculate the kinetic energy of a Ford Territory, travelling at:

**a** 5 m/s (18 km/h)

**b** 16 m/s (57.6 km/h)


### Solution

**a** Ford Territory at 5 m/s

$E_k = \frac{1}{2}mv^2$

$= \frac{1}{2} \times 2025 \times 5^2$

$= 25\,312.5$ J or about 25.3 kJ

**b** Ford Territory at 16 m/s

$E_k = \frac{1}{2}mv^2$

$= \frac{1}{2} \times 2025 \times 16^2$

$= 259\,200$ J or 259.2 kJ

## Potential energy

**Potential energy** is energy that an object has because of its position or structure. For example, chemicals in foods and explosives contain energy in their chemical bonds. Potential energy is often called stored energy. Potential energy gives objects the capacity to makes things happen, or to do work.

### Elastic potential energy

A stretched or compressed spring or elastic material has **elastic potential energy**. This energy is converted into kinetic energy when the spring is released and returns to its original shape. Springs on a trampoline, car bumpers, bungee cords, sling shots, mouse traps (Figure 8.4.5) and even tennis balls store elastic potential energy and release it in different ways.

p285

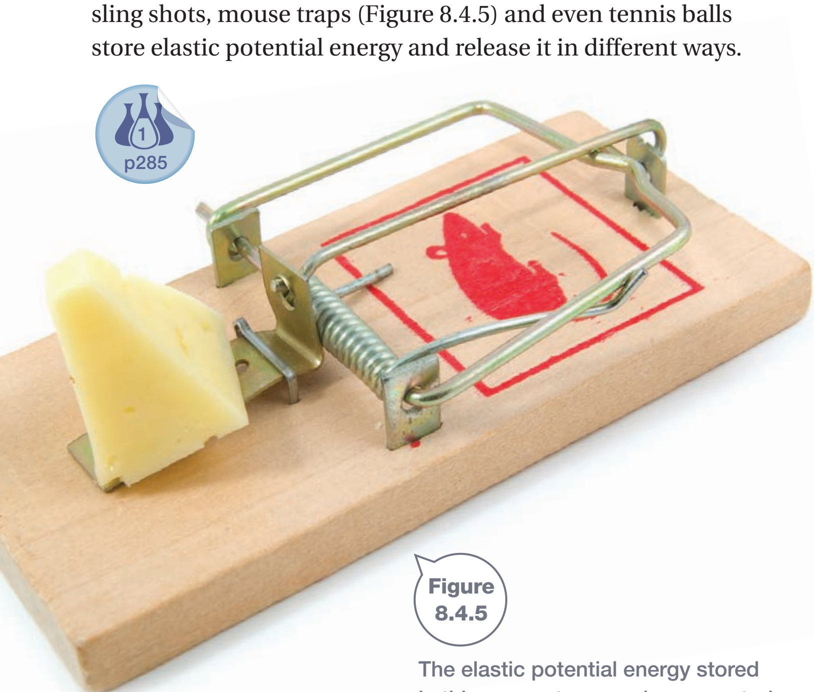


Figure 8.4.5 The elastic potential energy stored in this mouse trap can be converted in an instant into kinetic energy, sound energy and heat energy.

### Gravitational potential energy

An object positioned above the ground has **gravitational potential energy**. For example, a tree branch has gravitational energy. If it falls, it will do work on any car it hits. The branch does work on the car because it moves it, or parts of it, into a different shape.

Gravitational potential energy, $E_p$, can be calculated using the equation:

$$E_p = mgh$$

where $m$ is the mass (kg), $g$ is the acceleration due to gravity (9.8 m/s$^2$ for objects near Earth) and $h$ is the height (m).

**WORKED EXAMPLE**

**Calculating potential energy**

Sara is 6 years old and has a mass of 30 kg.
Calculate Sara's gravitational potential energy:

**a** when she climbs 2 m up a vertical ladder to the top of a slide

**b** at the bottom of the slide.

**Solution**

**a** $E_p = mgh$

$= 30 \times 9.8 \times 2$

$= 588$ J

Sara's gravitational potential energy at the top of the slide is 588 J.

**b** At the base of the slide, Sara's height above ground is zero, and so her gravitational potential energy is zero.

## Conservation of energy

The **law of conservation of energy** states that energy may be transferred from one object to another, but is never created or destroyed. For any situation in which energy is transferred between objects, there is always the same amount of energy at the end as there was at the start. In other words, the total energy ($E_t$) involved in the system remains the same. This can be expressed by stating:

$$E_t = E_p + E_k$$

An example of this is shown in Figure 8.4.6. A tennis ball dropped from a height initially has only gravitational potential energy. As it falls, its gravitational potential energy decreases and its kinetic energy increases and the ball speeds up. Just before the ball hits the ground, all of the energy it started with has been converted into kinetic energy.

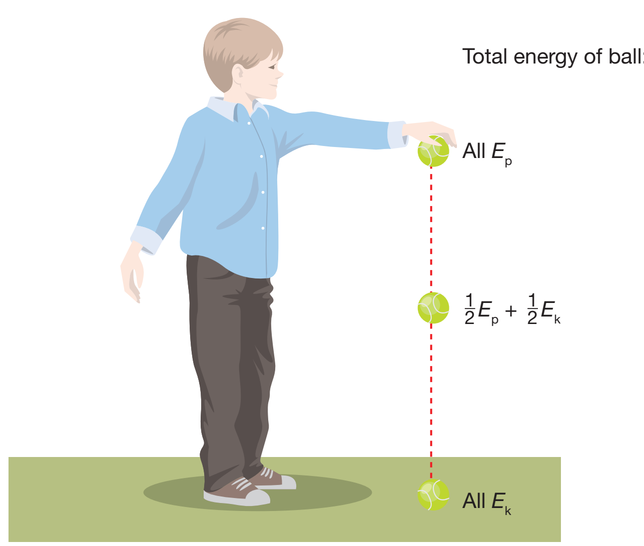



Figure 8.4.6 The total energy possessed by the tennis ball remains constant at each stage of its motion.

## WORKED EXAMPLE
### Converting potential to kinetic

#### Problem

A 0.5 kg ball is dropped from a height of 3 metres. Calculate its:

- **a** gravitational potential energy when it is released
- **b** total energy when it is released
- **c** kinetic energy when it has fallen half way
- **d** kinetic energy when it hits the ground.

#### Solution

**a** $m = 0.5$ kg, $g = 9.8$ m/s$^2$, $h = 3$ m

$E_p = mgh$

$= 0.5 \times 9.8 \times 3$

$= 14.7$ J

**b** When released, the ball has no kinetic energy, so the total energy is 14.7 J.

**c** Half way, the ball is at a height of 1.5 m and has gravitational potential energy:

$E_p = mgh$

$= 0.5 \times 9.8 \times 1.5$

$= 7.35$ J

The total energy is still 14.7 J, so the kinetic energy must be $14.7 - 7.35 = 7.35$ J.

The ball has the same amount of kinetic energy as potential energy at this point.

**d** When it reaches the ground, there is no gravitational potential energy, so kinetic energy is 14.7 J.

## Efficiency

Some energy is 'lost' as heat and sound energy each time a ball bounces. If this was not the case, a ball would keep bouncing forever. Similarly, in the previous Worked Example, although most of the gravitational potential energy Maddie had at the top of the slide was converted into useful kinetic energy, some of this gravitational potential energy was converted into sound energy and heat energy. These are not useful energy transformations.

The **efficiency** of an energy conversion is a measure of how much useful energy is produced. It can be expressed as:

$$\text{Efficency} = \frac{\text{useful energy}}{\text{total energy}} \times 100\%$$

2 p286

8.6

SciFile

### Inductive charging

When using wires and cables to charge up electronic devices such as phones, cameras and MP3 players, some energy is lost as wasted heat energy. A number of companies developed a more efficient way to transfer energy. Through a process called inductive charging, the receiver in a device needing power is able to wirelessly accept energy from a transmitter in a charging pad.


SciFile

### Efficient travel

Cycling at speeds around 16–24 km/h is the most efficient form of transport for humans. 500 kJ can power a cyclist a distance of around 5 km, but the same energy will only power a car about 100 m!

SciFile

### Efficiency of pets

Dogs are more efficient than cats when it comes to eating food! Dogs convert about 70% of their energy used to walk into forward motion. In contrast a cat typically only converts between 20–38% of the energy used to walk into actually moving forward.

# 8.4 Unit review

## Remembering

1 **State** the units used to measure:
- a energy
- b work done.

2 **Recall** the equation used to calculate kinetic energy.

3 **State** whether a car has more kinetic energy when travelling at 10 km/h or when travelling at 60 km/h.

4 **Recall** the three factors that change the amount of gravitational potential energy possessed by an object.

5 **List** three objects that use elastic potential energy to do work.

## Understanding

6 **Describe** what happens to the:
- a gravitational potential energy of an object when its height above the ground is doubled
- b kinetic energy of an object when its speed is doubled.

7 Energy is sometimes defined as 'the ability to do work'. **Explain** how an object with potential energy or kinetic energy can do work.

## Applying

8 A child of weight 250 N climbs 1.5 metres up a rope ladder in 5 seconds. **Calculate** the:
- a work done
- b power of the climb.

9 **Identify** in which of the following situations work is being done.
- a A softball is thrown into the air.
- b A person rests against a chair.
- c Water runs from a tap into a sink.
- d A car is held on a hill by its brakes.

10 **Calculate** the kinetic energy of:
- a an 80 kg jogger running at 4 m/s
- b a 10 000 kg bus travelling at 54 km/h
- c a 100 g tennis ball hit at 30 m/s.

11 **Calculate** the gravitational potential energy of a:
- a 0.5 kg bird flying 20 m above the ground
- b 20 000 kg helicopter hovering 300 m above the ground
- c 2 kg money box sitting on a bookshelf at a height of 2 m.

## Analysing

12 A 1 kg ball is dropped onto concrete from a height of 2 m. **Analyse** this situation and **calculate**:
- a its gravitational potential energy before it is dropped
- b its kinetic energy as it hits the ground
- c the speed with which it hits the ground (round off to one decimal place).

## Evaluating

13 Researchers estimate that the risk of serious injury or death approximately doubles for every 5 km/h that a car travels above 60 km/h. **Justify** how this could be possible.

14 Figure 8.4.7 shows a section of a rollercoaster used at a theme park.

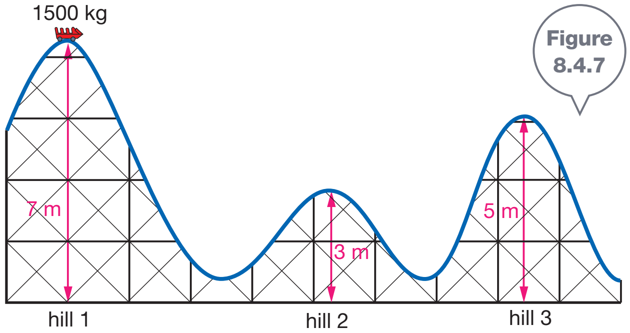



Figure 8.4.7

The rollercoaster, fully loaded with passengers, has a total mass of 1500 kg. Assume that it starts from rest and ignore the effects of friction.
- a **Calculate** its gravitational potential energy at the start of its journey.
- b **Calculate** its kinetic energy at the top of hill 2.
- c **Calculate** its kinetic energy at the top of hill 3.
- d **Calculate** its speed (to one decimal place) over hill 3.
- e If friction was taken into account, **propose** how your answers to these questions would differ.

15 **Justify** why the first hill on a rollercoaster track is usually the largest.

## Inquiring

1 View footage from Pearson Reader of a collision at 60 km/h and another at 100 km/h. Compare the damage caused in these two collisions and suggest why around 40% of road deaths are due to excessive speed.

2 Investigate regenerative braking and explain how this makes a vehicle more energy efficient.

3 Investigate and explain how a plug-in hybrid electric vehicle (PHEV) operates. Outline the advantages and disadvantages of this form of transport.

4 Investigate the rebound height of different types of bouncing balls dropped from the same height and compare the energy losses of each.

# 8.4 Practical activities

## 1 Extension of an elastic band

### Purpose

To investigate the effect of weight on the stretching of an elastic band.

### Materials

- 2 similar elastic bands
- retort stand and clamp
- 5 × 50 g hanging masses
- ruler

### Procedure

1. Copy the table in the results section. Use it or a spreadsheet to record your findings.
2. Hang an elastic band from a retort stand as shown in Figure 8.4.8 and measure its natural, unstretched length.
3. Hang a 50 g mass from the elastic band and measure its new length.
4. Calculate the extension caused by the 50 g mass.
5. Repeat for 100, 150, 200 and 250 g.
6. Repeat this process using two elastic bands looped together end to end and then positioned in parallel. (Make sure you first record the unstretched length of each combination.)

### Results

1. Copy and compete the following table.

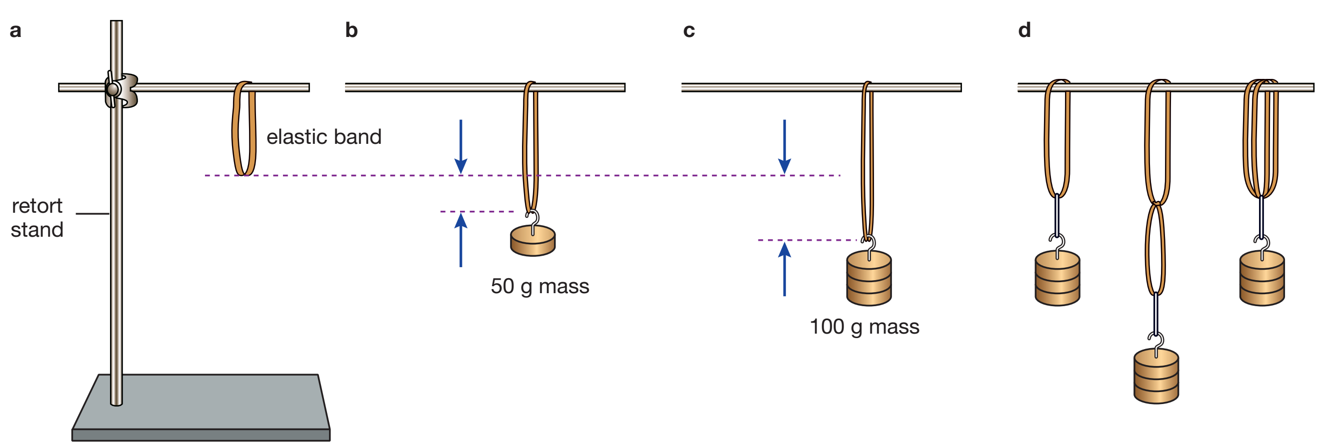
| Mass attached (g) | Elastic band length (mm) | | | Extension of single band (mm) | Extension of two bands end to end (mm) | Extension of two parallel bands (mm) |
|---|---|---|---|---|---|---|
| | Single | Two bands end to end | Two bands parallel | | | |
| 0 | | | | 0 | 0 | 0 |
| 50 | | | | | | |
| 100 | | | | | | |
| 150 | | | | | | |
| 200 | | | | | | |
| 250 | | | | | | |

2. Plot a graph of the extension (mm) on the vertical axis against mass (g) on the horizontal axis. Draw a line of best fit through the points.
3. On the same set of axes, plot the graphs for the double elastic band combinations.

### Discussion

1. **State** which type of energy is stored in the elastic bands.
2. **Explain** how, when stretched, these rubber bands have the ability to do work.
3. **Describe** which arrangement produced the stiffest combination of elastic bands.
4. **Discuss** any sources of error from your experiment.

Figure 8.4.8



## 2 Energy changes in a rollercoaster

The efficiency of a rollercoaster can be found by calculating:

$$\text{efficiency} = \frac{\text{height ball reaches}}{\text{height ball was released}} \times 100\%$$

### Purpose

To investigate the efficiency of three rollercoaster tracks of different designs.

### Materials

You can use your own selection of materials, which may include:

- clear plastic tubing or computer cable channel
- retort stands and clamps
- marbles or ball bearings.

### Procedure

1. Design and construct three arrangements of track to investigate, such as those shown in Figure 8.4.9.
2. Record the height of the release of the marble and the height it reaches in each case.

### Results

Construct diagrams to show the design of each track, marked with the heights of release and finish heights.

### Discussion

1. **Calculate** the efficiency of each design and explain why the efficiency was less than 100%.
2. **Discuss** any areas of difficulty you encountered in your investigation.
3. **Propose** an additional experiment you could conduct about energy conversions using this equipment.

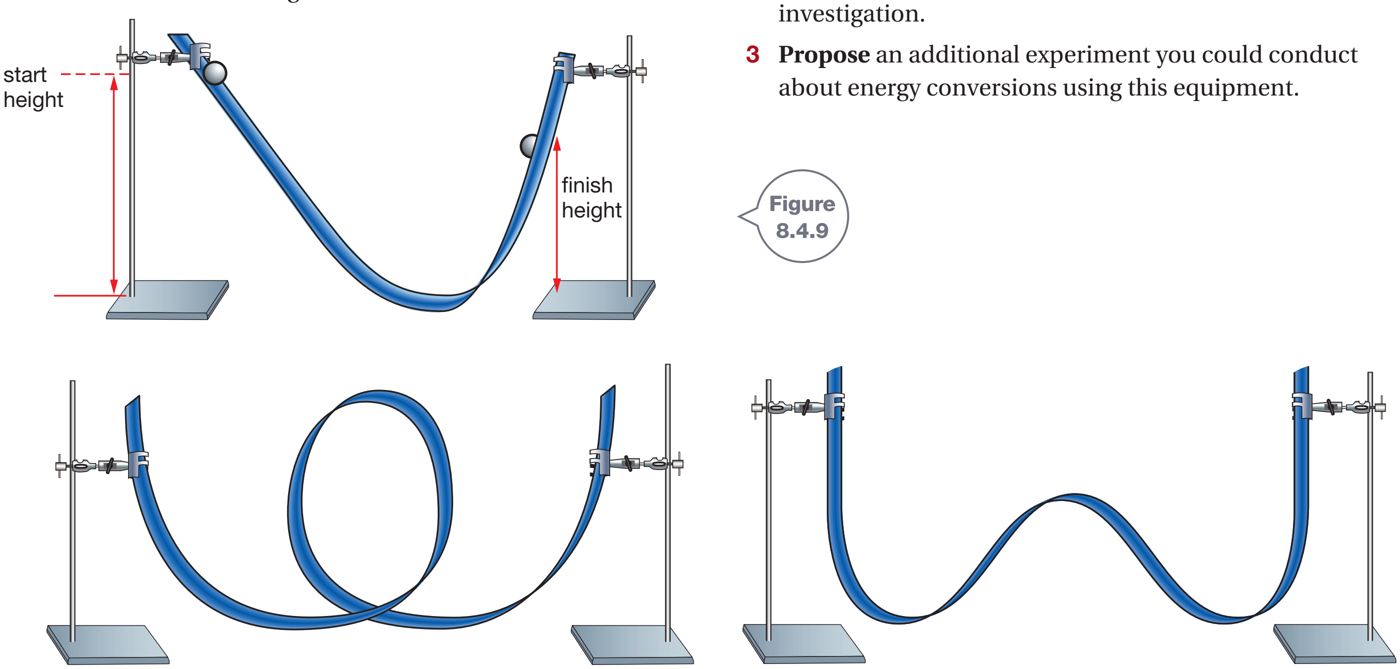



Figure 8.4.9

# Chapter review

8

## Remembering

**1** **Recall** the SI units from the following list: kilogram, centimetre, second, gram, milligram, year, hour, tonne, minute, kilometre.

**2** **State** how to convert a speed from km/h into m/s.

**3** **State** what is represented by the gradient of a:

**a** distance–time graph

**b** velocity–time graph.

## Understanding

**4** **Explain** why if a horse stops running when it comes to a fence, its rider can be thrown over the top of it.

**5** **Explain** why wearing a helmet when riding a bike reduces the force of an impact if the rider is involved in a collision.

## Applying

**6** Figure 8.5.1 shows the displacement of Steve as he rides his bike.

**Use** this to find:

**a** the total distance travelled

**b** his displacement

**c** his speed in the first 2 hours

**d** at which time he was stationary

**e** his speed in the last 3 hours of her journey

**f** his average speed over the entire trip (in km/h).

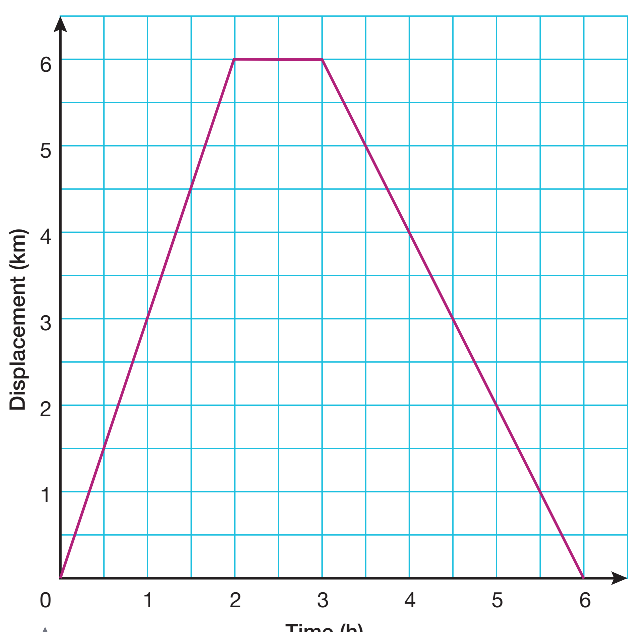



Figure 8.5.1

**7** Carlo rides a tricycle down a hill, with constant acceleration of 0.1 m/s$^2$. This means that his speed increased by 0.1 m/s each second. If he has an initial speed of 0.2 m/s, **calculate**:

**a** his speed after 3 seconds

**b** this speed in km/h.

**8** Two astronauts, William and Sage, are making in-flight repairs to their space shuttle. Sage asks William to pass her a toolbox, which has a mass of 5 kg. William gives the toolbox a push of 7 N. **Calculate** the acceleration of the toolbox.

**9** **Calculate** the kinetic energy of a:

**a** 0.1 kg apple thrown across a room at 2 m/s

**b** 75 kg athlete running at 5 m/s

**c** 2500 kg delivery van travelling at 80 km/h. (Hint: Convert this speed to m/s.)

**10** **Calculate** the potential energy of:

**a** a 9 kg rock suspended on a ledge 7 m above the ground

**b** an 80 kg man who has climbed 40 m up a vertical rock face

**c** a 15 kg chimpanzee sitting on a tree branch 20 m high.

**11** Figure 8.5.2 represents a constant force applied to push a couch 6 m across a floor. **Calculate** the work done when it has shifted:

**a** 2 m

**b** 6 m.

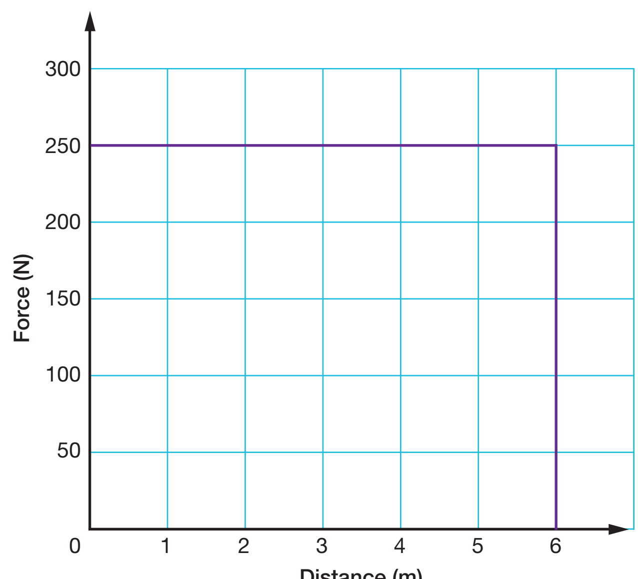



Figure 8.5.2

# 8 Chapter review

12 Tahlia is caught in a burning building and needs to jump from a window near the top of the building to be saved by the rescue team below. The total energy in a system is conserved. **Use** this fact to **calculate** the missing values in the diagram.

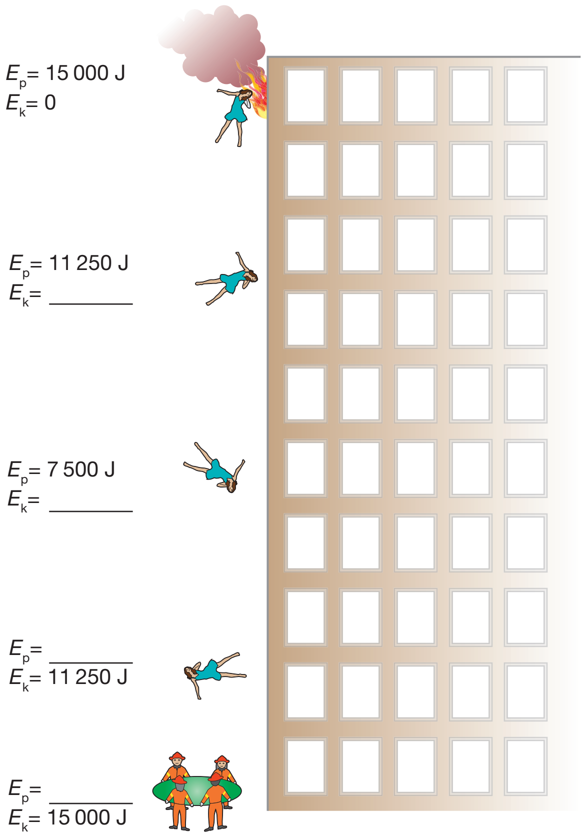



Figure 8.5.3

## Analysing

13 **Analyse** the three speed–time graphs shown in Figure 8.5.4 and **describe** the motion represented by each.

## Evaluating

14 **Justify** why your body is thrown to the right when turning a sharp left corner on a rollercoaster.

16 You travel from the ground to the 20th floor in a city lift. **Propose** why you feel very heavy through most of the journey

## Creating

15 The table below contains data about the speed of the racehorse *Newton's wings* in a race.

| Time (s) | 0 | 20 | 40 | 60 | 80 | 100 | 120 | 140 | 160 | 180 |
|---|---|---|---|---|---|---|---|---|---|---|
| Speed (m/s) | 0 | 3 | 5 | 7 | 9 | 9 | 9 | 9 | 9 | 9 |

a **Construct** a speed–time graph of this data

b **Calculate** Newton's wings' top speed in km/h.

c **Use** your graph to calculate the distance run by the horse in the race.

17 **Use** the following ten key terms to **construct** a visual summary of the information presented in this chapter.
distance
displacement
speed
velocity
acceleration
force
Newton's laws
work
kinetic energy
gravitational potential energy

8.7

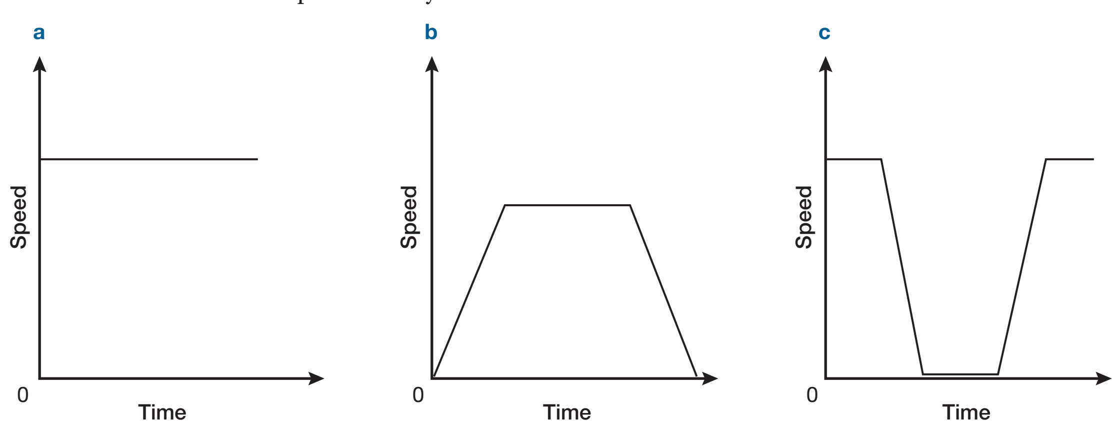
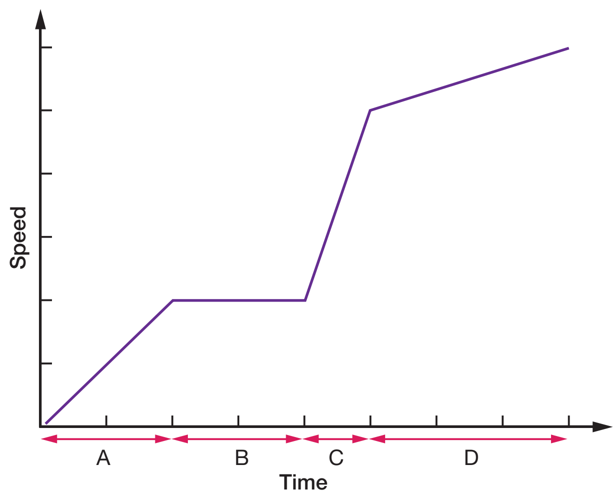



Figure 8.5.4

# Thinking scientifically

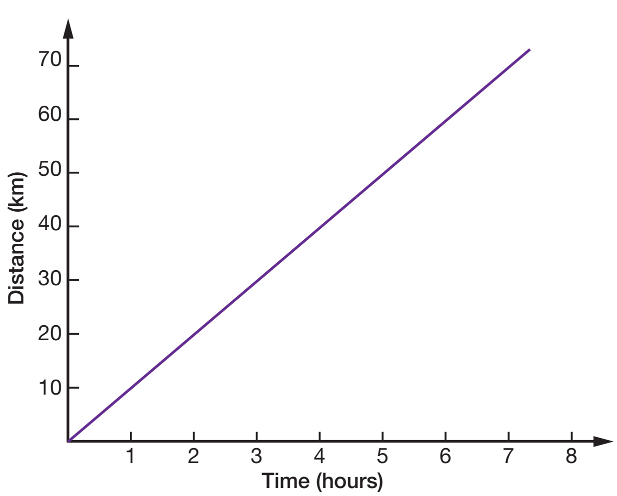
**Q1** The graph below shows the motion of Tina, riding a bike home from school. Given that the gradient of a speed–time graph is Tina's acceleration, the time interval over which Tina has the greatest acceleration is:

**A** section A
**B** section B
**C** section C
**D** section D.

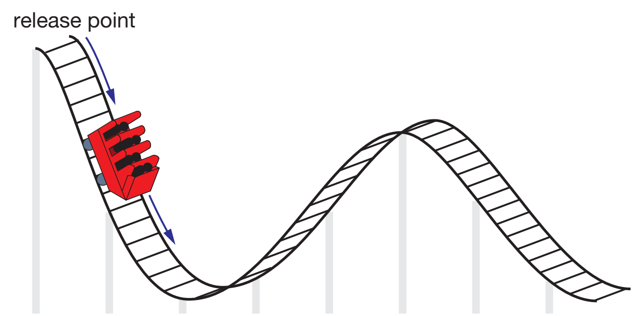



**Q2** The distance–time graph of Ben's motion as he rides in a long-distance cycling event is shown below. Given that Ben's average speed is the distance travelled divided by time taken, his average speed across this time interval is:

**A** 10 km/h
**B** 10 m/s
**C** 1 km/h
**D** 1 m/s.



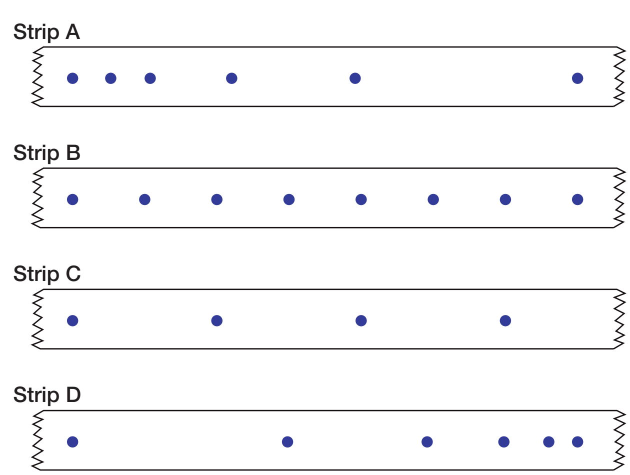

**Q3** The diagram shows the position of a rollercoaster cart soon after it is released on a track. Select the alternative that describes how its energy is changing at this moment in time.




**A** increasing kinetic energy, constant gravitational potential energy
**B** increasing kinetic energy, decreasing gravitational potential energy
**C** decreasing kinetic energy, increasing gravitational potential energy
**D** decreasing kinetic energy, constant gravitational potential energy

**Q4** The hammer on a ticker timer vibrates up and down 50 times per second. The following four strips of ticker tape were attached to a moving object. These dots display a record of its motion. The strip that indicates the fastest constant speed is:

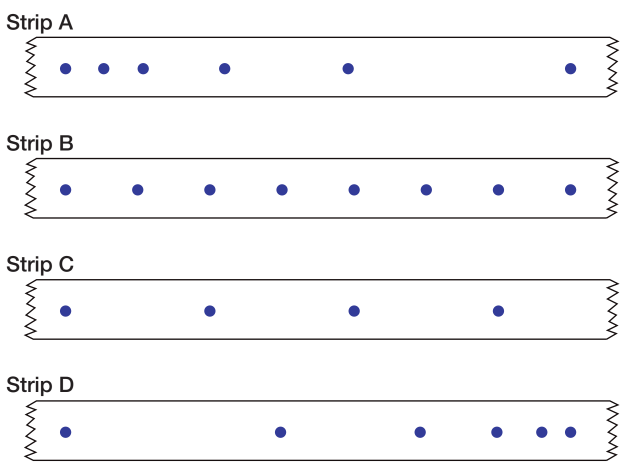
**A** strip A
**B** strip B
**C** strip C
**D** strip D.



# Thinking scientifically

**Q5** The hammer on a ticker timer vibrates up and down 50 times per second. The following four strips of ticker tape were attached to a moving object. These dots display a record of its motion. The strip that indicates an object that is slowing down is:

**A** strip A
**B** strip B
**C** strip C
**D** strip D.

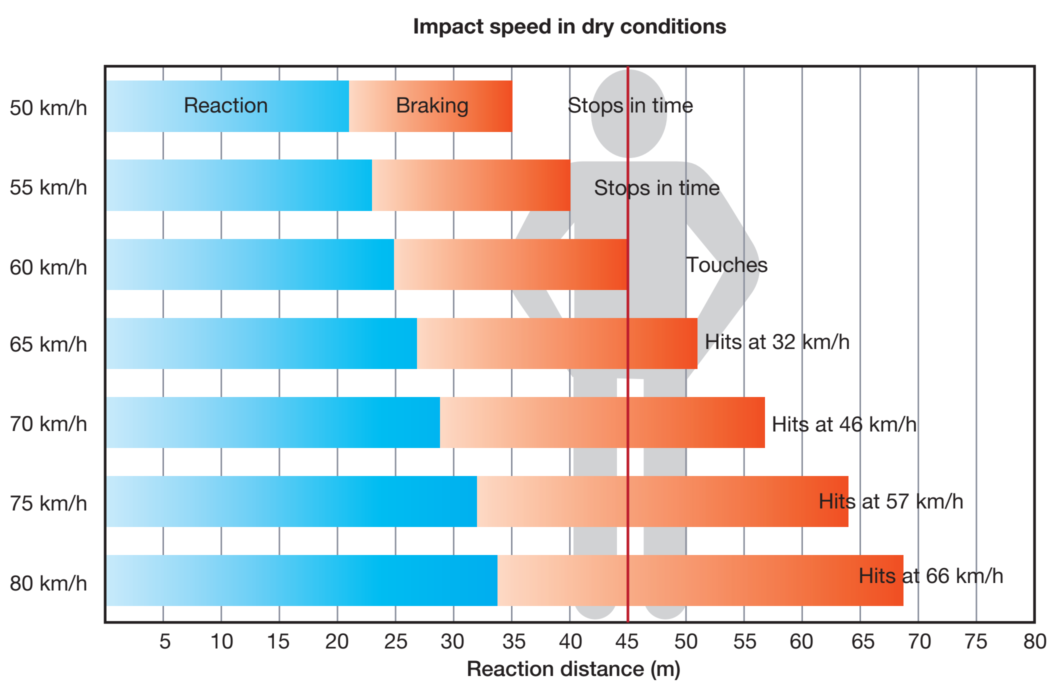



**Q6** Cathy pushes a shopping cart of mass *m* with force *F*. By Newton's second law of motion (and ignoring friction), the cart has acceleration $a = F/m$. Cathy now uses the same-sized force to push a cart that has three times the mass. Its acceleration is:

**A** double the acceleration of the first cart
**B** three times the original acceleration
**C** one-third of the original acceleration
**D** half of the original acceleration.

**Q7** Study the graph below, which estimates the typical reaction time and reaction distance for drivers travelling at various speeds. Imagine that two cars are travelling along a multilane highway, car A at 55 km/h and car B at 75 km/h. A wombat staggers onto the road 50 m ahead of the cars the instant they are both the same distance away from it. Assuming the drivers react as shown in the graph, determine the correct alternative.

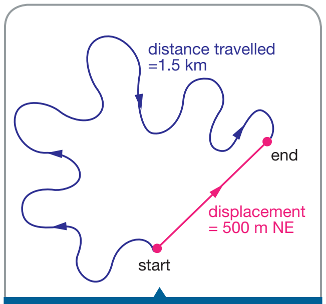
**A** Both cars stop in time.
**B** Only car A stops in time.
**C** Only car B can stop in time.
**D** Neither car is able to stop in time.



# Glossary

## Unit 8.1

**Displacement:** a measurement of the change in position of a moving body; a straight line connecting the start and end points is specified in terms of length and direction



Displacement
Distance

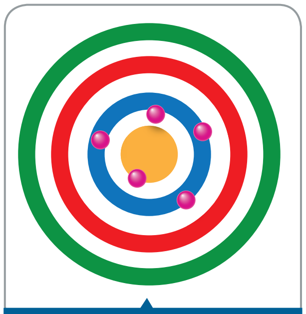
**Distance:** a measurement of how far apart objects are

**Error:** the difference between the value that is measured and the actual measurement

**Gradient:** slope of a hill of a graph: gradient = $\frac{\text{rise}}{\text{run}}$

**Instantaneous speed:** the speed of an object at a particular moment

**Precision:** how close measured values are to each other


Precision

**Random error:** error that changes

**Reaction distance:** distance moved while reacting to an emergency

**Reaction time:** the length of time it takes a driver to respond to a hazard

**Scalar quantity:** a quantity, such as distance or time that has size but not direction

**Speed:** the rate of change of distance

**Systematic error:** error that always differs by the same amount

**Vector quantity:** a quantity, such as displacement or velocity, that has size and direction

**Velocity:** the rate of change of displacement

Acceleration

## Unit 8.2

**Acceleration:** rate of change of velocity

**Air resistance:** friction between the air and a moving object

**Terminal velocity:** the final velocity that an object falls with no further acceleration possible due to air resistance

## Unit 8.3

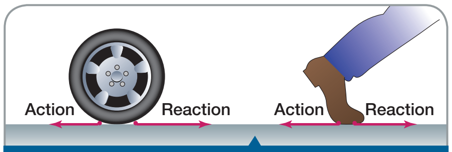
**Inertia:** the tendency of an object to resist changes in its motion


Inertia

**Newton's first law of motion:** an object at rest will remain this way unless it is acted upon by an unbalanced force; an object that is moving will continue to move in the same manner unless acted upon by an unbalanced force

**Newton's second law of motion:** an object will accelerate in the direction of an unbalanced force acting upon it such that: $F_{net} = m \times a$

**Newton's third law of motion:** for every action, there is an equal and opposite reaction

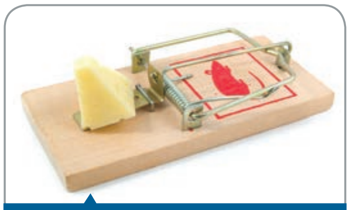


Newton's third law of motion

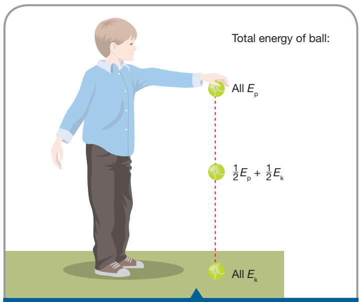
## Unit 8.4

**Efficiency:** a measure of the useful energy output of an energy transfer

**Elastic potential energy:** energy stored in a stretched or compressed material, such as a spring or elastic band


Elastic potential energy

**Gravitational potential energy:** the potential energy possessed by an object due to its position above the ground



Gravitational potential energy

**Kinetic energy:** the energy of a moving body

**Law of conservation of energy:** energy may be transferred but is never created or destroyed

**Potential energy:** energy possessed by an object because of its position or structure, also called stored energy

**Power:** the rate at which work is done; measured in watts (W)

**Work:** the energy transferred by a force that acts over a certain distance; measured in joules (J)