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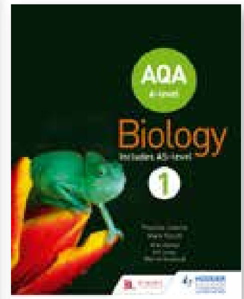

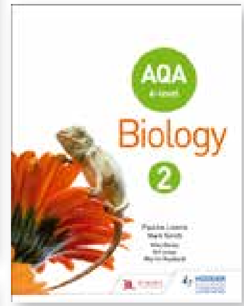

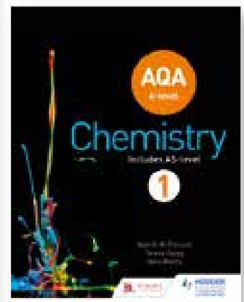

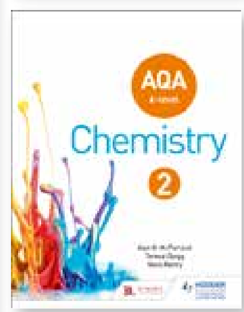

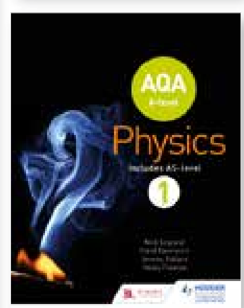

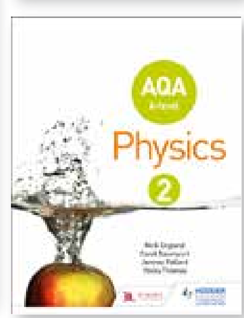

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11 Momentum

PRIOR KNOWLEDGE

- Momentum is defined as mass multiplied by velocity: $p = mv$.
- Momentum is a vector quantity.
- Newton's second law of motion states that resultant force is the mass multiplied by the acceleration: $F = ma$.
- Newton's third law of motion states that to every force there is an equal and opposite force. Such paired forces are of the same type, act along the same line, and act on separate bodies.
- Acceleration is the change of velocity divided by time: $a = \Delta v/\Delta t$
- kinetic energy = $\frac{1}{2}$ mass × (velocity)^2
- The principle of conservation of energy states that energy cannot be created or destroyed, but it can be transferred from one type of energy to another.

TEST YOURSELF ON PRIOR KNOWLEDGE

1 Explain why the definition of momentum shows it must be a vector quantity.

2 Calculate the momentum of a man of mass 80 kg, running with a velocity of 8 m s^{-1}. State the units of momentum.

3 A car experiences a resultant forwards force of 1470 N. It accelerates from a speed of 6 m s^{-1} to 14 m s^{-1} in 4 seconds. Calculate the car's mass.

4 You hold a book with a weight of 2 N in your hand. How big is the equal and opposite force to that weight, and on what body does that force act?

5 A car with mass 1200 kg travelling at a speed of 25 m s^{-1} applies its brakes and comes to a halt.

a) Calculate the kinetic energy which is transferred to other types of energy.

b) Describe the energy transfers in this process.

Introducing momentum

Momentum is a useful quantity in physics, because the amount of momentum in a system always remains the same provided no external forces act on that system. This principle allows us to predict what will happen in a collision or an explosion.

Figure 11.1 An understanding of momentum and energy enables us to explain what is going on here.

Momentum The product of mass and velocity. The unit of momentum is kg m s^{-1}. The symbol p is used for momentum.

$p = mv$

In the example of the exploding firework, chemical potential energy is transferred to thermal energy, light energy and kinetic energy of the exploding fragments. However, during the explosion the momentum remains the same. Momentum is a vector quantity; the momentum of a fragment travelling in one direction is balanced by the momentum of a fragment travelling in the opposite direction. The same laws of physics apply equally to all masses whether they are planets, objects we meet every day, or the sub-atomic particles studied by nuclear physicists.

EXAMPLE

A ball of mass 0.1 kg hits the ground with a velocity of 6 m s^{-1} and sticks to the ground. Calculate its change of momentum.

Using the formula for momentum change:

$$\Delta p = m\Delta v$$

$$= 0.1\,\text{kg} \times 6\,\text{m s}^{-1}$$

$$= 0.6\,\text{kg m s}^{-1}$$

EXAMPLE

A ball of mass 0.1 kg hits the ground with a velocity of 6 m s^{-1} and bounces back with a velocity of 4 m s^{-1}. Calculate its change of momentum.

Using the formula for momentum change, where *mu* is the momentum of the ball when it hits the ground and *mv* is its momentum when it begins to bounce back upwards:

$$\Delta p = mv - mu$$

$$= 0.1\,\text{kg} \times 4\,\text{m s}^{-1} - (-0.1\,\text{kg} \times 6\,\text{m s}^{-1})$$

$$= 1.0\,\text{kg m s}^{-1}$$

In this case the momentum before and the momentum after are in opposite directions so one of them must be defined as a negative quantity; we have defined upwards as positive and downwards as negative.

TIP

When a ball hits a wall with momentum p and bounces back in the opposite direction with momentum $-p$, the change of momentum is $2p$.

Momentum and impulse

Newton's second law can be used to link an applied force to a change of momentum:

$$F = ma$$

Substituting

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

gives

$$F = \frac{m\Delta v}{\Delta t}$$

or

$$F = \frac{\Delta(mv)}{\Delta t}$$

This can be put into words as follows: force equals the rate of change of momentum. This is a more general statement of Newton's second law of motion.

The last equation may also be written in the form:

$$F\Delta t = \Delta(mv)$$

or

$$F\Delta t = mv_2 - mv_1$$

Impulse The product of force and time. The unit of impulse is N s.

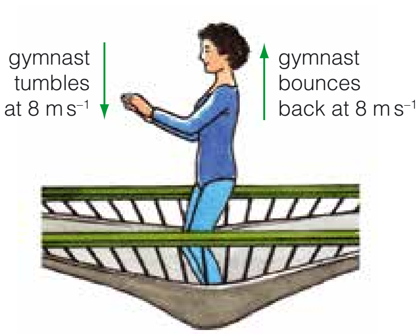
where v_2 is the velocity after a force has been applied and v_1 the velocity before the force was applied. The quantity $F\Delta t$ is called the **impulse**.

TIP

$F\Delta t$ has the unit N s. Make sure you leave a space between N and s, so that your unit does not look like newtons (plural).

Note that momentum can be expressed in kg m s^{-1} or N s.

EXAMPLE



A gymnast is practising her skills on a trampoline.

She lands on the trampoline travelling at 8 m s^{-1} and leaves the trampoline at the same speed. Her mass is 45 kg and she is in contact with the trampoline for 0.6 s. Calculate the average force acting on the gymnast while she is in contact with the trampoline.

$$F = \frac{mv_1 - mv_2}{t}$$

$$= \frac{45\,\text{kg} \times 8\,\text{m s}^{-1} - (45\,\text{kg} \times -8\,\text{m s}^{-1})}{0.6\,\text{s}}$$

$$= 1200\,\text{N}$$

Gymnasts use trampolines to reach and then fall from considerable heights, for example 5 m. If you jumped from 5 m and landed on a hard floor, you would hurt yourself and might even break a bone in your foot, ankle or leg. The equation $F = \Delta(mv)/\Delta t$ helps you to understand why.

When you fall you have an amount of momentum, which is determined by how far you fall. The force on you when you stop moving depends on the time interval, Δt, in which you stop. On the trampoline Δt is long, so the force is small; on the hard floor Δt is short and the force much larger.

Figure 11.3 An impulsive force: the momentum of the tennis ball is changed by a large force acting for a short time.

TEST YOURSELF

1 Use the ideas of impulse and change of momentum to explain the following:
   a) why you bend your legs when you jump from a wall on to the ground
   b) why hockey players wear shin pads to protect their legs
   c) why you move your hands backwards when you catch a fast-moving ball coming towards you.

2 A gymnast jumps from a wall of height 3 m. When she lands, her legs stop her moving in 0.2 s.
   a) Calculate her momentum on landing.
   b) Calculate the force on her legs when she lands.

Car safety

The idea of impulse is vital in designing cars safely. Figure 11.4 shows two force–time graphs for passengers A and B in a high-speed car crash. Marked on the graph is a small area $F\Delta t$; but this is equal to the change in momentum in that time interval, $m\Delta v$.

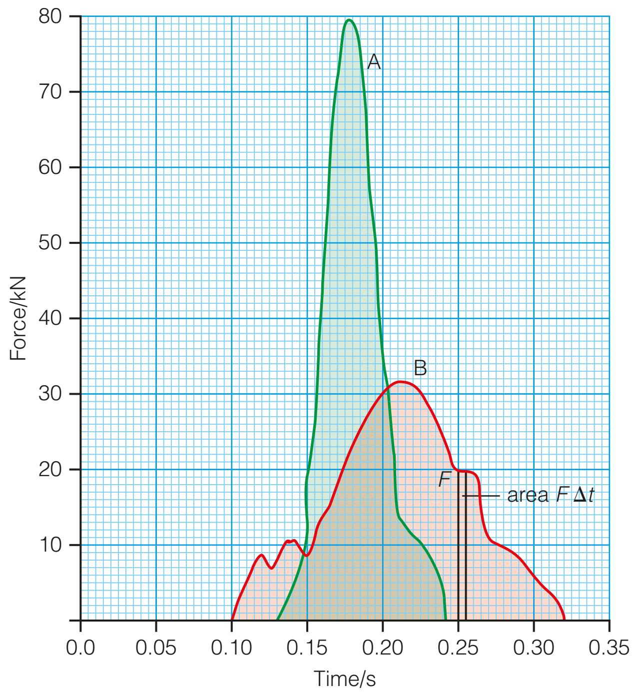


Figure 11.4 Force–time graphs for two passengers in a car crash.

So the total change of momentum of one of the passengers in the crash is the sum of all the small areas: $\sum F\Delta t$. Thus:

change of momentum = area under the force–time graph

The two passengers have different masses, so the areas under each graph are different. However, passenger B was strapped in by his safety belt, and he was stopped in the time it took the crumple zones at the front of the car to buckle. Passenger A, in the back of the car, was not restrained and was stopped as he hit the seat in front of him. He stopped in a shorter time, so the maximum force on him was much greater.

TIP

It is useful to remember that the area under a force–time graph equals the change of momentum.

Figure 11.5 In this test the dummy is protected by an airbag, and the crumple zone at the front of the car allows time for the passengers to slow down.

TEST YOURSELF

3 a) Explain why crumple zones and seat belts are vital safety measures for passengers in cars.

b) If a helicopter crashes it is most likely that the impact will take place on the bottom of the craft. Explain what safety features should be built into the seats in the helicopter.

4 In an impact, a person who experiences an acceleration of 300 $m\,s^{-2}$, of short duration, will receive moderately serious injuries. However, a much larger acceleration is likely to inflict gravely serious injuries.

a) i) Explain why rapid accelerations cause injury.

ii) Explain why injuries are likely to be more severe if a very high acceleration or deceleration acts over a longer period of time.

In the car crash described in Figure 11.4, passenger A has a mass of 82 kg and passenger B a mass of 100 kg.

b) Describe the likely injuries to both passengers A and B.

c) By using the area under graph B, show that the car crashes at a speed of about 35 $m\,s^{-1}$.

5 A karate expert can break a brick by hitting it with the side of his hand.

a) He moves his hand down at a velocity of 12 $m\,s^{-1}$ and the hand bounces back off the brick with a velocity of 4 $m\,s^{-1}$. Calculate the impulse delivered to the brick, if the hand and forearm have a mass of 2.2 kg.

b) The time of contact between the hand and brick is found to be 64 ms. Calculate the average force exerted by the hand on the brick.

c) Calculate the average force exerted by the brick on the man's hand.

ACTIVITY

Investigating varying forces

You can investigate how forces vary with time by using a 'force plate' which is connected to a data logger. Such plates use piezoelectric crystals, which produce a p.d. that depends on the pressure applied to the crystal.

A student investigates his reaction force on the ground in various activities. He uses a force plate and a data logger, which records the changes in force with time.

In his first activity, the student steps on to the plate in a crouching position; then he stands up, before he steps off the plate again. See Figure 11.6.

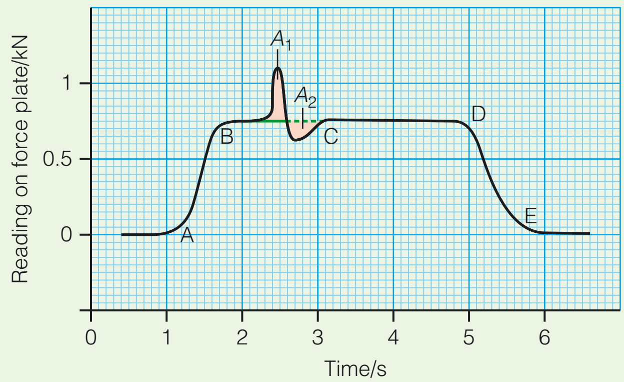


Figure 11.6

Answer the following questions, based on the student's investigation

1 a) Explain what is happening over each of the following times.
AB, BC, CD, DE

b) Explain why the areas A_1 and A_2 on the graph are equal.

c) The student now jumps on to the force plate. Sketch a graph to show how the reaction force changes now.

2 In the next activity the student measures his reaction force on the plate while running on the spot. This is recorded in Figure 11.7.

a) Use the graph to show that the student's change of momentum on each footfall is about 250 kg m s^{-1}.

b) Explain why his upward momentum as he takes off on one foot is 125 kg m s^{-1}.

c) The student's mass is 80 kg. Show that his centre of mass rises by a height of about 12 cm between each stride. (Here you will need to use the equations of motion which you learned in Chapter 10).

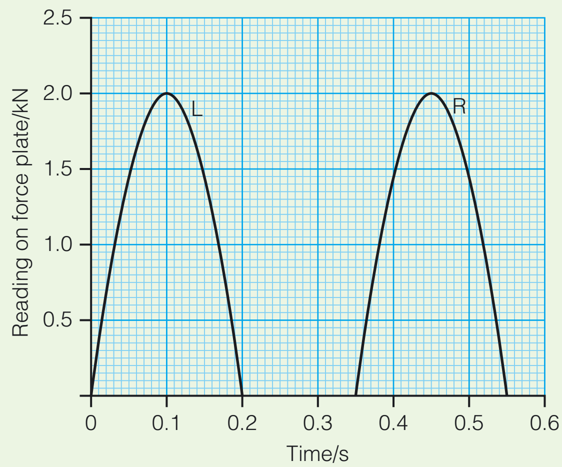


Figure 11.7

d) Sketch a graph to show how the horizontal component of the foot's reaction on the ground varies with time, when the runner is moving at a constant speed.

Conservation of linear momentum

Linear momentum The momentum of an object that moves only in one dimension.

We use the term **linear momentum** when we refer to collisions (or explosions) that take place in one dimension, i.e. along a straight line.

Figure 11.8 shows a demonstration of a small one-dimensional explosion. The head of a match has been wrapped tightly in aluminium foil. A second match is used to heat the foil and the head of the first match, which ignites and explodes inside the foil. The gases produced cause the foil to fly rapidly one way, and the matchstick flies in the opposite direction. (It is necessary to use 'strike-anywhere' matches, the heads of which contain phosphorous. The experiment is safe because the match blows out as it flies through the air, but common-sense safety precautions should be taken – do this in the laboratory, not in a carpeted room at home, and dispose of the matches afterwards.)

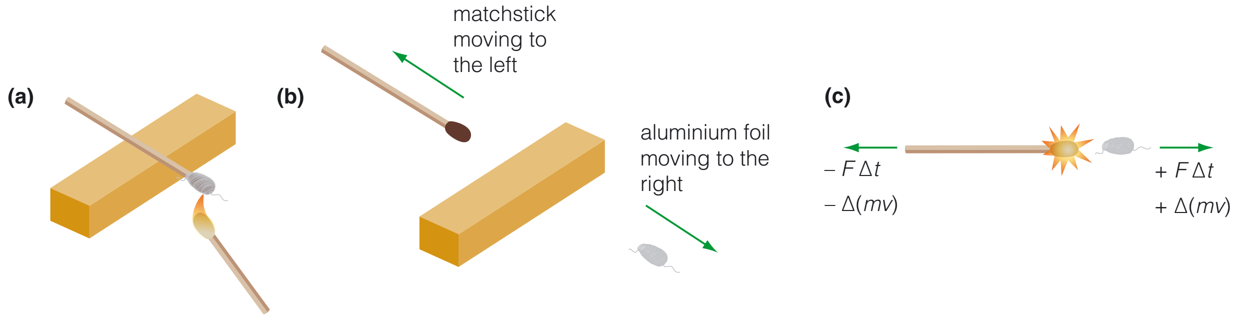


Figure 11.8 A simple experiment that demonstrates the conservation of linear momentum.

In all collisions and explosions, both total energy and momentum are conserved, but kinetic energy is not always conserved.

In this case, the chemical potential energy in the match head is transferred to kinetic energy of the foil and matchstick, and also into thermal, light and sound energy.

As the match head explodes, Newton's third law of motion tells us that both the matchstick and foil experience equal and opposite forces, F. Since the forces act for the same interval of time, Δt, both the matchstick and foil experience equal and opposite impulses, $F\Delta t$.

Since $F\Delta t = \Delta(mv)$, it follows that the foil gains exactly the same positive momentum, as the matchstick gains negative momentum.

We can now do a vector sum to find the total momentum after the explosion (see Figure 11.8c):

$$+\Delta(mv) + [-\Delta(mv)] = 0$$

Conservation The total momentum of two bodies in a collision (or explosion) is the same after the collision (or explosion) as it was before.

So there is **conservation** of momentum: the total momentum of the foil and matchstick was zero before the explosion, and the combined momentum of the foil and matchstick is zero after the explosion.

Collisions on an air track

Collision experiments can be carried out using gliders on linear air tracks. These can demonstrate the conservation of linear momentum. The air blowing out of small holes in the track lifts the gliders so that frictional forces are very small.

TIP
Momentum is always conserved in bodies involved in collisions and explosions. This is the principle of conservation of momentum.

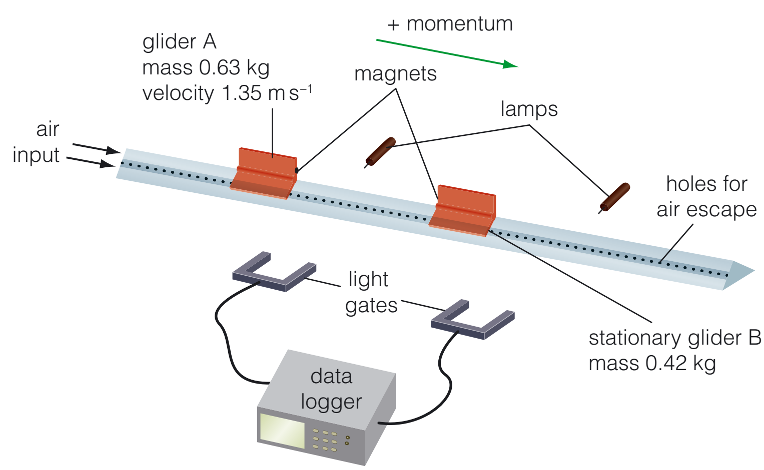


Figure 11.9 A laboratory air track with gliders.

EXAMPLE

In one air-track experiment a moving glider collides with a stationary glider. To get the gliders to stick together, a bit of Blu-Tack can be stuck to each glider at the point of impact. We can use the principle of momentum conservation to predict the combined velocity of the gliders after impact.

In Figure 11.9 we define positive momentum to the right.

$$\text{momentum before} = m_A v_A + m_B v_B$$
$$= 0.63\,\text{kg} \times 1.35\,\text{m}\,\text{s}^{-1} + 0$$
$$= 0.85\,\text{kg}\,\text{m}\,\text{s}^{-1}$$

The two gliders have the same velocity after the collision because they have stuck together.

$$\text{momentum after} = (m_A + m_B)v$$
$$= (0.63\,\text{kg} + 0.42\,\text{kg}) \times v$$
$$= 1.05v\,\text{kg}\,\text{m}\,\text{s}^{-1}$$

So, from conservation of momentum,

$$1.05v\,\text{kg}\,\text{m}\,\text{s}^{-1} = 0.85\,\text{kg}\,\text{m}\,\text{s}^{-1}$$
$$v = 0.81\,\text{m}\,\text{s}^{-1}$$

Both gliders move to the right at $0.81\,\text{m}\,\text{s}^{-1}$. A result such as this can be confirmed by speed measurements using the light gates and data logger.

EXAMPLE

In a second experiment, glider B is pushed to the left with a velocity of $2.7\,\text{m}\,\text{s}^{-1}$ and glider A is pushed to the right with a velocity of $1.5\,\text{m}\,\text{s}^{-1}$. What happens after this collision?

$$\text{momentum before} = m_A v_A + m_B v_B$$
$$= 0.63\,\text{kg} \times 1.5\,\text{m}\,\text{s}^{-1} - 0.42\,\text{kg} \times 2.7\,\text{m}\,\text{s}^{-1}$$
$$= -0.19\,\text{kg}\,\text{m}\,\text{s}^{-1}$$

Note that B has negative momentum, and that the total momentum of both gliders together is negative.

$$\text{momentum after} = (m_A + m_B)v$$

So

$$-0.19\,\text{kg}\,\text{m}\,\text{s}^{-1} = 1.05v\,\text{kg}\,\text{m}\,\text{s}^{-1}$$
$$v = -0.18\,\text{m}\,\text{s}^{-1}$$

So both trolleys move to the left with a velocity of $0.18\,\text{m}\,\text{s}^{-1}$.

TEST YOURSELF

6 A student decides to investigate the dynamics of the exploding match, as in Figure 11.8. Using a data logger she discovers that a match starts to move at $7.1\,m\,s^{-1}$ immediately after the explosion.

a) The mass of the matchstick is 0.15 g and the mass of the aluminium foil is 0.06 g. Calculate the initial speed of the foil.

b) Calculate the kinetic energy of

i) the aluminium foil

ii) the matchstick.

c) Calculate the minimum chemical potential energy stored in the match head before it explodes. Explain why the stored energy is likely to be greater than your answer.

d) The student discovers that the matchstick travels further than the foil. She expected the foil to travel further. What factors affect the distance travelled by the matchstick and the foil? (You may need to refer back to the work on drag in Chapter 10).

7 This question refers to the collisions between the two gliders on the air track, Figure 11.9. In each of the following cases, calculate the velocity of the gliders after they have collided.

a) Before the collision, glider A is moving to the right at $2.0\,m\,s^{-1}$ and glider B is moving to the right at $1.0\,m\,s^{-1}$.

b) Before the collision, glider A is stationary and glider B is moving to the left at $2.0\,m\,s^{-1}$.

c) Before the collision, glider A is moving to the right at $1.0\,m\,s^{-1}$ and glider B is moving to the left at $1.5\,m\,s^{-1}$.

8 A student now investigates some more collisions between gliders on an air track, but he makes changes to the apparatus. He replaces the Blu-Tack in Figure 11.9 with two magnets, which repel each other. Now when a collision takes place, the two gliders move independently after the collision.

Calculate the velocity of glider B after each of the following collisions.

a) Before the collision, glider A is moving to the right at $2.0\,m\,s^{-1}$ and glider B is moving to the right at $1.0\,m\,s^{-1}$. After the collision, glider B is moving at $1.2\,m\,s^{-1}$ to the right.

b) Before the collision, glider A is stationary and glider B is moving to the left at $2.0\,m\,s^{-1}$. After the collision, glider A is moving at $1.6\,m\,s^{-1}$ to the left.

c) Before the collision, glider A is moving to the right at $1.0\,m\,s^{-1}$ and glider B is moving to the left at $1.5\,m\,s^{-1}$. After the collision glider A is moving at $1.0\,m\,s^{-1}$ to the left.

Momentum and energy

In collisions between two or more bodies, both momentum and energy are conserved. However, the total kinetic energy of the bodies does not always stay the same, because the kinetic energy can be transferred to other types of energy. Collisions in which the kinetic energy of the particles is the same after the collision as it was before are described as **elastic**. Collisions in which kinetic energy is transferred to other forms of energy are described as **inelastic**. Most collisions on a large scale are inelastic, but collisions between atomic particles are often elastic.

Elastic Collisions in which kinetic energy is conserved.

Inelastic Collisions in which kinetic energy is not conserved. Some or all of the kinetic energy is transferred to heat or other types of energy.

Some useful equations

Although momentum and kinetic energy are very different quantities, they are linked by some useful equations.

Momentum is given the symbol p.

$$p = mv$$

Kinetic energy is given the symbol E_k.

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

But E_k can also be written in this form:

$$E_k = \frac{m^2v^2}{2m}$$

giving

$$E_k = \frac{p^2}{2m}$$

It is important to remember that momentum is a vector quantity and kinetic energy is a scalar quantity. We give momentum a direction: for example, $+p$ to the right and $-p$ to the left. A vehicle travelling with momentum p has as much kinetic energy when travelling to the right as it does to the left.

To the right:

$$E_k = \frac{(+p)^2}{2m} = \frac{p^2}{2m}$$

To the left:

$$E_k = \frac{(-p)^2}{2m} = \frac{p^2}{2m}$$

When a vector is squared, it becomes a scalar quantity.

TEST YOURSELF

To answer Questions 9 and 10, you may need to refer back to definitions from Chapters 6 and 4.

9 Define the volt.

10 a) Calculate the speed of an electron that has been accelerated through a potential difference of 5000 V.

b) Which has the larger momentum, a proton that has been accelerated through a p.d. of 20 kV, or an electron that has been accelerated through 20 kV? ($m_p = 1.67 \times 10^{-27}$ kg; $m_e = 9.1 \times 10^{-31}$ kg; $e = 1.6 \times 10^{-19}$ C)

Elastic and inelastic collisions

Figure 11.10 shows an unfortunate situation: a van just fails to stop in a line of traffic and it hits a stationary car, and they move forwards together. Is this an elastic or inelastic collision? Without doing any calculations, we know that this is an inelastic collision because the crash transfers kinetic energy to other forms – the car is dented, so work must be done to deform the metal, and there is noise. However, we can calculate the kinetic energy transferred as shown in the Example.

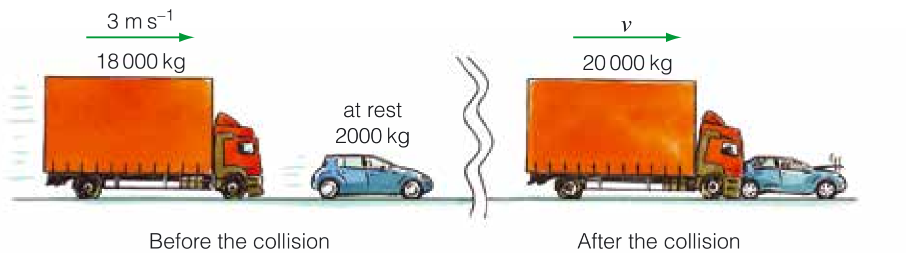


Figure 11.10 An inelastic collision.

EXAMPLE

In Figure 11.10 the momentum before the crash is equal to the momentum after the crash.

$$18\,000\,\text{kg} \times 3\,\text{m s}^{-1} + 0 = 20\,000\,\text{kg} \times v$$

$$v = 2.7\,\text{m s}^{-1}$$

Before the crash the kinetic energy of the van was:

$$E_k = \tfrac{1}{2} m_v v_v^2$$

$$= \tfrac{1}{2} \times 18\,000\,\text{kg} \times (3\,\text{m s}^{-1})^2$$

$$= 81\,\text{kJ}$$

After the collision the kinetic energy of the van and car together is:

$$E_k = \tfrac{1}{2}(m_v + m_c)v^2$$

$$= \tfrac{1}{2} \times 20\,000\,\text{kg} \times (2.7\,\text{m s}^{-1})^2$$

$$= 73\,\text{kJ}$$

So about 8 kJ of kinetic energy is transferred to other forms of energy.

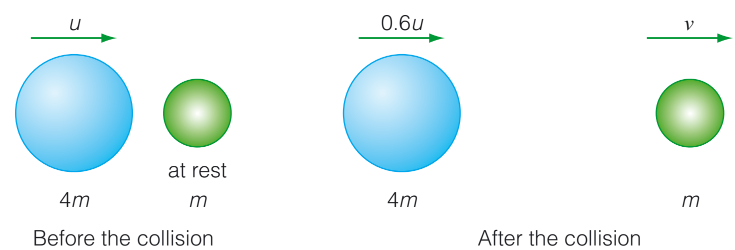
In the world of atomic particles, collisions can be elastic because, for example, electrostatic charges can repel two atoms or nuclei without a transfer of kinetic energy to other forms.

TIP

In elastic collisions, kinetic energy is conserved. In inelastic collisions energy is transferred to other forms.

EXAMPLE

A helium nucleus of mass $4m$ collides head on with a stationary proton of mass m. Use the information in the diagram to show that this is an elastic collision.



The velocity of the proton can be calculated as follows.

The momentum before the collision equals the momentum after the collision.

$$4mu + 0 = 4m \times 0.6u + mv$$

$$mv = 4mu - 2.4mu$$

$$v = 1.6u$$

The total kinetic energy before the collision was:

$$E_k = \tfrac{1}{2} \times 4mu^2$$

$$= 2mu^2$$

The total kinetic energy after the collision was:

$$E_k = \tfrac{1}{2} \times 4m(0.6u)^2 + \tfrac{1}{2} \times m(1.6u)^2$$

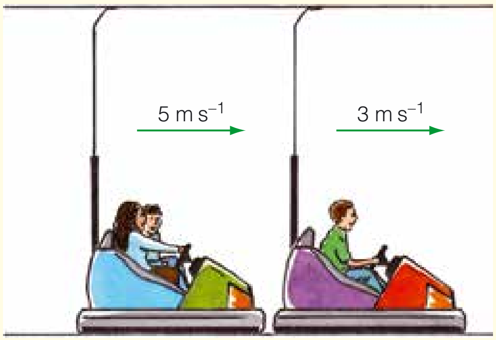
$$= 2m(0.36u^2) + \tfrac{1}{2}m(2.56u^2) = 0.72mu^2 + 1.28mu^2$$

$$= 2mu^2$$

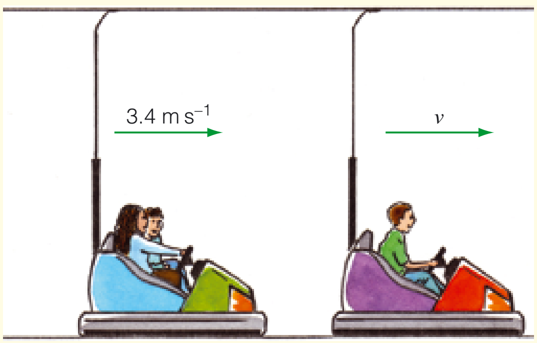
So the total kinetic energy is conserved in this collision. It is a useful rule to know that in an elastic collision the relative speeds of the two particles is the same before and after the collision.

TEST YOURSELF

11 Look at the diagram of two dodgem cars in collision at the funfair.



Before the collision



After the collision

a) Use the information in the diagram to calculate the velocity of car B after the collision.

b) Explain whether this is an elastic or an inelastic collision.

12 Two ice skaters, each of mass 65 kg, skate towards each other. Each skater has a velocity of 1 m s^{-1} relative to the ice. The skaters collide; after the collision each skater returns back along their original path with a velocity of 2 m s^{-1}.

a) Show that momentum is conserved in the collision.

b) Calculate the gain in kinetic energy of each skater during the collision.

c) Explain where the extra energy has come from.

13 Look again at Question 8. Show that each of the collisions between the two gliders is elastic.

14 A ball, of mass 0.1 kg, falls from a height of 3.2 m, and rebounds to a height of 3.2 m. For this question assume $g = 10\,\mathrm{m\,s^{-2}}$.

a) Calculate the velocity of the ball just before it hits the ground.

b) Calculate the velocity of the ball just after it has hit the ground.

c) The ball is in contact with the ground for 0.004 s. Calculate the average force which acts on the ball in this time.

d) The momentum of the ball has changed during this process. The principle of the conservation of momentum states that 'momentum is always conserved'. Explain how in this case momentum is conserved. [Hint: there is another body involved in this collision – what is its momentum?]

More advanced problems in momentum

The generalised form of Newton's second law of motion enables you to solve some more complicated problems.

force = rate of change of momentum

$$F = \frac{\Delta(mv)}{\Delta t}$$

EXAMPLE

Calculate the force exerted by water leaving a fire hose on the firefighter holding the hose. The water leaves with a velocity of $17\,\mathrm{m\,s^{-1}}$; the radius of the hose is 3 cm; the density of water is $1000\,\mathrm{kg\,m^{-3}}$.

The mass of water leaving the hose each second is $\Delta m/\Delta t$. This is equal to the density of water (ρ) × the volume of water V flowing per second:

$$\frac{\Delta m}{\Delta t} = \rho \frac{\Delta V}{\Delta t}$$

But the volume flow per second is the cross-sectional area of the hose (A) multiplied by the velocity of the water (v). So:

$$\frac{\Delta m}{\Delta t} = \rho A v$$

Thus the force, or change of momentum per second, is:

$$\begin{aligned} F = \frac{\Delta p}{\Delta t} &= \rho A v \times v \\ &= \rho A v^2 \\ &= 1000\,\mathrm{kg\,m^{-3}} \times \pi \times (0.03)^2\,\mathrm{m^2} \times (17\,\mathrm{m\,s^{-1}})^2 \\ &= 820\,\mathrm{N} \end{aligned}$$

This large force explains why a hose is sometimes held by two firefighters, and why hoses have handles.

Collisions in two dimensions

An interesting special result occurs when two atomic particles of the same mass collide elastically, when one of the particles is initially stationary.

If the two particles (protons for example) collide, then the momentum and kinetic energy of the moving proton (A) is transferred completely to the stationary proton (B). See Figure 11.13.

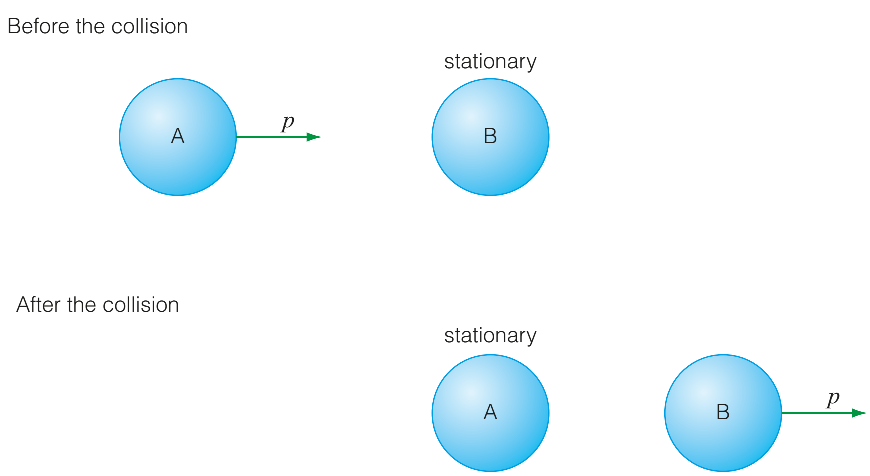


Figure 11.13 Head-on collision of two protons.

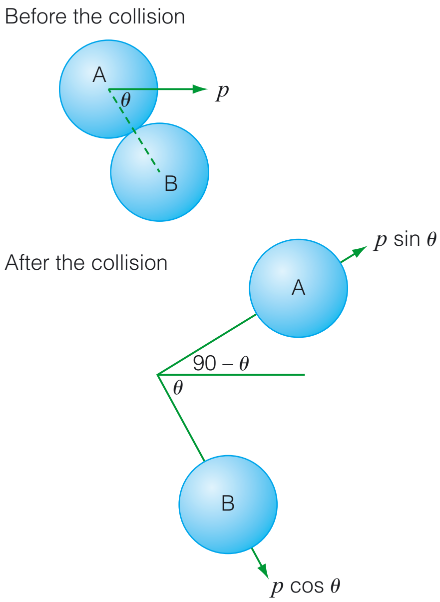


Figure 11.14 Non-head-on collision of two protons.

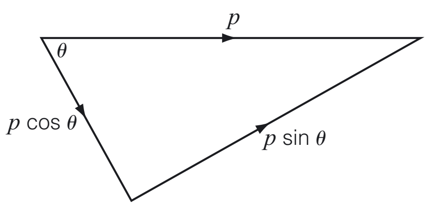


Figure 11.15 In vector terms, $p = p\cos\theta + p\sin\theta$.

In this way both momentum and kinetic energy are conserved. This only happens when the particles are of the same mass; in all other cases both particles will be moving after the collision.

What happens when two particles of the same mass collide, but the collision is not head on, as shown in Figure 11.14? The momentum of particle A can be resolved into two components: $p\cos\theta$ along the line of collision and $p\sin\theta$ perpendicular to the line of the collision. As in Figure 11.13, all of the momentum of A along the line of the collision (here $p\cos\theta$) is transferred to particle B. This leaves particle A with the component $p\sin\theta$, which is at right angles to the line of the collision.

So in a non-head-on elastic collision between two particles of the same mass, they always move at right angles to each other.

Figure 11.15 shows how momentum is conserved as a vector quantity.

Kinetic energy is also conserved. Before the collision the kinetic energy is

$$\frac{p^2}{2m}$$

After the collision the kinetic energy of the two particles is

$$\frac{p^2}{2m}\cos^2\theta + \frac{p^2}{2m}\sin^2\theta$$

However, since $\cos^2\theta + \sin^2\theta = 1$, the kinetic energy after the collision is the same as before, $\frac{p^2}{2m}$.

TEST YOURSELF

15 An alpha particle with a mass of 4 amu is emitted from a uranium nucleus, mass 238 amu, with a kinetic energy of 4.9 MeV.

a) Calculate the momentum of the alpha particle.

b) Calculate the momentum of the nucleus, after the alpha particle has been emitted.

c) Calculate the kinetic energy of the nucleus after the alpha particle has been emitted.

d) Discuss where the kinetic energy has come from in this process.

1 amu (atomic mass unit) = 1.67×10^{-27} kg; $e = 1.6 \times 10^{-19}$ C

16 A rocket of mass 400 000 kg takes off on a voyage to Mars. The rocket burns 1600 kg of fuel per second ejecting it at a speed of 2600 m s^{-1} relative to the rocket.

a) Calculate the force acting on the rocket due to the ejection of the fuel.

b) i) Calculate the acceleration of the rocket at take-off.

ii) Calculate the acceleration of the rocket 90 seconds after take-off.

Exam practice questions

1 Which of the following is a correct unit for momentum? *(1)*

A N s **C** $N\,s^{-1}$

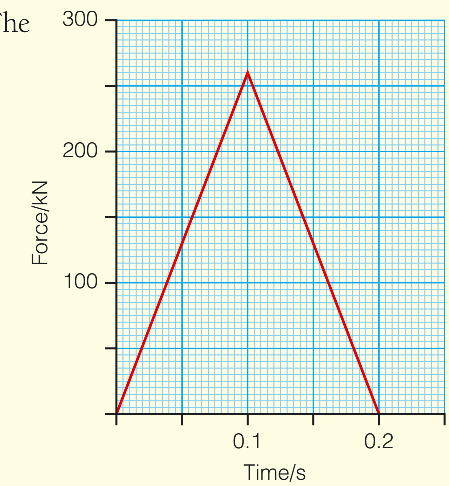
B $kg\,m\,s^{-2}$ **D** $kg\,m^{-1}\,s$

2 A body is in free fall. Which of the following quantities is equal to the rate of increase of the body's momentum? *(1)*

A kinetic energy **C** weight

B velocity **D** decrease in potential energy

3 A car travelling at speed collides with a wall and comes to a halt. The force acting on the car during the crash is shown in the diagram.



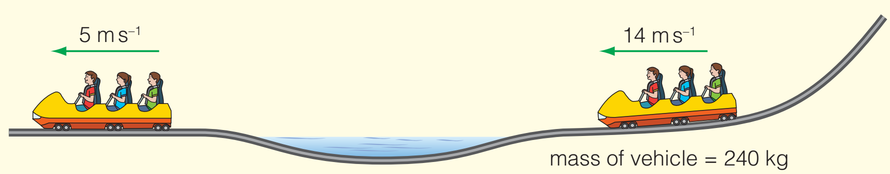
a) Use the graph to show that the change of momentum of the car in the crash is approximately 26 000 N s. *(3)*

b) The car and its passengers have a mass of 1300 kg. Calculate the speed of the car before the crash. *(2)*

c) There were two passengers in the car. One was wearing a seat belt and the second was not. Explain why the one without the seat belt is more likely to receive serious injuries. *(3)*

d) Sketch a graph to show how the velocity of the car changed with time during the crash. *(3)*

4 The diagram illustrates part of a ride in a funfair. One of the vehicles, with a mass of 240 kg, reaches the bottom of the slope reaching a speed of $14\,m\,s^{-1}$. It is slowed down to a speed of $5\,m\,s^{-1}$ by passing through a trough of water. The vehicle slows down over a time of 0.6 s. When it hits the water, a mass of water is thrown forwards with a velocity of $18\,m\,s^{-1}$.



a) Explain what is meant by the principle of conservation of momentum. *(2)*

b) Show that the mass of water thrown forwards by the vehicle is about 120 kg. *(3)*

c) Calculate the change in kinetic energy of the vehicle, and the increase in kinetic energy of the water, as the vehicle splashes into the trough. *(4)*

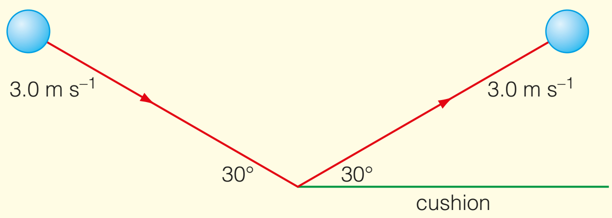
d) Explain how energy is conserved during this process. *(2)*

e) Calculate the average deceleration of the vehicle in the water. *(2)*

5 a) A neutron travelling with a velocity of $1.2 \times 10^7\,m\,s^{-1}$ is absorbed by a stationary uranium-238 nucleus. Calculate the velocity of the nucleus after the neutron has been absorbed. *(3)*

b) An alpha particle decays from a nucleus of polonium-208. The speed of the alpha particle is $1.5 \times 10^7\,m\,s^{-1}$. Calculate the velocity of the polonium nucleus. The alpha particle has a relative atomic mass of 4. *(3)*

6 A snooker ball of mass 160 g collides elastically with the cushion of a snooker table. Use in the information in the diagram to calculate which of the following is the correct value for the change of momentum of the ball in the direction normal (perpendicular) to the cushion. *(1)*



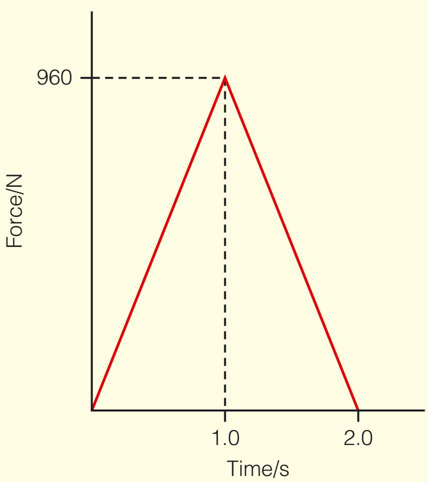
A 0

B $0.24\,kg\,m\,s^{-1}$

C $0.42\,kg\,m\,s^{-1}$

D $0.48\,kg\,m\,s^{-1}$

7 A driver, passing through a town, sees a hazard and brings his car to an emergency stop. The driver has a mass of 80 kg. The graph shows how the force exerted on him by his seat belt varies while the car slows down. Use the graph to calculate which of the following gives the correct value for initial speed of the car, before the brakes were applied. *(1)*



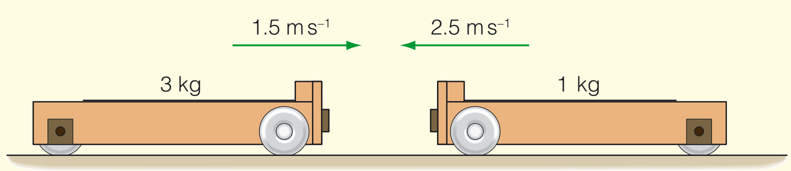
A $24\,m\,s^{-1}$

B $16\,m\,s^{-1}$

C $12\,m\,s^{-1}$

D $6\,m\,s^{-1}$

8 Two trolleys collide as shown in the diagram. After the collision they stick together. Use the information in the diagram to calculate which of the velocity values below is the correct value for the trolleys after the collision. *(1)*



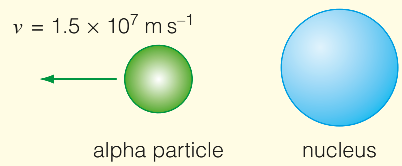
A $1.75\,m\,s^{-1}$ to the right

B $1.75\,m\,s^{-1}$ to the left

C $0.25\,m\,s^{-1}$ to the left

D $0.50\,m\,s^{-1}$ to the right

9 In the diagram an alpha particle has just been emitted from a large nucleus. It is repelled by the large nuclear charge and leaves with a velocity of $1.5 \times 10^7\,\text{m s}^{-1}$.

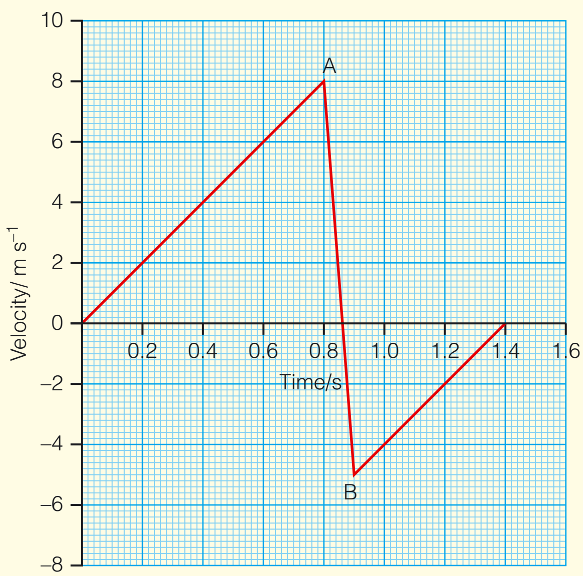


a) The alpha particle has a mass of 6.8×10^{-27} kg and the nucleus a mass of 4.0×10^{-25} kg. Calculate the recoil velocity of the nucleus. *(3)*

b) Calculate the total kinetic energy of the alpha particle and nucleus. Express your answer in MeV. ($e = 1.6 \times 10^{-19}$ C) *(5)*

c) Explain how momentum and energy have been conserved in this alpha decay process. *(2)*

10 A soft rubber ball is allowed to fall onto the ground and bounce back up again. A data logger measures the speed as the ball falls. The graph shows how the ball's velocity changes with time.



a) Use the graph to determine the time of the ball's bounce over the region AB. *(1)*

The ball has a mass of 0.08 kg.

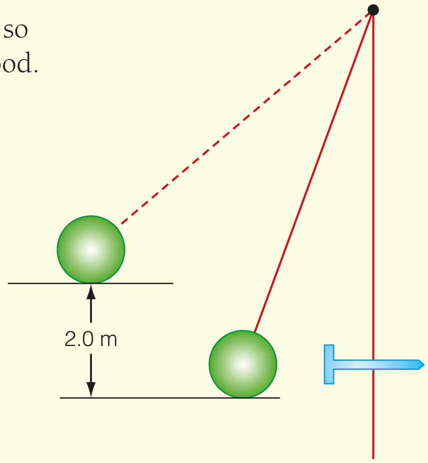
b) Determine the momentum change of the ball as it hits the ground. *(3)*

c) Use your answer to part (b) to calculate the force exerted by the ground on the ball as it is in contact with the ground. *(2)*

d) How big is the force that the ball exerts on the ground while it is in contact? *(1)*

e) A hard rubber ball of the same mass, 0.08 kg, is now dropped from the same height. When it is in contact with the ground it exerts a larger force than the soft ball. Explain **two** changes you might see in the graph of velocity against time, measured by the data logger. *(4)*

11 A steel ball of diameter 10 cm is allowed to fall from a height of 2 m, so that it collides with a steel spike which is embedded in a piece of wood.



a) Steel has a density of $9000\,\text{kg}\,\text{m}^{-3}$. Show that the ball has a mass of about 4.7 kg. *(2)*

b) Determine the ball's speed as it comes into contact with the steel spike. *(2)*

The ball now moves forwards with the spike together. The spike has a mass of 2.6 kg.

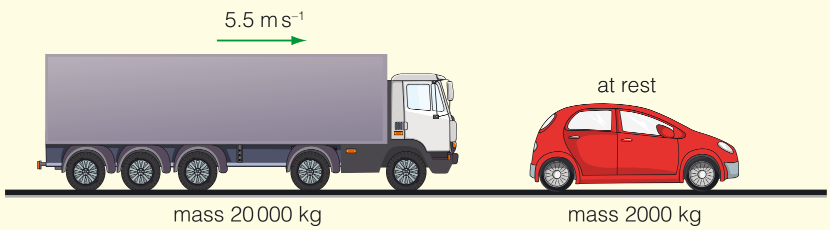
c) Calculate the velocity of the ball and spike as they move forwards. *(2)*

d) By calculating the change of kinetic energy in the collision, explain whether this is an elastic or inelastic collision. *(4)*

The spike penetrates 3.5 cm into the wood before coming to rest.

e) Calculate the average force acting to slow the ball and spike. *(3)*

12 A lorry travelling at $5.5\,\text{m}\,\text{s}^{-1}$ collides with a stationary car. After the collision, the lorry and car move forwards together. Use the information in the diagram to calculate which of the following values is the correct velocity of the car and lorry after the collision. *(1)*



A $5.5\,\text{m}\,\text{s}^{-1}$ **C** $5.0\,\text{m}\,\text{s}^{-1}$

B $2.75\,\text{m}\,\text{s}^{-1}$ **D** $1.5\,\text{m}\,\text{s}^{-1}$

13 In the collision described in Question 12, some of the kinetic energy of the lorry is transferred to other forms, such as heat and sound. Which of the following gives the correct value for the change of kinetic energy during the crash? *(1)*

A 300 000 J **C** 150 000 J

B 275 000 J **D** 27 500 J

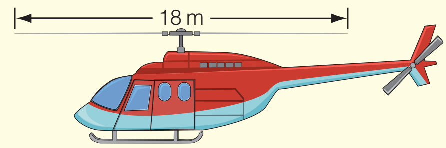
14 A rubber ball of mass 0.2 kg lands on a floor with a velocity of $6\,\text{m}\,\text{s}^{-1}$; it bounces back up with a velocity of $3\,\text{m}\,\text{s}^{-1}$. The ball is in contact with the floor for 0.06 s. Which of the following is the correct value for the average force that the floor exerts on the ball during the bounce? *(1)*

A 60 N **C** 20 N

B 30 N **D** 10 N

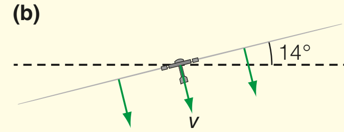
Stretch and challenge

15 The rotor blades of a helicopter push air vertically downwards with a speed of 5.0 m s^{-1}.



a) Use the information in part (a) and the value for the density of air, 1.2 kg m^{-3}, to calculate the momentum of the air pushed downwards per second.

b) When the helicopter pushes air downwards with a speed of 5.0 m s^{-1}, it hovers stationary. Calculate the helicopter's mass.



c) The helicopter's rotor blades are now tilted forwards at an angle of 14° to the horizontal (part (b)). The speed of rotation is increased, so that the helicopter flies horizontally and accelerates forwards.

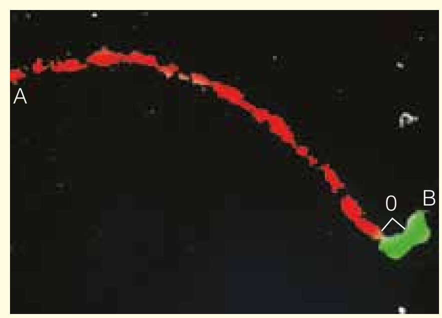
Calculate:

i) the speed of air being pushed away from the blades, v

ii) the initial horizontal acceleration of the helicopter.

16 A firework rocket is launched upwards. When it reaches its highest point, it explodes symmetrically into a spherical ball with 100 fragments, each of which has a mass of 20 g. The chemical energy stored in the explosives is 2 kJ; 80% of this energy is transferred to kinetic energy of the fragments. Calculate the speed of each fragment.

17 The photo shows a computer-enhanced image of a cloud chamber photograph. The event shown is the radioactive disintegration of a helium-6 nucleus, ${}^{6}_{2}He$, into a lithium-6 nucleus, ${}^{6}_{3}Li$, and a β-particle. The helium nucleus was originally stationary at point O. The β-particle is ejected along the thin broken red track OA, and the lithium-6 nucleus travels a short distance along the thick green track OB. Both particles travel in the plane of the paper. The β-particle's track is curved due to the presence of a strong magnetic field.



a) Deduce the direction of the magnetic field.

b) Explain why the lithium nucleus track is short and thick, and the β-particle track longer and thinner.

c) Judging from the cloud chamber tracks, momentum is not conserved in this decay process. Explain why this appears to be the case.

Since physicists accept the principle of conservation of momentum to be a universal law, it was suggested that another particle must be emitted in β-decay. This particle is the antineutrino, which is uncharged and leaves no track in the cloud chamber.

d) The β-particle has momentum p_1 and the lithium nucleus momentum p_2. Use the principle of momentum conservation to determine the momentum of the antineutrino. Express your answer in terms of p_1 and p_2, giving both a magnitude and direction.

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1

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