MOTION AND ENERGY

7

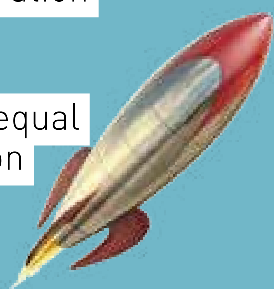
7.1 Displacement is change in position with direction

7.2 Velocity is speed with direction

7.3 Acceleration is change in velocity over time

7.4 An object in motion remains in motion until a force acts on it

7.5 Force equals mass × acceleration



7.6 Each action has an equal and opposite reaction

7.7 Momentum is conserved in a collision

7.8 Work occurs when an object is moved or rearranged. Energy can be calculated

7.9 Energy is always conserved

7.10 Car safety features require an understanding of Newton's laws and momentum

What if?

What you need:

stopwatches, trundle wheel

Do not distract drivers in any way during this activity because this could have serious consequences. Always remain on the footpath at a safe distance from the road.

What to do:

1 Working in a group of three or four, find a straight stretch of road near your school and set up a 'speed trap'. Measure a distance along the side of the road and, using a stopwatch, time the motion of vehicles over that distance.

2 You will need one person to stand at the start of the distance and wave to the others as each car passes them to indicate to the people in your group to start their stopwatches.

3 From your times and distance, work out the average speed of the vehicles in metres per second and then in kilometres per hour. Decide if any of the vehicles were speeding.

What if?

» What if you compared your results to a police speed gun? (Would they be the same?)

7.1 Displacement is change in position with direction

Distance describes how far an object travels in a set time. Displacement describes the final distance and direction of the object from its starting point. Displacement is a vector quantity because it has position and direction. The movement of an object can be shown on position–time graphs or distance and displacement diagrams.

Distance and displacement

During a normal day, you may cover a considerable distance – on the way to school, on the way home, around school from classroom to classroom. However, at the end of the day you will most likely end up in exactly the same place as where you started the day: bed! So, you could say that you haven't really gone anywhere at all.

Distance is how far an object travels over a certain period of time. **Displacement** describes the *change in position* of an object *and its direction* over a certain period of time. Displacement only compares the end position with the starting position, not all the in-between movements. If you end up back in bed after a whole day of moving, then your displacement is zero. For both distance and displacement, we use the symbol *d*, and the standard unit (or SI unit) is the metre (m).

Distance is known as a scalar quantity because it only has size (or **magnitude**) and no direction. Displacement is known as a **vector** quantity because it has size and direction. The direction part can be a compass direction (north, south, east, west) or a bearing, or it may be as simple as left, right, up, down, forwards or backwards.

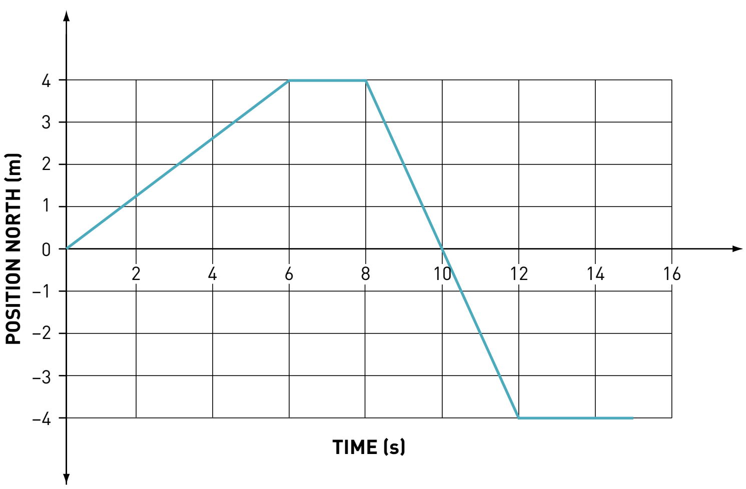


Figure 7.1 This position–time graph shows the position of a person walking north from the starting point for 6 seconds, stopping for 2 seconds and then walking south for 4 seconds. Their final position was 4 metres south of the starting point.

Position–time graphs

Have you ever seen a movie or read a book where a cryptic code is used to find the buried treasure or precious artefact? These codes often contain instructions such as 'walk 15 paces south and then 20 paces west', which could lead to a very different outcome depending on how big, or small, your steps are.

Motion graphs are a model or visual representation of a movement and can take many forms. The simplest is a position–time graph (also called a displacement–time graph). A position–time graph is a picture of the motion of an object. Position–time graphs are really only useful when the motion is linear; that is, in the same line, such as north–south or east–west or up–down. Time is always on the *x*-axis and position is always on the *y*-axis (Figure 7.1). Always remember to mark the units (e.g. seconds, metres) on the graph.

CHALLENGE 7.1: BRINGING GRAPHS TO LIFE
GO TO PAGE 221

Distance and displacement diagrams

The distance an object travels can also be represented by diagrams. Distance and displacement diagrams (as opposed to graphs) are most useful when the movement changes from linear to two dimensions. We can use arrows to show the directions and a scale to show the distances. North commonly points towards the top of the page. For example, Figure 7.2 shows a diagram of a person walking 5 metres north, then 4 metres west and then 2 metres south. This gives a total distance covered of 11 metres. However, this is not their displacement. Their displacement only compares where they finish to where they started.

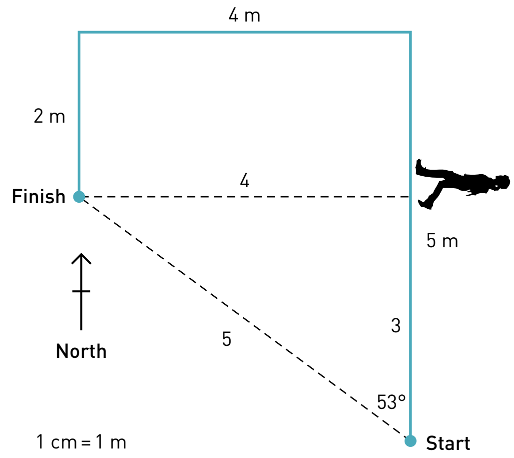


Figure 7.2 This person walks a total of 11 metres. The displacement can be calculated by drawing a right-angled triangle and using Pythagoras' theorem. The final position of the person is 5 m north 53° west or 5 m on a bearing of 307°.

Check your learning 7.1

Remember and understand

1 Describe a motion that has zero displacement.

2 What is the difference between displacement and distance?

Apply and analyse

3 An object moves 14 metres north and then 14 metres south. What distance has it covered? What is its displacement?

4 What is the difference between a vector quantity and a scalar quantity?

5 A person runs 50 metres north, then 20 metres south and then 30 metres west. What is the total distance covered? What is the person's displacement?

6 A car starts from rest (stationary) and moves north at a constant rate for 400 metres, then stops for 10 seconds before moving north another 150 metres. On a piece of paper, draw this movement as a position–time graph.

7 Consider the graph in Figure 7.3.

   a Describe the motion shown.

   b What is the distance covered in the graph?

   c What is the displacement shown?

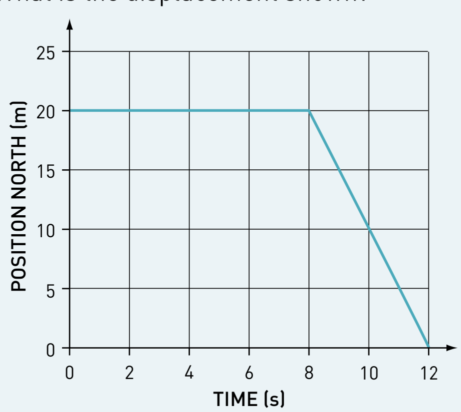


Figure 7.3

7.2 Velocity is speed with direction

Speed is a scalar quantity that measures the distance travelled in a set time. The average speed can be determined by dividing the distance travelled by the total time taken. A speedometer measures the instantaneous speed of an object. Velocity is a vector quantity and it measures the change in displacement over time.

Speed

Speed is a measure of how fast a car or a person or any moving object is travelling. It is measured in SI units of metres per second (m/s or m s^{-1}), although kilometres per hour (km/h or km h^{-1}) is often used instead, especially for cars and planes.

Speed is defined as the distance travelled per unit of time. Hence, a speed of 5 m/s means the object travels 5 metres in every second of its motion. Speed is a scalar quantity because it only has size and no direction.

Average speed

Often it is more convenient to work out (or calculate) an object's average speed. The symbol for average speed is s_{av}. To calculate average speed, divide the total distance travelled by the total time taken. The units for speed depend on the units of distance and time.

The formula for calculating the average speed is:

$$s_{av} = \frac{d}{t}$$

Figure 7.4 The cheetah is the fastest land animal. It can reach speeds of up to 112 km/h.

This rule, or formula, can also be expressed in a triangle as shown in Figure 7.5. The triangle is a good memory tool to help you work out three formulas from the one diagram.

Average speed can also be determined by the gradient (or slope) of a position–time graph (Figure 7.6).

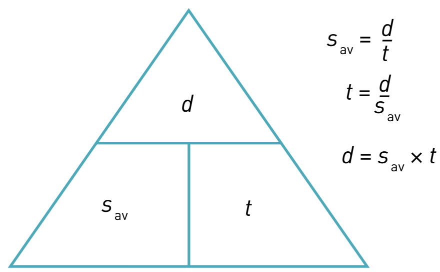


Figure 7.5 The average speed triangle is used to work out the formula for average speed. Cover the quantity you want to calculate with your finger and the other two quantities will form the formula.

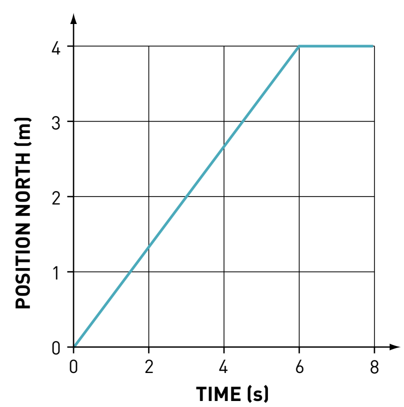


Figure 7.6 The speed of the object in this position–time graph can be calculated by determining the gradient of the graph. Gradient = change in position ÷ change in time = rise ÷ run = 4 m ÷ 6 s = 0.67 m/s.

EXPERIMENT 7.2A: THE TICKER TIMER
GO TO PAGE 222

EXPERIMENT 7.2B: USING A MOTION SENSOR
GO TO PAGE 223

Figure 7.7 A speedometer measures the instantaneous speed of a vehicle.

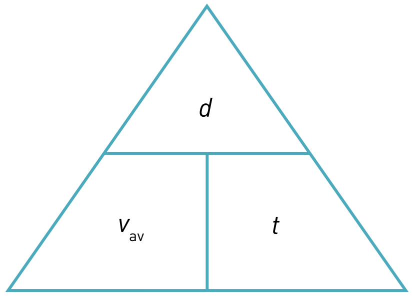


Figure 7.8 The average velocity triangle. Cover the quantity you want to calculate and the other two quantities will form the formula.

Instantaneous speed

Over the course of a bus or car trip, your speed changes. The speedometer in the vehicle gives the instantaneous speed in km/h (Figure 7.7). This is the speed at each moment of the trip.

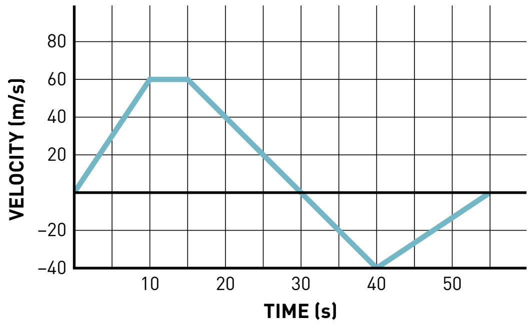


Figure 7.9 This velocity–time graph shows an object with changing velocity. The object increases its velocity from 0 m/s to 60 m/s in the first 10 seconds. It then travels at a constant 60 m/s for 5 seconds before slowing down. At 30 seconds, it has stopped and then starts travelling in the opposite (negative) direction before eventually slowing to a stop. The area under the graph describes the displacement as 1050 metres in the positive direction and 500 metres in the negative direction. The total displacement will be 250 metres in the positive direction.

Velocity

Pilots and sailors need to know both the speed of the wind and its direction. **Velocity** is speed in a particular direction and is therefore a vector quantity (a measurement of both size and direction). It has the same unit as speed (m/s). The average velocity of an object is calculated in a similar way to average speed, but displacement is used instead of distance (see Figure 7.8).

The direction of the average velocity is the same as the direction of the displacement. Like speed, average velocity can be determined from the gradient of a position–time graph, but the nature of the gradient indicates the direction. For example, if the gradient is positive (sloping upwards) in the north direction, then the velocity will be positive in the north direction. If the gradient is negative (sloping downwards), then the velocity will be negative in the south direction.

Graphing speed

It is useful to represent an object's speed graphically. This is called a speed–time graph. In these graphs, speed is plotted on the *y*-axis and time on the *x*-axis. The area under the graph determines the distance travelled in that time.

Figure 7.10 The wind's speed and direction affect the speed of a yacht.

Check your learning 7.2

Remember and understand

1. Is 4 m/s a speed or a velocity? Explain your answer.
2. Use the average velocity triangle to write the three different formulas.
3. What does the gradient of a position–time graph indicate?
4. What does the area under a velocity–time graph indicate?

Apply and analyse

5. What other units do you know that are used to measure speed?
6. Convert 80 km/h to metres per second.
7. An object travels 40 km in 5 hours. What is its average speed?

Evaluate and create

8. Create a story that describes the motion of a person moving according to the graph in Figure 7.11. Describe their displacement from the point of origin.

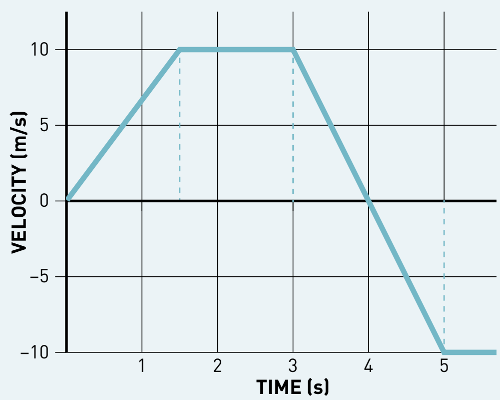


Figure 7.11

7.3 Acceleration is change in velocity over time

Acceleration is the rate at which the speed of an object changes. This is measured in m/s^2 or km/h^2. Deceleration is the rate at which the speed slows down. An object travelling at a constant, unchanging speed has an acceleration of zero. Gravity acceleration is the increase in speed of an object as it falls under the sole influence of gravity. This is calculated as 10 m/s^2 (9.8 m/s^2).

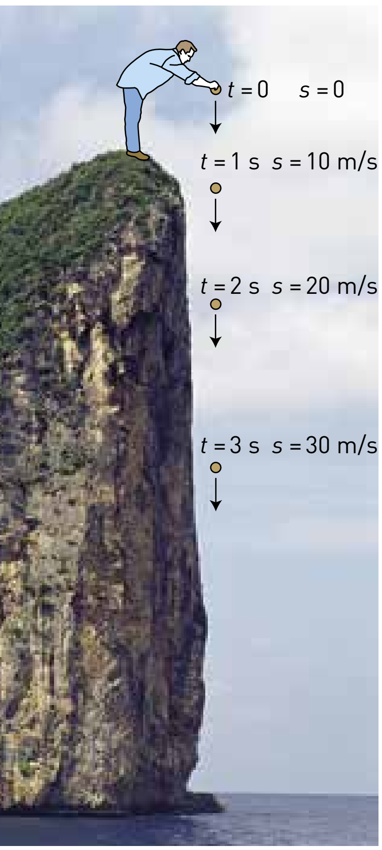


Figure 7.12 Each second, the speed of the falling rock increases by almost 10 m/s, ignoring air resistance. This means the acceleration is 10 m/s^2.

Acceleration

Pressing the accelerator pedal in a car makes the car move forwards and increase in speed. This is the same as saying the car accelerates. Acceleration is the rate of change of speed. The term 'rate' in this case refers to time, so acceleration is the change of speed over time.

Just as the accelerator pedal causes a car to speed up, the brake pedal causes a car to slow down. This is called **deceleration** (or negative acceleration).

Acceleration is measured in units of metres per second per second (m/s/s) or metres per second squared (m/s^2 or $m\ s^{-2}$) because speed is usually measured in metres per second and time is usually measured in seconds. However, other units for acceleration are possible depending on the units of speed and time.

To understand acceleration, we will only consider objects travelling in one direction in a straight line and under constant acceleration. Consider a falling object, such as the rock shown in Figure 7.12.

When held out to one side and dropped vertically (not thrown), the rock starts at rest and increases in speed as it falls. If it were dropped from high enough, the rock may accelerate to quite a high speed.

After 1 second, it should reach a speed of almost 10 m/s due to gravity (actually, it is 9.8 m/s, which is very close to 10). We say it has accelerated at a rate of 10 metres per second in 1 second or at 10 metres per second per second (written as 10 m/s/s or 10 m/s^2 or 10 $m\ s^{-2}$).

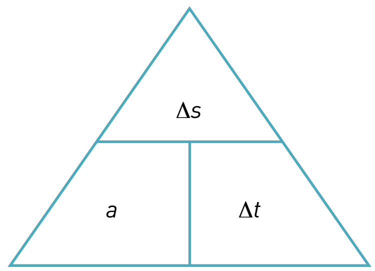


Figure 7.13 The acceleration triangle. Cover the quantity you want to calculate and the other two quantities will form the formula.

After another second at the same rate, the rock would reach a speed of almost 20 m/s.

After 3 seconds, it would reach a speed of almost 30 m/s. Of course, this analysis ignores the effects of air resistance, which would prevent the rock from reaching a speed of 30 m/s after 3 seconds.

The acceleration value of 10 m/s^2 is called **acceleration due to gravity** and is given the special symbol of g. When people skydive, their movement follows the pattern of the rock. They speed up as they fall until they open their parachute and slow down to land.

Calculating acceleration

The formula for calculating acceleration is:

$$a = \frac{\Delta s}{\Delta t}$$

where Δ is the Greek letter 'delta' and means 'change in'. This can also be seen in the acceleration triangle (Figure 7.13).

This can also be written as:

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

where v is the final speed and u is the initial, or starting, speed.

CHALLENGE 7.3: MEASURING ACCELERATION BY TIMING OR USING A MOTION SENSOR
GO TO PAGE 223

Acceleration is indicated by the gradient of a speed–time graph. The size of the gradient indicates the size of the acceleration. This is shown in Figures 7.14 and 7.15.

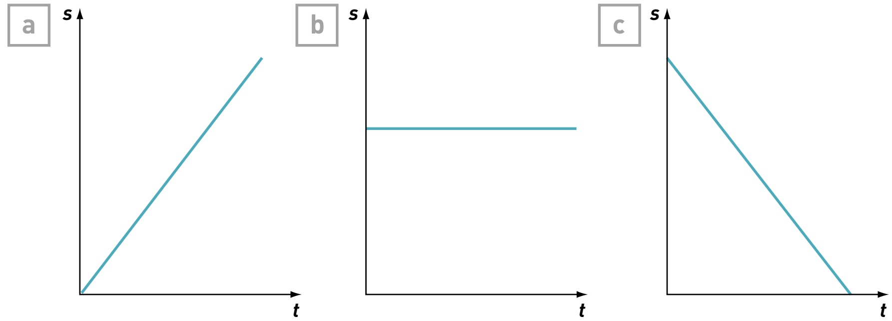


Figure 7.14 Speed–time graphs showing (a) constant positive acceleration (i.e. speeding up), (b) zero acceleration (i.e. constant speed) and (c) negative acceleration (i.e. slowing down or decelerating).

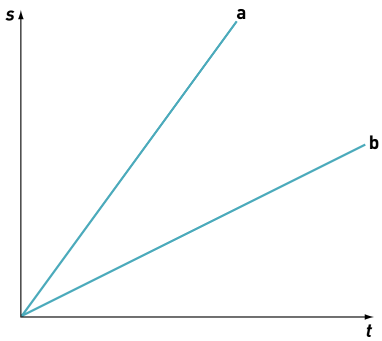


Figure 7.15 Speed–time graphs showing a (a) steep gradient, indicating high acceleration, and (b) gentle gradient, indicating lower acceleration.

Figure 7.16 Timing how long an object takes to fall also provides a practical way to measure distance. You can calculate the depth of a well by dropping a rock into the well and measuring the time required for it to reach the bottom. The depth can be calculated from the formula $d = \frac{1}{2}gt^2$.

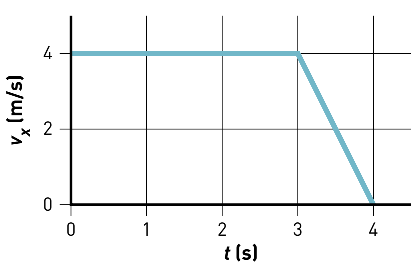


Figure 7.17 The object in this graph is travelling at a constant speed of 4 m/s for the first 2 seconds. Its gradient (and hence its acceleration) is zero. The object then slows down to 0 m/s in the last 2 seconds. Its acceleration according to the acceleration triangle is −2 m/s². The negative number indicates the object has decelerated.

Figure 7.18 Acceleration is the change in speed over time.

Check your learning 7.3

Remember and understand

1 Use the acceleration triangle to write the three different formulas.

2 What is meant by the term 'deceleration'?

3 What is the acceleration of an object if its velocity is constant?

Apply and analyse

4 Describe the motion of an object with the speed–time graph shown in Figure 7.19.

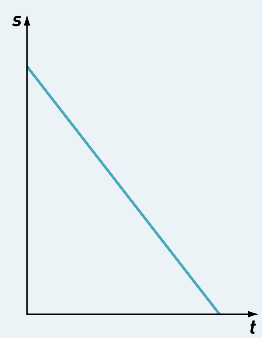


Figure 7.19

5 An object starts from rest and accelerates at a rate of 4 m/s². State its speed after each second for 5 seconds.

6 What do accelerating and decelerating objects have in common?

7.4 An object in motion remains in motion until a force acts on it

Newton's first law (of inertia) states: 'An object remains at rest or in constant motion in a straight line unless acted on by a net unbalanced force.' The greater the mass of an object, the larger the inertia. This means an object will remain at rest until an outside force acts on it. An object that is moving at a constant speed will not change its speed unless an outside force acts on it.

Sometimes high-speed movement, such as cruising in an aeroplane, is barely noticeable. You may not even feel that you are moving until you look out of the aeroplane's window and see the gradual movement of the land far below you. How can you be going so fast and hardly notice it? A force is a push or a pull acting upon an object as a result of its interaction with another object. Force has the symbol F and is measured in newtons (N). In relation to motion, a force is something that can change an object's motion. A force is not necessarily needed to keep an object moving, but most objects slow down because of the force of friction.

Newton's first law

English scientist Isaac Newton (1642–1727) formulated three laws of motion. In his book the *Philosophiae Naturalis Principia Mathematica*, Newton outlined his laws of motion and his law of universal gravitation. Newton's formulation of his second law of motion and his law of universal gravitation led to nearly all the important advances in physics in the areas of magnetic, electrical and atomic forces for the next 200 years.

The law of inertia

Newton's first law, also known as the law of inertia, has two applications. A stationary object, such as someone sitting on a chair (Figure 7.21), has the force of gravity (its weight force) acting on it to pull it down. It doesn't move because there is another force, equal in magnitude (strength) to the weight force but acting in the opposite direction, pushing up on the object from the surface. Because these two forces are equal in magnitude and opposite in direction, and because they both act on the same object, we say that the object has zero **net force** (or zero resultant force) acting on it. The two forces are balanced. The movement (or lack of movement) will only change if another force is added (such as someone pushing the object). This will cause the forces to become unbalanced.

Figure 7.20 Newton is famous for the story of the apple falling from a tree as he sat in his family orchard. Although the story is fictional, Newton himself is responsible for its creation.

CHALLENGE 7.4A: MAKE AN ACCELEROMETER
GO TO PAGE 224

CHALLENGE 7.4B: HOW DO YOU LIKE YOUR EGGS?
GO TO PAGE 224

Figure 7.21 Zero net force.

> Newton's first law states: 'An object remains at rest or in constant motion in a straight line unless acted on by a net unbalanced force.'

How Newton's first law applies if the object is already moving

Think of any motion you have experienced today, maybe in a car, bus, train or tram, or even on a bike. In constant motion, you sometimes hardly notice you are moving, but if you stop or start suddenly or turn a sharp corner, your body may move unexpectedly.

If you are a passenger in a car and not wearing a seatbelt and the car comes to a very sudden stop, your body will continue moving forwards. This is due to **inertia**. Inertia is the property of matter that keeps it in its existing state of motion (Figure 7.23). The friction of the brakes stops the car; however, they do not stop you. Your seatbelt is the only thing stopping you moving at 60–100 km/h. If you are not wearing your seatbelt, Newton's first law says that you will keep moving at the same speed, through the windscreen and onto the road. The same thing also happens in a bus, train or tram, especially if you are standing up and not holding on to something. The larger the mass of the object, the more inertia it has and the harder it will be to change its motion.

Figure 7.22 Inertia is responsible for vehicles tilting as they turn. Without friction from tyres gripping the road, turning would be nearly impossible.

Figure 7.23 Seatbelts are an inertia device. They are often called 'inertia reel seatbelts'. The aim of a seatbelt is to transfer the force on the car to the passenger wearing the seatbelt so that the person moves with the car. You start moving when the car starts moving and, when wearing your seatbelt, you stop moving when the car stops moving.

Check your learning 7.4

Remember and understand

1. What is meant by the term 'net force'?
2. What happens to a stationary object with zero net force acting on it?
3. What happens to a moving object with zero net force acting on it?
4. What is inertia?

Apply and analyse

5. Give an example of how inertia affects your motion inside a car, bus, tram or train.
6. Why do people lurch backwards in a tram when it starts moving suddenly?

7.5 Force equals mass × acceleration

Newton's second law states: 'The acceleration of an object is directly related to the magnitude and direction of the force acting on the object, and inversely related to the mass of the object: $F = ma$'. This means a heavy object (with a lot of mass) needs a greater force to start moving than a lighter object. Weight is a measure of the gravitational force acting on an object. It is measured in newtons (N).

Figure 7.24 Pedalling provides the thrust force when riding a bike.

Force affects acceleration

If an object experiences an unbalanced net force, the object will change its speed, direction or both. A moving object will speed up (accelerate) if the net force acts on it in the same direction as it is moving. A bike will speed up if you pedal harder to increase the driving force (known as thrust) (Figure 7.24).

When the net force acts in the opposite direction, the moving object will slow down (decelerate) and eventually stop. The brake adds a friction force to a moving bike. This means there is a net force in the opposite direction to bike's movement. This net force causes the bike to change its speed. It decelerates or slows down (Figure 7.25).

Force and mass

Would you need more push force to start moving a car or start moving a bike? A car has a greater mass than a bike; therefore, it needs a greater force to change its motion. A bike, with less mass, needs less force to changes its speed.

We can express this relationship in a simple equation:

$$\text{net force} = \text{mass} \times \text{acceleration}$$

This relationship can also be expressed in a force triangle (Figure 7.26). You need a larger force to accelerate a heavy object from rest than to accelerate a lighter object from rest.

Mass or weight

Newton's second law also connects an object's mass to its weight. We often use the term 'weight' to indicate how much mass something has in kilograms but, strictly speaking, in physics weight is a force not a mass. Weight is the force of gravity acting on an object. Because it is a force, weight is measured in newtons. For example, gravity on the Moon is approximately 1.6 m/s^2 and on the Earth is 10 m/s^2. This means an object with a mass of 100 kg would have a weight of 160 N (100 kg × 1.6 m/s^2) on the Moon, and 1000 N (100 kg × 10 m/s^2) on the Earth.

An object on the Moon will have less weight (N) but the same mass (kg).

Figure 7.25 Braking provides a drag force.

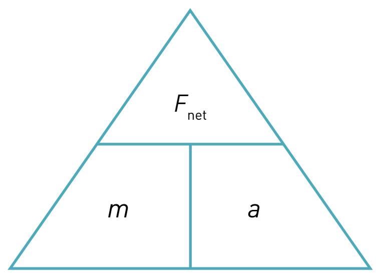


Figure 7.26 The net force equation can be written as a triangle. Cover the quantity you want to calculate and the other two quantities will form the formula.

EXPERIMENT 7.5A: RESULTANT FORCES
GO TO PAGE 225

EXPERIMENT 7.5B: ACCELERATING MASSES
GO TO PAGE 226

Figure 7.27 Cars can accelerate faster than trucks mainly because of their smaller mass. Cars will also decelerate faster. This means a truck will take longer to stop than a car.

Calculating acceleration

When mass is in kilograms (kg) and the acceleration is in metres per second squared (m/s^2), the net force will be in newtons (N). Acceleration and net force are both vectors and always act in the same direction:

$$\text{net force} = \text{mass} \times \text{acceleration}$$
$$F_{net} = m \times a$$

Often, you need to consider all the individual forces acting on an object in order to work out the net force.

Consider the cyclist and bike with a mass of 90 kg shown in Figure 7.29. The forwards-acting thrust force is 400 N and the total drag force from air resistance and friction is 300 N backwards. As a result, the net force is 100 N forwards. This would produce an acceleration of (100 N ÷ 90 kg) 1.11 m/s^2. The cyclist would increase his speed by 1 m/s every second.

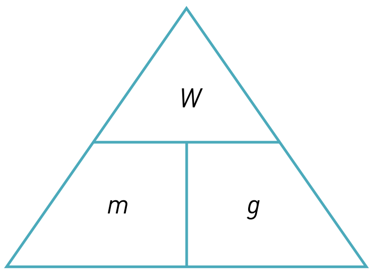


Figure 7.28 Weight is the force of gravity acting on an object's mass. Weight (force) = mass × acceleration due to gravity.

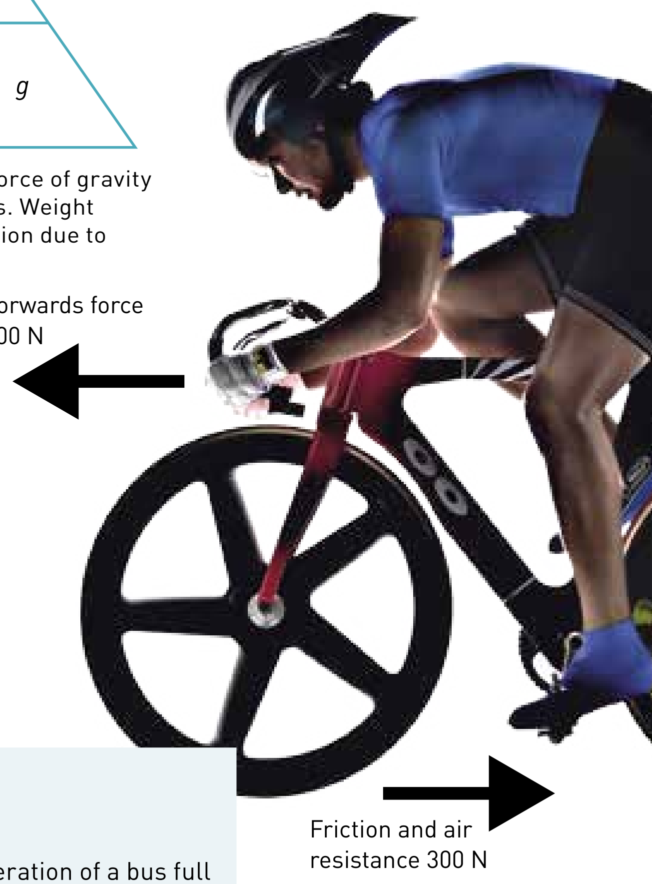


Figure 7.29 Various forces act on a cyclist.

Check your learning 7.5

Remember and understand

1. What is meant by the term 'weight force'?
2. What happens to a moving object if it is acted on by a net force in the same direction as its motion?
3. What happens to a moving object if it is acted on by a net force in the opposite direction to its motion?

Apply and analyse

4. How does the acceleration of a bus full of passengers compare with that of an empty bus for the same net force?
5. Why does a bike slow down on a level road when the rider stops pedalling?
6. A net force causes a mass of 10 kg to accelerate at 2 m/s^2. What is the magnitude of the net force?

7.6 Each action has an equal and opposite reaction

Newton's third law states: 'For every action, there is an equal and opposite reaction on the other object.' Action–reaction pairs always act on different objects and therefore cannot cancel each other out. This reaction is used to propel rockets through space, car wheels along roads and jet planes through the air.

Newton's third law

If you blow up a balloon and let it go, it flies around the room like a crazy rocket. As the air is forced backwards out of the opening, the balloon is propelled forwards by another force. These two forces are equal in magnitude and opposite in direction. They form an action–reaction pair and obey Newton's third law. The action force in this example is the rubber of the balloon contracting and pushing the air backwards. The reaction force is the force of the air rushing out, pushing forwards on the balloon.

Action and reaction pairs always act on different objects. When you lean against a wall, you exert a force on the wall. The wall exerts a force on you (you can feel it pushing against your hands). Because these two forces act on different objects (you and the wall), they cannot be described as being balanced or cancelling each other out. A net force is balanced or zero when all the forces acting on a *single object* are equal and opposite. Action–reaction pairs can never cancel under any circumstances because the two forces act on different objects.

When an insect hits a car windscreen, the action on the windscreen is equal and opposite to the reaction on the insect. The insect is much smaller, so its mass is less able to withstand the deceleration.

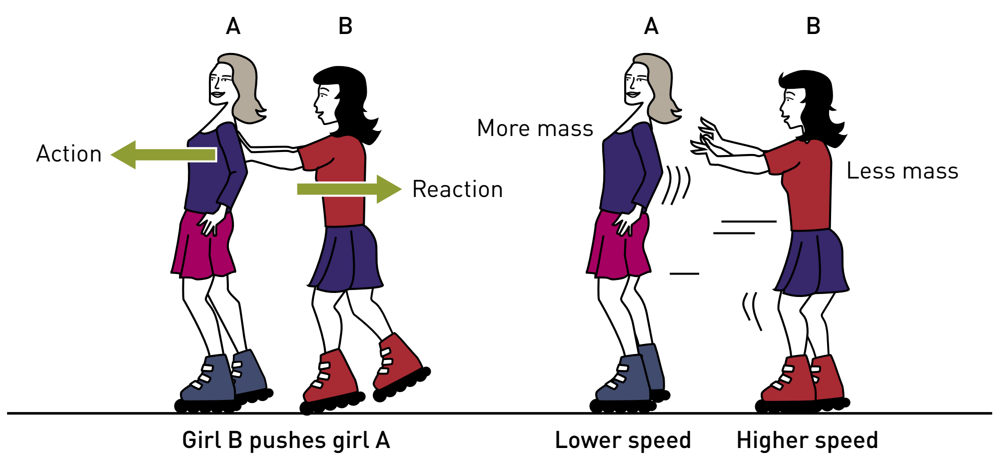


Figure 7.30 Different masses have different accelerations and reach different speeds even though the forces shown by the arrows are equal in size.

EXPERIMENT 7.6: NEWTON'S ROCKET
GO TO PAGE 227

The motion of a girl on roller blades pushing off from another girl (Figure 7.30) works in a similar manner. The two girls experience an identical but opposite force. Newton's second law tells us that smaller masses have higher accelerations for the same force. So, if the two girls have different masses, the lighter girl will have a higher acceleration and will reach a higher speed while the force is acting.

Rockets, missiles and jet engines work on the action–reaction principle. For many years, it was thought that rocket ships would not be able to accelerate in space as there was very little air for the rocket to push against. However, rocket fuel undergoes a combustion reaction, producing exhaust gases. These gases are forced out of the back of the rocket, producing an opposite and equal reaction on the rocket. This moves the rocket forwards.

Figure 7.31 The rocket pushes exhaust gases back. As a result the rocket is propelled forwards.

Check your learning 7.6

Apply and analyse

1. A person pushes forwards on an object with a force of 30 N. What reaction force acts on the person?
2. A boy of weight 500 N sits on a chair. What reaction force acts on the boy?
3. In space, an astronaut pushes on another astronaut with a force of 80 N. What is the reaction force in this case? Why might the second astronaut have a higher acceleration than the first astronaut?
4. Identify the action–reaction pair when a sprinter uses a set of starting blocks for the start of a sprint race.
5. Identify the action–reaction pair when a softball player hits a home run.

7.7 Momentum is conserved in a collision

Momentum is the product of the mass and velocity of an object.
The law of conservation of momentum states that in an isolated system, the total momentum does not change during a collision.

Modern cars are fitted with many safety devices, but arguably the most important are the airbags that deploy in the event of a crash. Sensors inside the car act like mini accelerometers and when they detect rapid deceleration, the airbag system is triggered. These innovations are the result of the scientific understanding of movement and, more importantly, collisions. All collisions involve force, mass and momentum, and these quantities link together to provide the laws of motion as we know them.

Momentum

All moving objects possess **momentum**. Momentum is not a form of energy, although the faster an object travels, the more momentum it has. A cricket ball is harder to stop than a tennis ball travelling at the same speed. This is because the cricket ball has more mass than the tennis ball. So, objects with more mass have more momentum. The formula for calculating momentum is:

$$\text{momentum} = \text{mass} \times \text{velocity}$$

$$p = m \times v$$

where mass is in kilograms (kg), velocity is in metres per second (m/s), and momentum is in kilogram metres per second (kg m/s).

This relationship can also be expressed in a momentum triangle (Figure 7.32).

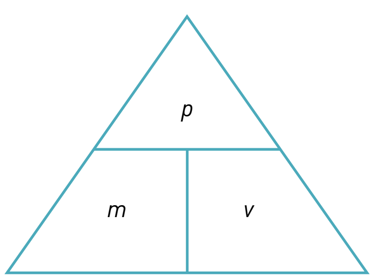


Figure 7.32 The momentum triangle. Cover the quantity you want to calculate and the other two quantities will form the formula.

In an isolated system, momentum is passed from one object to another in a collision but the total momentum of the system is conserved, or remains constant. This means the initial momentum before the crash is equal to the final momentum of all objects after the crash. This is known as the **law of conservation of momentum** and is similar to the law of conservation of energy.

The isolated system referred to in the law of conservation of momentum is the set of objects that interact in the collision. In the case of Newton's cradle (Figure 7.33), this would be the two spheres that collide. Because velocity is a vector, momentum is also a vector quantity. We can indicate opposite directions in a collision as positive and negative.

To stop a moving object, a force is used to reduce its momentum. In a car crash, a large force stops the car in a short time. If the brakes are applied slowly, a smaller force is used over a long time. In both examples, the force exerted on the car is related to the initial momentum of the car. The average force involved in a collision equals the change in momentum divided by the time it takes for the collision to occur.

Figure 7.33 Newton's cradle clearly demonstrates how momentum can be passed from one object to another.

EXPERIMENT 7.7: COLLIDING TROLLEYS
GO TO PAGE 228

Figure 7.35 represents a relatively safe head-on collision between two dodgem cars. If we take movement to the right as positive, the initial momentum (p) of the green car is given by mass (m) multiplied by initial velocity (u):

$$\begin{aligned} p &= m \times u \\ &= 701 \times 0.8 \\ &= 561 \text{ kg m/s} \end{aligned}$$

The initial momentum of the blue car is:

$$\begin{aligned} p &= m \times u \\ &= 660 \times 0.7 \\ &= 462 \text{ kg m/s} \end{aligned}$$

Because the cars are moving in opposite directions, the vector quantity of momentum must reflect this. Movement to the right becomes positive and movement to the left becomes negative. Therefore, the total initial momentum of the two cars is $561 - 462 = 99$ kg m/s to the right.

The final momentum of the blue car is:

$$\begin{aligned} p &= m \times v \\ &= 660 \times 0.15 \\ &= 99 \text{ kg m/s to the right} \end{aligned}$$

The final momentum of the green car is zero because it stops. Therefore, the total final momentum is 99 kg m/s to the right.

This shows that there is no change in the total momentum for the isolated system of the two dodgem cars and their drivers during the collision.

Figure 7.34 The rapid change in momentum as a result of a car crash can be seen in the crushed panels of this car.

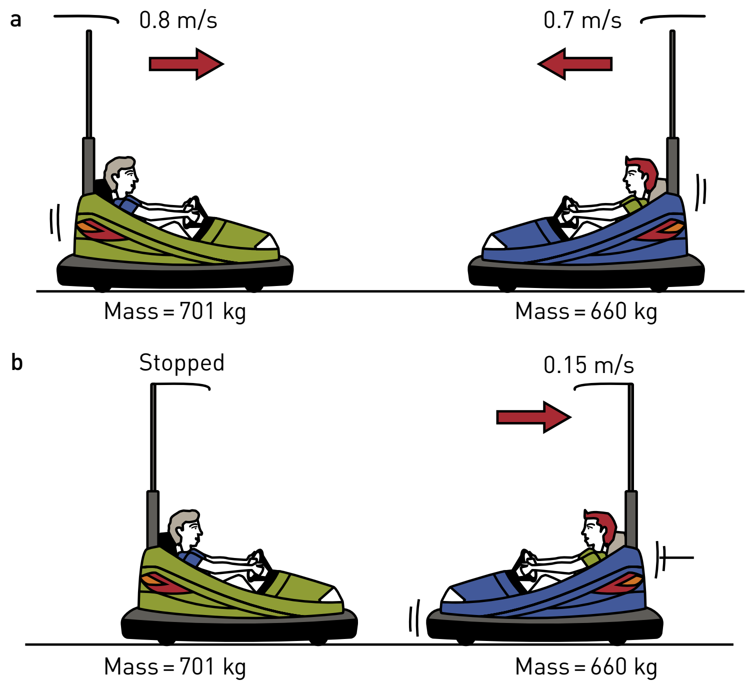


Figure 7.35 (a) Before the collision. (b) After the collision.

Check your learning 7.7

Remember and understand

1 What are the units of momentum?
2 What is the law of conservation of momentum?

Apply and analyse

3 Use the momentum triangle to write the three different formulas.
4 Is it harder to stop a cricket ball or a tennis ball travelling at the same velocity? Why?
5 Is it harder to stop a fast-moving tennis ball or a slow-moving tennis ball? Why?
6 If a 600 kg golf cart is travelling at 0.8 m/s, what is its momentum?

7.8 Work occurs when an object is moved or rearranged. Energy can be calculated

Work is a measure of how much energy has been transferred into moving or rearranging an object. If an object is not moved by a force, then no work has been done. Kinetic energy is a measure of how much movement energy an object has. This is affected by the object's speed and mass. Gravitational potential energy is a measure of how much energy is stored in an object because of its height above the ground. This is also affected by the mass of the object. Elastic potential energy is the energy stored in an object because of its deformation.

Work

In a car crash, the crumple zones of a car are designed to absorb energy by crumpling. In scientific terms, we say that work is done. **Work** happens whenever things are moved or rearranged by a force. The larger the force acting, the greater the work done. The longer the distance over which the force acts, the greater the work done. Hence, the amount of work done depends on the size of the force and the distance (see Figure 7.36):

$$\text{work} = \text{force applied} \times \text{distance moved}$$

$$W = F \times d$$

Work and energy are scalar quantities, so no direction is needed. If you apply a force to an object and it doesn't move, no work is done.

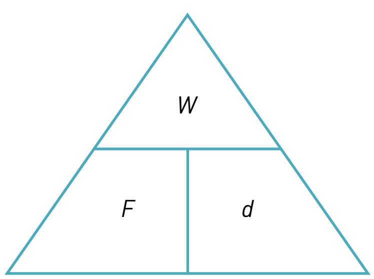


Figure 7.36 The work triangle. Cover the quantity you want to calculate and the other two quantities will form the formula.

When a force is applied to an object and it moves, the object will gain (kinetic) energy. Therefore, work is a measure of how much energy has been transferred from one object to another.

If the force is measured in newtons (N) and the distance is measured in metres (m), the work done will be in units called joules (J). For example, when 1 N of force is used to move an object 1 m, the amount of work done is 1 J.

Kinetic energy

Motion is needed for cars to crash. The energy of motion is called **kinetic energy** (KE). The larger the mass of an object, the greater its kinetic energy. In addition, the faster an object is travelling, the greater its kinetic energy. Kinetic energy depends on the speed of the object, squared:

$$\text{kinetic energy} = \frac{1}{2} \times \text{mass} \times \text{speed squared}$$

$$\text{KE} = \frac{1}{2} \times m \times v^2$$

where mass is in kilograms (kg), speed is in metres per second (m/s), and KE is in joules (J).

EXPERIMENT 7.8: WHAT IF AN ELASTIC BAND WAS STRETCHED FURTHER?
GO TO PAGE 229

Figure 7.37 The gravitational potential energy of a roller coaster is transformed into kinetic energy.

Figure 7.38 When the ball hits the ground, the ball becomes deformed transforming the kinetic energy into elastic potential energy.

When a car driver presses on the brake pedal, all the kinetic energy of the car is dissipated (released) by the brakes as heat. In a car crash, the kinetic energy is dissipated much quicker, mainly as work as the car crumples and deforms.

Gravitational potential energy

If we lift an object to a height, we use energy and the object gains **gravitational potential energy** (GPE). The larger the mass and the height, the more energy we use and the more gravitational potential energy the object gains:

Gravitational potential energy = mass × gravity × height

$$\text{GPE} = m \times g \times h$$

where mass is in kilograms (kg), height is in metres (m) and GPE is in joules (J). Gravity has its normal value of 9.8 or 10 m/s^2.

Elastic potential energy

Bouncing a ball is a collision – with the ground (Figure 7.38). It involves gravitational potential energy, kinetic energy and **elastic potential energy** (EPE), plus usually a small amount of sound and heat energy. As the ball hits the ground, it compresses and stores elastic energy. This energy transforms to kinetic energy when the ball expands again and is propelled upwards into the air. A 'flat' ball cannot transform this energy, so it doesn't bounce.

elastic potential energy = $\frac{1}{2}$ × spring constant × extension (or compression) squared

$$\text{EPE} = \frac{1}{2} \times k \times x^2$$

where k is the spring constant (a measure of how 'stiff' the object is) in newtons per metre (N/m), x is the extension (or compression) in metres (m) and EPE is in joules (J).

Check your learning 7.8

Remember and understand

1 When is the scientific term 'work' done?

2 Use the work triangle to write the three different formulas.

Apply and analyse

3 How much work is done if a force of 200 N moves an object 6 m?

4 How much work is done if a force of 400 N is applied to a heavy object and it doesn't move?

5 How is the kinetic energy of an object affected if its mass decreases and the other variables remain constant?

6 How is the gravitational potential energy of an object affected if its height increases and the other variables remain constant?

7 How is the elastic potential energy of an object affected if its stiffness increases and the other variables remain constant?

7.9 Energy is always conserved

*

The law of conservation of energy states that energy cannot be created or destroyed. This means that any energy that is transferred Aato an object can be released. Waste energy in the form of heat and sound energy can be formed in the transformation. The efficiency of the energy transformation can be calculated.

Whenever energy is converted from one form into other forms, the total energy of the system remains constant because extra energy cannot be created, nor can energy be destroyed. This is called the **law of conservation of energy**.

This is most obvious when you jump on a trampoline (Figure 7.39). When you are high above the trampoline, you have gravitational potential energy. As you start to move down, you gain velocity and therefore kinetic energy. The closer to the ground you get, the less gravitational potential energy and the more kinetic energy you have. Just before you touch the trampoline, you are travelling at your fastest velocity. As soon as you start stretching the trampoline, you start slowing down. Your kinetic energy is being transformed into elastic potential energy in the trampoline. Eventually you will stop moving and the trampoline will be completely stretched. All the kinetic energy has been transformed into elastic potential energy. Eventually the elastic potential energy is transformed back into kinetic energy and gravitational potential energy, and you will start moving up into the air again.

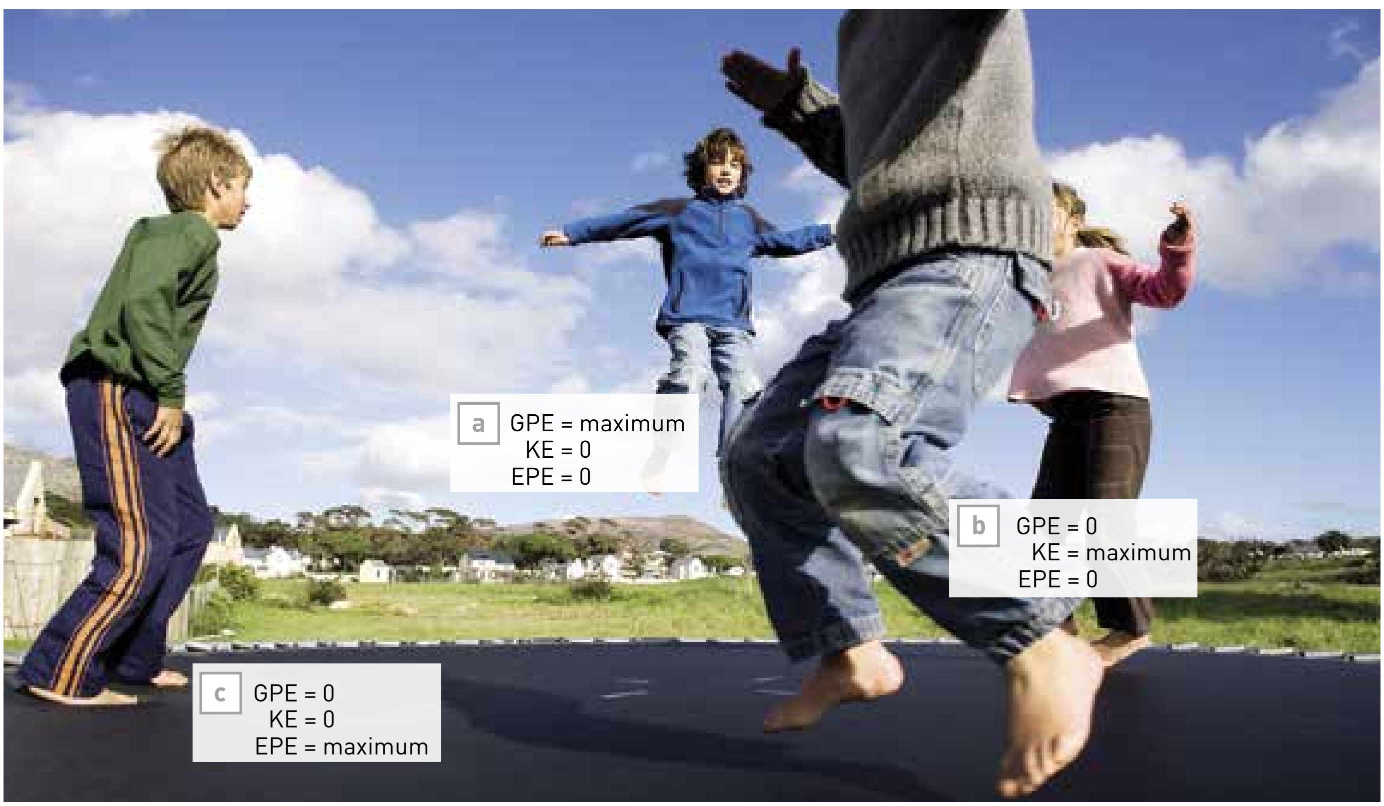
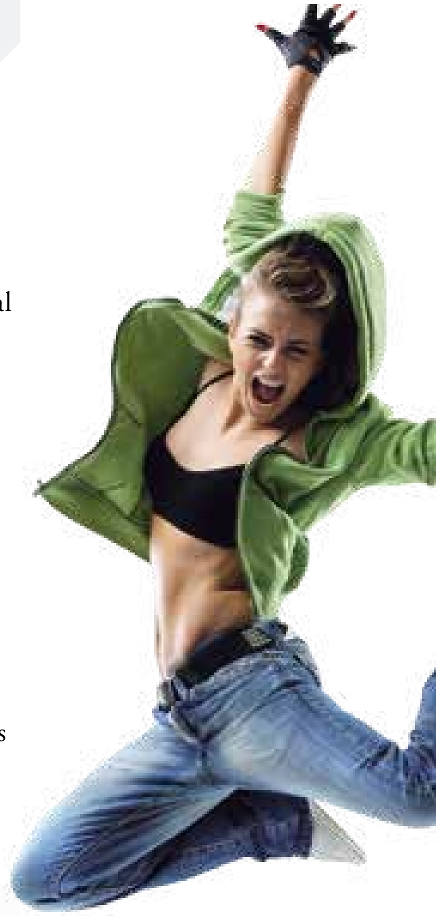


Figure 7.39 Although the individual energy quantities vary between the highest point (a), through position (b) to the lowest position (c), the total energy of the 'system' remains constant.

CHALLENGE 7.9: CONSERVATION IN ACTION
GO TO PAGE 230



Theoretically, the total amount of energy is constant when you jump on a trampoline. In reality, there may be a small amount of heat energy produced as you fall due to air resistance. This 'loss' of energy is not really a loss, just a transfer of energy to a non-usable form. The efficiency can be calculated by comparing how high above the trampoline you started, and the height you reached on the rebound (usable final energy):

energy efficiency = amount of usable final energy ÷ amount of initial energy × 100

Any difference in height is a result of heat or sound energy.

Pendulums

A pendulum is a mass that is attached by a string to a pivot point. When the mass is drawn upwards, it gains gravitational potential energy. When the mass is let go, the force of gravity pulls it back to its original position, converting the gravitational potential energy to kinetic energy. The momentum built up by the moving mass, causes the mass to then swing in the opposite direction. This means all the kinetic energy is converted back into gravitational potential energy. However, pendulums (like a swing in a playground (Figure 7.40)) are a good example of how energy efficiency can be measured. Some kinetic energy is always lost as waste energy, when it is transformed to heat (and sometimes sound). This is evident when the pendulum does not quite reach the height at which it started.

Figure 7.40 A swing will not reach its original height because it loses energy as heat and sound energy.

Check your learning 7.9

Remember and understand

1 Explain the law of conservation of energy, using an example of your own.

2 What is waste energy?

Apply and analyse

3 Some people claim energy is lost. Do you agree? Justify your answer using the law of conservation of energy.

4 Describe the conservation of energy that occurs when you use a slinky.

5 The following statements are incorrect. Rewrite them to make them correct.

a The energy efficiency of all systems is always 100%.

b The law of conservation of energy doesn't always apply.

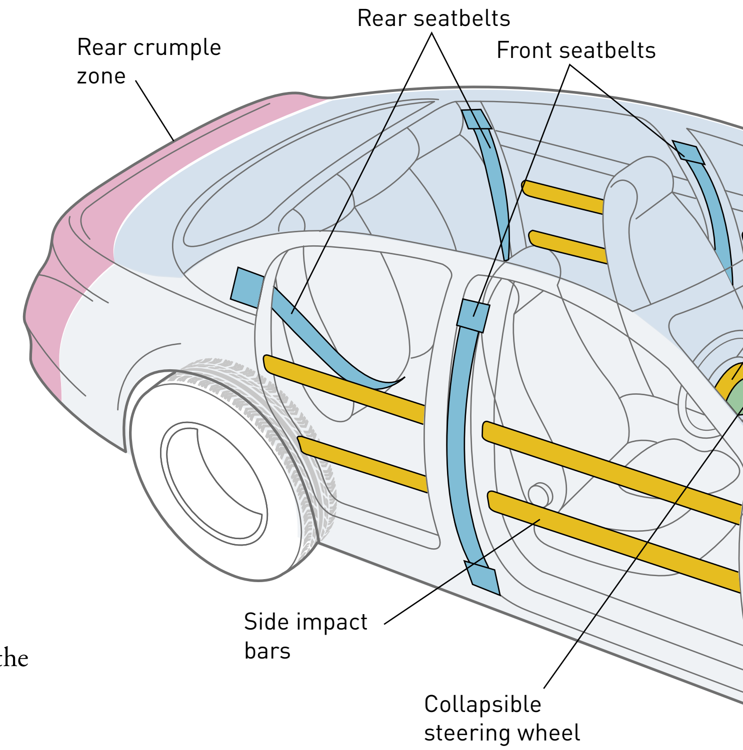
c Pendulums always return to their original height.

d A roller coaster rolling down a ramp will stop at the bottom of the ramp.

//SCIENCE AS A HUMAN ENDEAVOUR//

7.10 Car safety features require an understanding of Newton's laws and momentum

Many cars have a series of safety features that ensure the survival of passengers. These structures include flexible seatbelts, child safety restraints, airbags and crumple zones. The safety features are designed with an understanding of Newton's three laws of motion and momentum.



Seatbelts

The need for seatbelts is illustrated by Newton's first law (an object in constant motion will remain in motion until acted on by a net unbalanced force). When a car is travelling at 60 km/h, the passengers in the car are also travelling at 60 km/h. If the brakes or an accident stop the car suddenly, the passengers will keep moving at 60 km/h until something stops them. This is usually the seatbelt.

Seatbelt flexibility

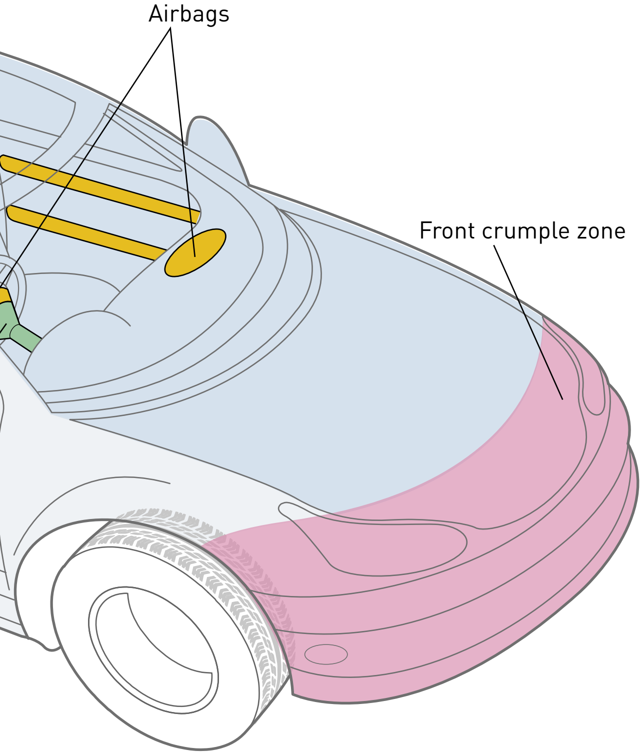
A seatbelt is usually made out of a slightly flexible material. A person travelling in a car has momentum. When the car stops suddenly, there is a rapid decrease in momentum over a short time. The rapid deceleration exerts a force on the passenger that is proportional to their mass (Newton's second law). The quicker the car stops and the greater the mass of the passenger, the larger the force experienced ($F = ma$). A seatbelt that flexes provides more time for the passenger to stop. This decreases the deceleration and lessens the force they experience. Therefore a flexible seatbelt will do less damage (bruising) than a rigid seatbelt.

Child safety seats

In Australia, before the introduction of laws for the compulsory wearing of seatbelts in 1970, many children were held on their parent's laps when travelling in the car. Many parents were convinced that they would be able to prevent the child from being flung from the car in an accident. However, many parents failed to take into account the speed at which they and the child would be moving. The force of a child crashing at 50 km/h is equivalent to 30–60 times their body weight (depending on how quickly the car stops). This is more than most adults can hold. In 1978, it became compulsory for all children to wear seatbelts in moving vehicles. Today, all children under the age of 8 years must wear specially designed child restraints.

Rear-facing child restraints

Most young babies are placed in rear-facing child restraints. This is because in an accident, the child will continue moving forwards until the child restraint stops them (Newton's first law). A young baby does not have strong enough head and neck muscles to tolerate the forces from the rapid deceleration and therefore must be supported along the length of their back.



Air bags

In an accident, something needs to slow the driver and passengers when the car comes to a stop. If the driver is not wearing a seatbelt, they would hit the steering wheel. This action on the steering wheel would provide a reaction on the driver (Newton's third law). An airbag is designed to rapidly inflate with nitrogen gas during a car accident. The chemical reaction that produces the nitrogen gas occurs in as little as 20–30 milliseconds. An airbag has small holes or vents to let the gas escape. Without these holes, the airbag would become as rigid as the steering wheel and therefore cause damage when the driver hit it. Instead, the airbag is designed to increase the length of time the driver has to decelerate, lessening the force exerted on them by the steering wheel.

Crumple zones

A 1670 kg car travelling at 60 km/h (17 m/s) has a momentum of 28 390 kg m/s. If the car stops in 1 second, this momentum becomes 28 390 N of force exerted on the car and passengers. If the car takes 2 seconds to stop, the force of the passengers becomes 14 196 N. The crumple zone is an area at the front or rear of the car that is designed to crush in an accident, giving the car more time to decelerate. This then reduces the force experienced by the passengers.

Extend your understanding 7.10

1. Which of Newton's laws are used in the design of seatbelts? Explain your answer.
2. Which has more momentum; a 5000 kg car travelling at 40 km/h, a 20 000 kg truck travelling at 2 km/h or a 80 kg minibike travelling at 80 km/h? Provide working out to support your answer.
3. Some early kombi vans had no crumple zone. Instead, drivers were encouraged to store their spare tyre at the front of the car. Use Newton's laws to suggest a possible reason for this advice.
4. Australasia's New Car Assessment Program (ANCAP) is an independent vehicle safety advocate that tests new cars and advises the public on the safety of their cars. Research what features cars need to have to achieve a five-star rating. Choose one of these features and apply Newton's laws to explain why this feature increases the safety of the passengers.

Remember and understand

1 Match each word in the left column with its correct meaning in the right column.

vector	speed of an object at a moment in time
average velocity	measures how an object's speed changes
average speed	slope of a graph
acceleration	graph where speed is plotted against time
distance	quantity that has magnitude and direction
instantaneous speed	calculated by dividing distance by time
gradient	measures how far an object has travelled
speed–time graph	calculated by dividing displacement by time

2 What happens to an object's speed if it travels with zero acceleration?

3 What happens to an object's speed if it travels with constant deceleration?

4 Which of the following are true and which are false?

- A A force will only change an object's speed.
- B A force is always needed to keep an object in motion.
- C The quantity of weight is measured in kilograms.
- D A force has magnitude and direction, making it a vector.
- E Acceleration increases if the net force increases and the mass is kept constant.
- F A stationary object can have several forces acting on it.
- G Mass is a measure of how much space an object occupies.

5 Show, using the formula for kinetic energy, that if speed is doubled the energy of a car crash would be four times as high.

Apply and analyse

6 A car is driven along a straight road. Starting from rest, it takes 10 seconds of steady acceleration for the car to reach a speed of 20 m/s. The car then cruises for 60 seconds at 20 m/s, before slowing down to a halt over a period of 30 seconds.

- a What is the maximum speed of the car in km/h?
- b Plot a speed–time graph for the car using SI units.
- c Use the graph to calculate the distance moved in metres and then in kilometres.

7 Figure 7.41 shows a rear-end car crash between two dodgem cars. Before the collision, the green car had a velocity of 2.2 m/s and a mass of 140 kg. The blue car had a velocity of 1.7 m/s and a mass of 160 kg.

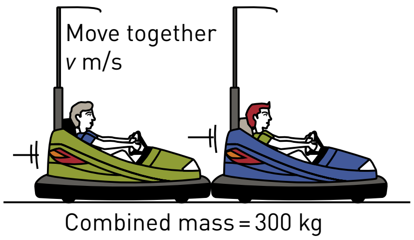


Figure 7.41

- a Calculate the momentum of each of the two dodgem cars before the collision.
- b Calculate the total momentum of the two dodgem cars before the collision.
- c Calculate the velocity of the two dodgem cars after the collision.

Evaluate and create

8 On a wet Monday morning, a school bus that has to travel 24 km leaves its starting place at 7.35 am and only manages an average speed of 36 km/h on its trip to school. There is a clear section on the highway when the bus has a speed of 74 km/h. The bus then does various runs during the day and arrives back at the school in time to depart at 3.45 pm. It arrived back exactly at its starting place at 4.25 pm.

- a What is the displacement of the bus between 7.35 am and 4.25 pm?
- b At what time will the bus arrive at school?
- c What is the average speed of the bus?
- d The bus's average speed on the way to school is 36 km/h, but on one stretch the bus moves at 74 km/h. Use this data to explain the difference between 'average speed' and 'instantaneous speed'.

9 Renee catches a softball.

a What is the action?

b What does the action do?

c What is the reaction?

d What does the reaction do?

10 What mass object would accelerate at 3.5 m/s^2 under the influence of a net force of 70 N?

11 Calculate the acceleration of a 500 g object under the influence of a net force of 500 N.

Critical and creative thinking

12 Some objects or devices require high accelerations that are many times greater than 9.8 m/s^2, the acceleration due to gravity. Think of an object or device in this category. Does it have an engine or some other propulsion mechanism? What fuel does it use? How does this enable it to achieve such a high acceleration?

13 Design a poster on motion that explains each of Newton's three laws. Give a detailed example that illustrates each law and is not already mentioned in the text.

14 Motion is the result of forces acting in different directions. Describe the forces you believe to be acting when an object is stationary, moving, accelerating and changing direction. Which forces are always acting?

15 Identify the safety features of the car shown in Figure 7.42. Which safety features are missing?

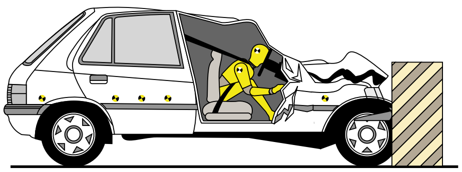


Figure 7.42

Research

16 Choose one of the following topics for a research project. Some questions have been included to help you begin your research. Present your report in a format of your own choosing.

> **Car safety features**
>
> Modern cars may be equipped with electronic stability control (ESC), anti-lock braking systems (ABS), electronic brake distribution (EBD), RVC tachometers, traction control systems (TCS) and park assist. Find out about each of these and other car safety features under development. How do they contribute to the safety of passengers?

> ***g*-forces**
>
> Aircraft pilots flying military jets and those in the Red Bull Air Race commonly experience *g*-forces. A ride at Luna Park is called '*g*-force'. When do pilots experience *g*-forces? What is the human tolerance of *g*-forces and what effect do they have on the body? What other examples are there of theme park rides or situations where people experience *g*-forces?

> **Movement of aircraft**
>
> Aircraft are the second fastest mode of transport, after rockets. Find out about the different types of aircraft and how they move. Explain the interactions between lift, weight, thrust and drag in aircraft movement. What speeds can aircraft attain?

7

acceleration due to gravity
the acceleration of an object due to a planet's gravitational field; on Earth, $g = 9.8$ or $10\ m/s^2$

deceleration
slowing down; also known as negative acceleration

displacement
a vector quantity that measures the change in position of an object and its direction over a certain period of time

elastic potential energy
the energy possessed by stretched or compressed objects

gravitational potential energy
the energy possessed by objects raised to a height in a gravitational field

inertia
the tendency of an object to resist changes in its motion while either at rest or in constant motion

kinetic energy
the energy possessed by moving objects

law of conservation of energy
a scientific law that states the total energy in a system is always constant and cannot be created or destroyed

law of conservation of momentum
a scientific law that states the total momentum in an isolated system does not change during a collision

magnitude
the size or extent of something

momentum
the product of an object's mass and its velocity

net force
the vector sum of all the forces acting on an object; also known as resultant force

speed
the distance travelled per unit of time

vector
a quantity that has size and direction (e.g. velocity, displacement)

velocity
the vector quantity that measures speed in a particular direction

work
occurs whenever an object is moved by a force