A measurement must be reported in a way that reflects its actual precision. For example, suppose you use a ruler to measure the diameter of a basketball. You judge that you can make this measurement with a precision of about 1 mm, or 0.1 cm. In this case, the ball's diameter is reported as 24.1 cm. We interpret this to mean that the actual value falls between 24.05 cm and 24.15 cm and thus rounds to 24.1 cm. Therefore, reporting the ball's diameter as only 24 cm is saying less than you know as you are withholding information. Reporting the diameter as 24.135 cm is incorrect as you are claiming knowledge and information that you do not possess.

The way to state your knowledge precisely is through the proper use of **significant figures**. You can think of a significant figure as a digit that is reliably known. For example, a measurement such as 17.2 cm has three significant figures; 1,7 and 2. However, the next decimal place following the 2 is not reliably known and is therefore not a significant figure. Similarly, a time measurement of 34.68 s has four significant figures, implying that the 8 in the hundredths place is reliably known. Zeros in a number with no decimal point are only significant when they lie between two integers, such as the zero in 101. Zeros in a number with no decimal point that trail an integer are not significant. For example, the three zeros in 1000 are not significant. Zeros in a number with a decimal point are significant when they trail the first integer and are not significant when they precede the first integer. For example, in 0.00030600, the four zeros that precede the first integer (3) are not significant, but the three zeros that trail the first integer are significant. When we perform a calculation, such as adding or multiplying two or more measured numbers, we cannot claim more accuracy for the result than the initial measurements. The correct number of significant figures is determined using the rules summarised below.

1. When you multiply or divide several numbers, the number of significant figures in the answer should match the number of significant figures of the least precisely known number used in the calculation:

   Three significant figures

   5.21 x 1.6 = 9.4

   Two significant figures

   Answer is given to the *lower* of the two, or two significant figures.

2. When you add or subtract several numbers, the number of decimal places in the answer should match the smallest number of decimal places of any number used in the calculation:

   13.03 — Two decimal places

   \+ 198.6 — One decimal place

   211.6

   Answer is given to the lower of the two, or one decimal place.

3. Exact numbers have no uncertainty and do not change the number of significant figures of measured numbers. Examples of exact numbers are physical constants such as *c*, mathematical constants such as π and whole numbers in a formula such as the 2 in $v^2 = v_0{}^2 + 2as$

E. There is one exception to the rules above:

   It is acceptable to keep extra digits during intermediate steps of a calculation to minimise round-off errors in the calculation. However, the final answer must be reported with the proper number of significant figures.

Position

To develop our understanding of motion further, we need to make quantitative measurements using numbers and calculations. When analysing a motion diagram, it is helpful to know where the object is, its **position**, and when the object was at that position, the **time**. When describing an object's position, we use three pieces of information: a reference point, a measurement, and a direction. A reference point, called the **origin**, is a fixed point used to specify the position of the object under analysis. The measurement is a numerical value defining how far the object is from the origin, and the direction specifies which side of the origin the object is currently located. Figure 1.06 shows a bus moving along a flat road. The position of this bus is described as being 400 m, east of the school.

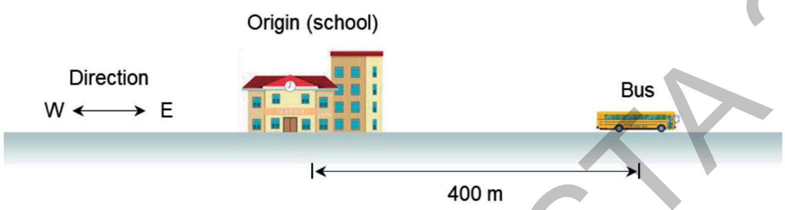


Figure 1.06: Describing position.

To specify how far our object is from the origin, we use an imaginary ruler placed along the line of the object's motion marked off in equally spaced divisions of distance. We place the zero mark of this ruler at the origin, allowing us to locate the object's position by reading the ruler mark where the object is. Finally, we need to specify which side of the origin our object is on. To do this, we imagine the ruler extending from one side of the origin with increasing positive markings; on the other side, the ruler is marked with increasing negative numbers. By reporting the position as either a positive or a negative number, we know which side of the origin the object is currently positioned. We call this a **coordinate system**. Figure 1.07 shows a coordinate system that can be used to locate various objects along a flat surface.

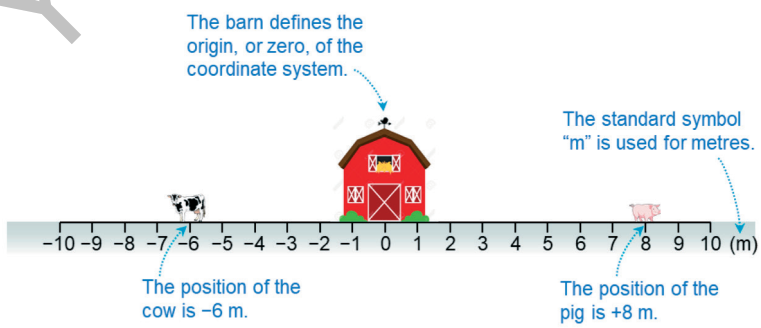


Figure 1.07: The coordinate system used to describe objects along a flat surface.

It should be noted that linear motion need not be horizontal. A rock falling vertically downward and a skier moving down a straight slope are examples of linear motion that are described using a coordinate system. A coordinate system is an essential tool in physics as you will frequently encounter problems in which the quantities describing an object's motion have different directions.

Displacement

When describing motion, it is necessary to measure the changes in position of an object that occur with time. Consider the following example: Rebecca is standing 25 m east of the corner of Marion Road and Henley Beach Road. She then walks to a second point 75 m east of Marion Road, as depicted in Figure 1.08. Rebecca's final position is +75 m, indicating that she is 50 m east of the origin. We see that Rebecca has changed position, and a change of position is called **displacement**. Displacement is also defined as the difference between the final and initial positions of an object and is represented by the symbol $\vec{s}$ from for the Latin word "spatium", meaning distance or space.

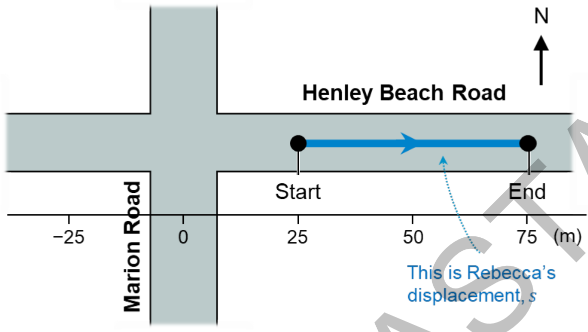


Figure 1.08: Rebecca's displacement.

Distance

In some cases, an object will not move in a straight-line path between two positions. Consider the following example: Joe moves from his house's front yard to the back yard following the path shown in Figure 1.09. Joe's displacement is 18 m, east of the origin, but he has travelled 30 m to reach this position. The total length of the path between Joe's initial and final positions is called **distance**.

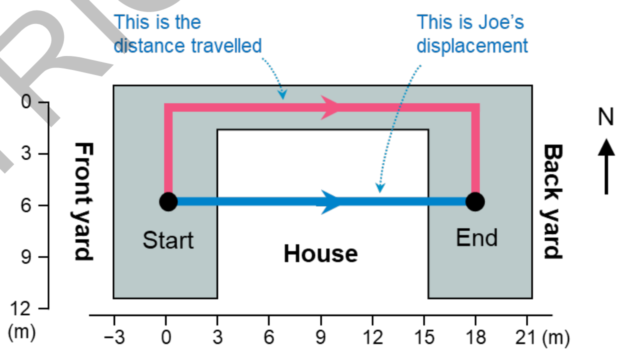


Figure 1.09: Joe's distance and displacement.

Distance is represented using a similar symbol (s), and the same SI unit as distance. Still, the two quantities often differ in magnitude as distance incorporates the entire path length travelled between two positions, whereas displacement considers only the length of a straight-line path between the two positions. In addition, distance is a scalar quantity and is represented by its magnitude only, whereas displacement is a vector quantity and is represented by its magnitude and direction.

Acceleration is a change in motion.

Uniformly accelerated motion is described in terms of relationships between measurable scalar and vector quantities, including displacement, speed, velocity, and acceleration.

- Solve problems using equations for constant acceleration and $a = \frac{\Delta v}{\Delta t}$.
- Interpret solutions to problems in a variety of contexts.
- Make reasonable and appropriate estimations of physical quantities in a variety of contexts.

The goal of this chapter is to describe motion. We have learned that velocity describes the rate at which an object changes position, but we require one additional motion concept to complete the description, one describing an object with a changing velocity. Any change in the velocity of an object is called **acceleration** (symbol $\vec{a}$). Consider the following example: the cyclist in Figure 1.15 accelerates by increasing their velocity by 2 m s^{-1} every second. After 1 second, their velocity is 2 m s^{-1}, after 2 seconds, their velocity is 4 m s^{-1}, and after 3 seconds, their velocity is 6 m s^{-1}.

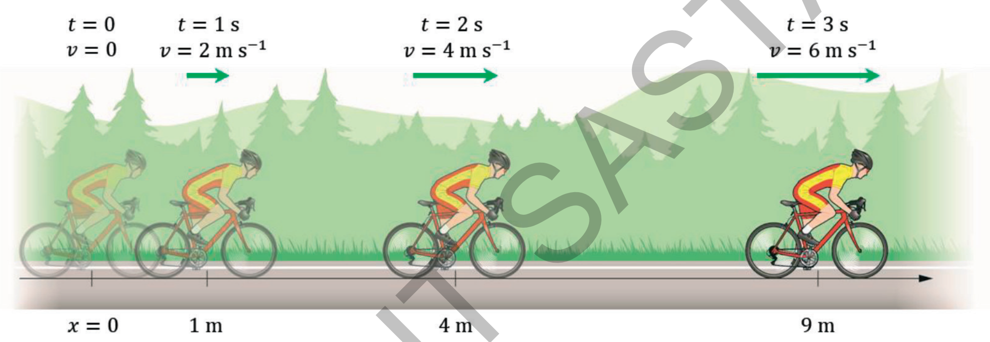


Figure 1.15: Acceleration of a cyclist.

The **average acceleration** of an object is defined as the change in velocity divided by the change in time and is calculated using the formula below. The change in velocity is calculated by subtracting the initial velocity (symbol $\vec{v}_0$) from the final velocity (symbol $\vec{v}$). The units of acceleration are metres per second per second, which we say as "metres per second squared."

Formula	$\vec{a} = \frac{\Delta \vec{v}}{\Delta t} = \frac{\vec{v} - \vec{v}_0}{t - t_0}$

Symbol	Variable	SI unit
$\vec{a}$	acceleration	m s^{-2}
$\Delta \vec{v}$	change in velocity	m s^{-1}
Δt	time interval	s

The cyclist's acceleration in Figure 1.15 between t = 2 and t = 3 s is calculated below.

$$\vec{a} = \frac{\Delta \vec{v}}{\Delta t}$$
$$\vec{a} = \frac{6-4}{3-2}$$
$$\vec{a} = 2 \text{ m s}^{-2}$$

Question 20

A Boeing 747 aeroplane reaches its take-off velocity of 250 km h^{-1} west in 35 s.

(a) Calculate the magnitude and direction of the average acceleration.

(3 marks) **KA4**

(a) The aeroplane lands at a velocity of 285 km h^{-1} east and comes to rest in 30 s.

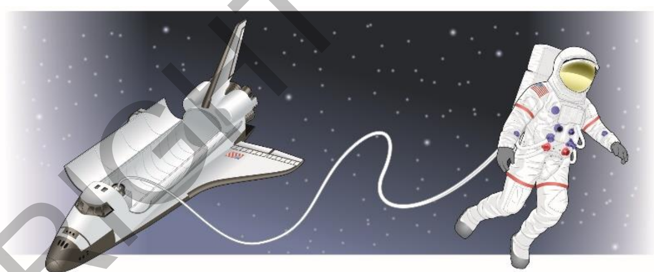
Calculate the magnitude and direction of the average acceleration.

(3 marks) **KA4**

Question 21

An astronaut exits a space shuttle on a tether to test a new personal manoeuvring device.

The astronaut moves along a straight line away from the shuttle.



(a) The astronaut performs their first manoeuvre by increasing velocity from 800 mm s^{-1} to 1400 mm s^{-1} over 3 s.

Calculate the magnitude and direction of the average acceleration.

(2 marks) **KA4**

(b) The astronaut then turns 180° to face the shuttle in preparation for their second manoeuvre.

The second manoeuvre involves decreasing velocity from 1000 mm s^{-1} to 400 mm s^{-1} in 2 s.

Calculate the magnitude and direction of the average acceleration.

(2 marks) **KA4**

Graphical representations can be used qualitatively and quantitatively to describe and predict aspects of linear motion.

- Use graphical methods to represent linear motion, including the construction of graphs showing position vs time, velocity vs time and acceleration vs time.
- Use graphical representations to determine quantities such as position, displacement, distance, velocity, and acceleration.
- Use graphical techniques to calculate the instantaneous velocity and instantaneous acceleration of an object.

It is often useful to visualise a particle's motion by sketching a graph of its position as a function of time. For example, suppose a particle moves back and forth along a single axis, with the positions and times shown in the motion diagram in Figure 1.18. The information in the motion diagram can be represented using a graph of position on the vertical axis against time on the horizontal axis. This is referred to as a **position-time graph** (Figure 1.18).

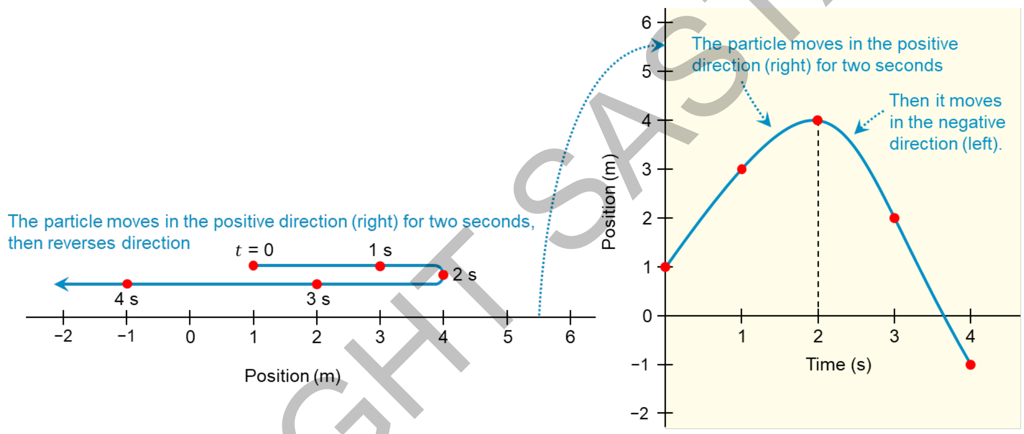


Figure 1.18: Motion diagram (left) and position-time graph (right).

A position-time graph allows us to determine the average velocity of a particle between two positions. For example, suppose you wish to know the particle's average velocity in Figure 1.18 from t = 0 to t = 3 s. We know that the average velocity is the particle's displacement over the time interval, and we relate this knowledge to the position-time graph by drawing a straight line connecting the position at t = 0 and the position at t = 3 s as in Figure 1.19.

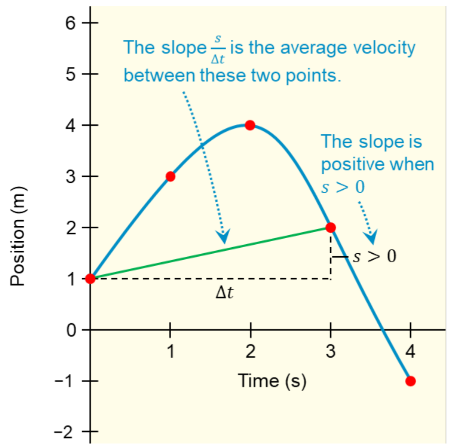
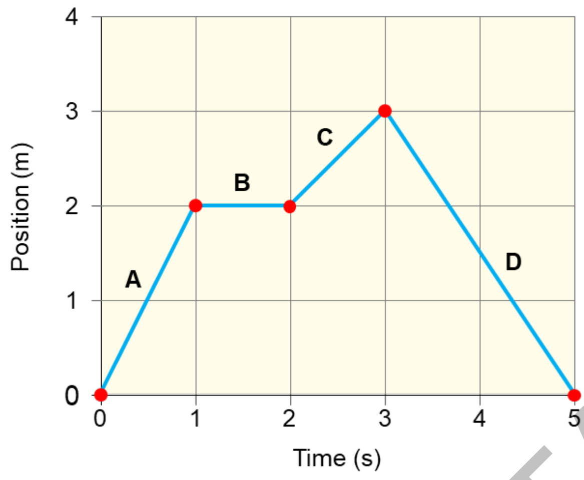


Figure 1.19: Average velocity between t = 0 and t = 3 s

Question 22

The position-time graph below describes the motion of an expectant father pacing back and forth.



(a) Without performing a calculation, indicate whether the father's velocity is positive, negative or zero in the segments labelled A to D.

A: ______________________ B: ______________________

C: ______________________ D: ______________________ (4 marks) KA1

(b) Without calculation, state the letter corresponding to the segment of the graph where the father's velocity is greatest and give a reason.

____

____ (2 marks) KA2

(c) Calculate the father's average velocity for the following segments:

(1) A

(2 marks) KA4

(2) C

(2 marks) KA4

(3) D

(2 marks) KA4

Velocity-time graphs

Another useful method of visualising a particle's motion is to sketch a graph of its velocity as a function of time. For example, suppose a boat moving at 1.50 m s^{-1} accelerates uniformly in a straight line to a final velocity of 13.5 m s^{-1} over 5 s. The information can be represented using a graph of velocity on the vertical axis against time on the horizontal axis. This is referred to as a **velocity-time graph** (Figure 1.24).

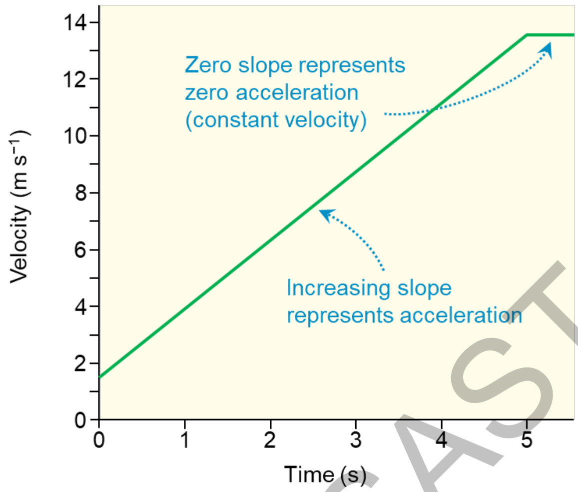


Figure 1.24: Velocity-time graph for a boat.

A velocity-time graph allows us to determine the average acceleration of a particle between two times. For example, suppose you wish to know the boat's average acceleration from t = 0 to t = 5 s. We know that the average acceleration is the change in velocity of the boat over the time interval, and we relate this to the velocity-time graph by drawing a straight line connecting the velocity at t = 0 to the velocity at t = 5 s as shown in Figure 1.25. The slope of the straight line in Figure 1.25 is equal to the rise over the run, which in this case is $\frac{\Delta\vec{v}}{\Delta t}$. Since $\frac{\Delta\vec{v}}{\Delta t}$ is the average acceleration, we conclude that the slope of a line connecting two points on a velocity-time graph is equal to the average acceleration during that time interval.

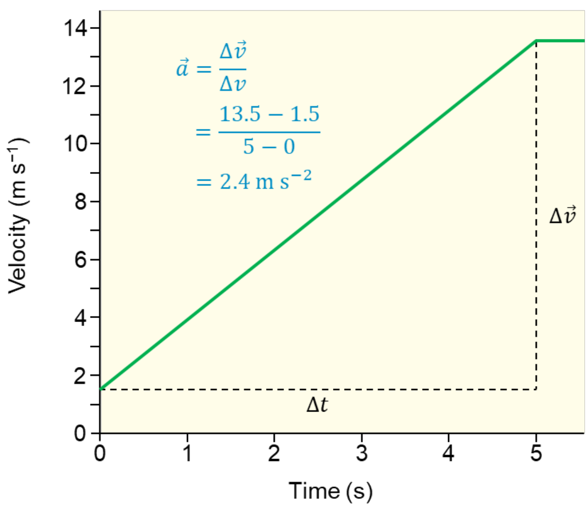


Figure 1.25: Average acceleration of the boat between t = 0 and t = 5 s.

The sign of the acceleration

A natural tendency is to think that a positive value of acceleration describes an object that speeds up while a negative value describes an object that slows down. Unfortunately, this simple interpretation does not work. Since an object can move right or left (or, equivalently, up or down) while either speeding up or slowing down, there are four situations to consider, and each of these is described in Figure 1.28. Since an object's acceleration is the slope of its velocity graph, a positive slope implies a positive acceleration, and a negative slope implies a negative acceleration. In a coordinate system for horizontal motion in which motion to the right corresponds to a positive velocity, an object has a positive acceleration when speeding up and moving to the right and a negative acceleration when it speeds up and moves to the left. Ultimately, whether or not an object that slows down has a negative acceleration depends on whether the object moves to the right or the left (or up or down).

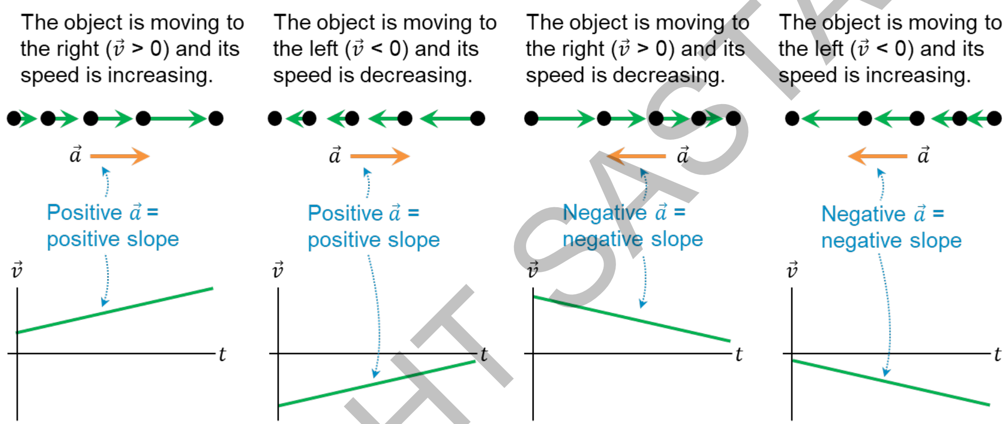


Figure 1.28: Determining the sign of the acceleration.

Instantaneous acceleration

Instantaneous acceleration is the acceleration of a particle at an instant in time. The instantaneous acceleration of a particle is determined from a velocity-time graph in the same way as instantaneous velocity is determined from a position-time graph, as the instantaneous acceleration at any point on the velocity-time graph equals the slope of the line tangent to the curve at that point (Figure 1.29).

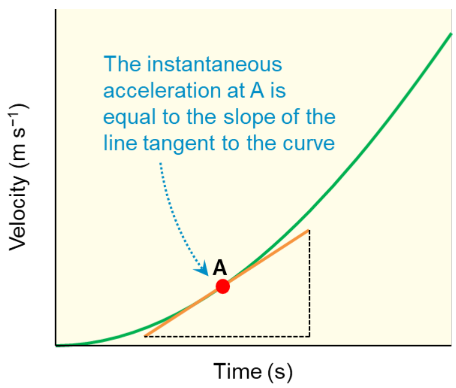


Figure 1.29: Calculating instantaneous acceleration for a particle with a variable velocity.

Relating position-time and velocity-time graphs

We have seen that it is possible to describe motion using both position-time and velocity-time graphs. Given that both types of graphs describe the same particle's motion, it is possible to construct a velocity-time graph using the information in a position-time graph and vice-versa. Consider the following example: suppose you left your maths classroom and begin walking toward your physics classroom, which is down the corridor to the west. You then realise that you left your physics workbook at your desk in your maths classroom, so you turn around and run back to the maths classroom to retrieve it. A velocity-time graph for this motion appears as the top graph in Figure 1.30. It is possible to deduce the position-time graph using the information in the velocity-time graph. There are two clear segments to the motion: walking away from class ($v = +1.0$ m s^{-1}) and running back ($v = -3.0$ m s^{-1}). For each of the two segments of the motion, the sign of the velocity tells us whether the slope of the position-time graph is positive or negative, and the magnitude of the velocity tells how steep the slope of each line on the position-time graph should be. Therefore, the first line on the position-time graph has a positive slope of 1.0 m s^{-1}, meaning that the line increases from 0 to 15 m from t = 0 to t = 15 s, and the second line has a negative slope of −3.0 m s^{-1}, meaning that the line decreases from 15 to 0 m between t = 15 to t = 20 s.

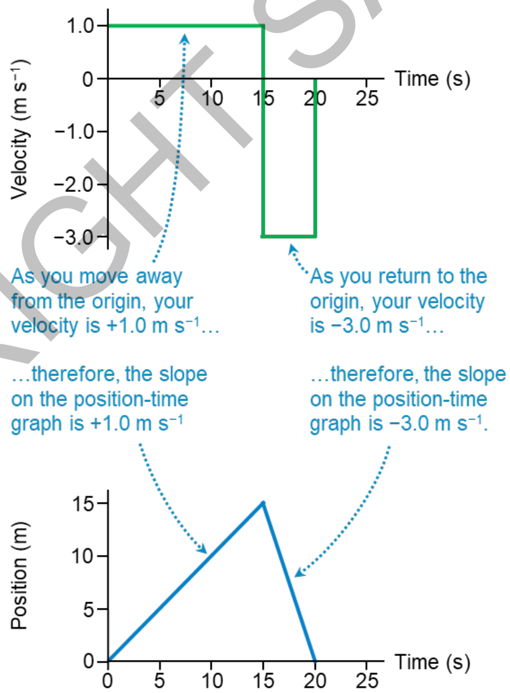
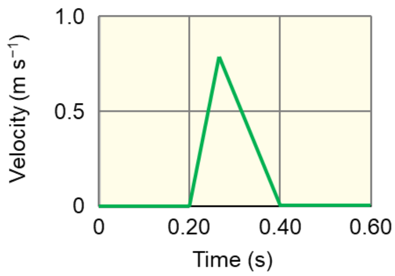


Figure 1.30: Deducing a position-time graph from a velocity-time graph.

One important detail was not mentioned in the preceding paragraph: how did we know that the origin of the position-time graph was 0 m? The velocity graph tells us the position-time graph's slope, but it does not tell us where the position graph should start. Although you are free to select any point you choose as the origin of the coordinate system, it is common to set the position-time graph's origin as 0 m.

Question 28

The velocity-time graph describes the blood in the ascending aorta during one heartbeat.



(a) Describe the motion of the blood between t = 0 s and t = 0.40 s.

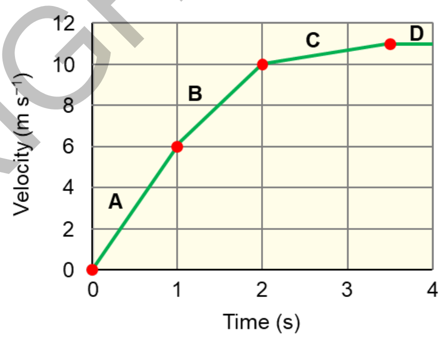
(3 marks) KA2

(b) Estimate the distance travelled by the blood in one heartbeat.

(2 marks) KA4

Question 29

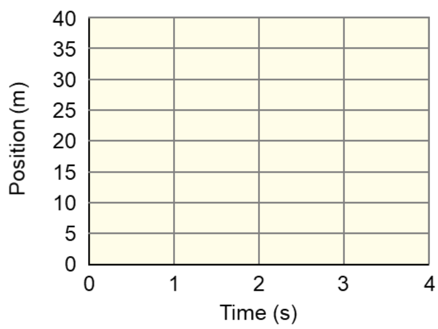
The simplified velocity-time graph below describes an Olympic sprinter starting a 100 m dash.



(a) State the instantaneous velocity of the sprinter at t = 1.5 s.

(1 mark) KA2

(b) Sketch a position-time graph for the sprinter over the first 4 s on the axes below.



(4 marks) KA4

Acceleration-time graphs

Another useful method of visualising a particle's motion is to sketch a graph of its acceleration as a function of time. For example, suppose a motorcycle accelerates uniformly at 5 m s^{-2} for 5 s before travelling at a constant speed for the 10 s and then decelerates uniformly at 2 m s^{-2} for 10 s. The information can be represented using a graph of acceleration on the vertical axis against time on the horizontal axis. This is referred to as an **acceleration-time graph** (Figure 1.31).

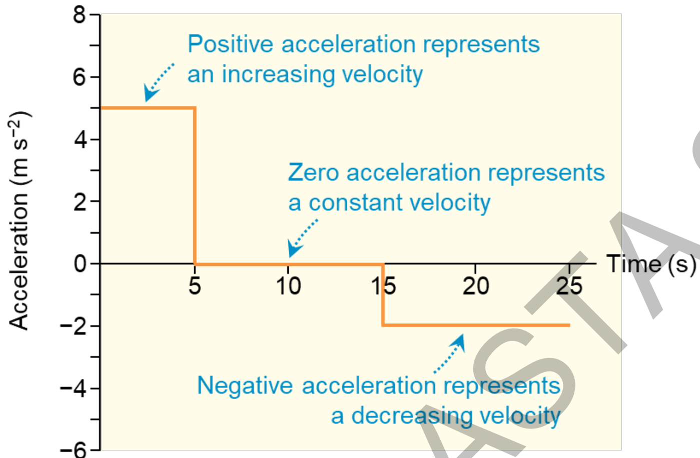


Figure 1.31: Acceleration-time graph for a motorcycle.

An acceleration-time graph allows us to determine the instantaneous acceleration of a particle and the change in velocity of a particle over a time interval. For example, suppose you wish to know the motorcycle's change in velocity between t = 0 and t = 5 s. We know that the change in velocity is equal to the average acceleration multiplied by the time interval ($\Delta v = at$), and this is equal to the area underneath the line on the acceleration-time graph. In this example, the area underneath the line from t = 0 s to t = 5 s is equal to the average acceleration of 5 m s^{-2} multiplied by the time interval of 5 s, which gives a change in velocity of 25 m s^{-1}, as depicted in Figure 1.32.

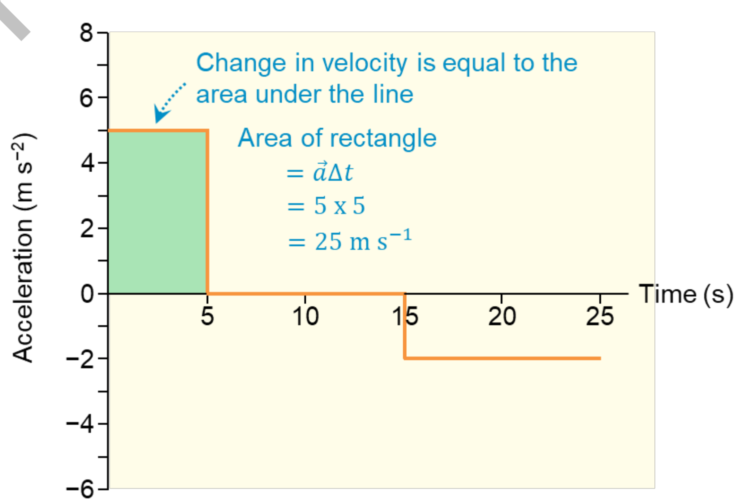


Figure 1.32: Change in the motorcycle's velocity between t = 0 and t = 5 s.

Relating velocity-time and acceleration-time graphs

We have seen that it is possible to describe motion using both velocity-time and acceleration-time graphs. Given that both types of graphs describe the same particle's motion, it is possible to construct an acceleration-time graph using the information in a velocity-time graph and vice-versa. Consider the following example: a car accelerates uniformly from rest to 20 m s^{-1} in 5 s before travelling at 20 m s^{-1} for 10 s and then decelerating uniformly to rest over 10 s. A velocity-time graph for this motion appears as the top graph in Figure 1.33. It is possible to deduce the acceleration-time graph using the information in the velocity-time graph. There are three clear segments to the motion: accelerating uniformly from rest to 20 m s^{-1}, travelling at a constant velocity of 20 m s^{-1} and decelerating uniformly to rest. For each of the three segments of the motion, the sign of the velocity tells us whether the acceleration is positive or negative. In both segments where the car's acceleration is non-zero, we are given the initial and final velocities and the time interval, allowing us to calculate the average acceleration and plot this on the acceleration time graph. In the segment where velocity is constant, the acceleration is zero, so we draw a horizontal line parallel to the y = 0 coordinate on the graph, as shown in the bottom graph in Figure 1.33. It is worth noting that the middle segment having zero acceleration does not mean that the velocity is zero. The velocity is constant, which means it is not changing, and thus the car is not accelerating.

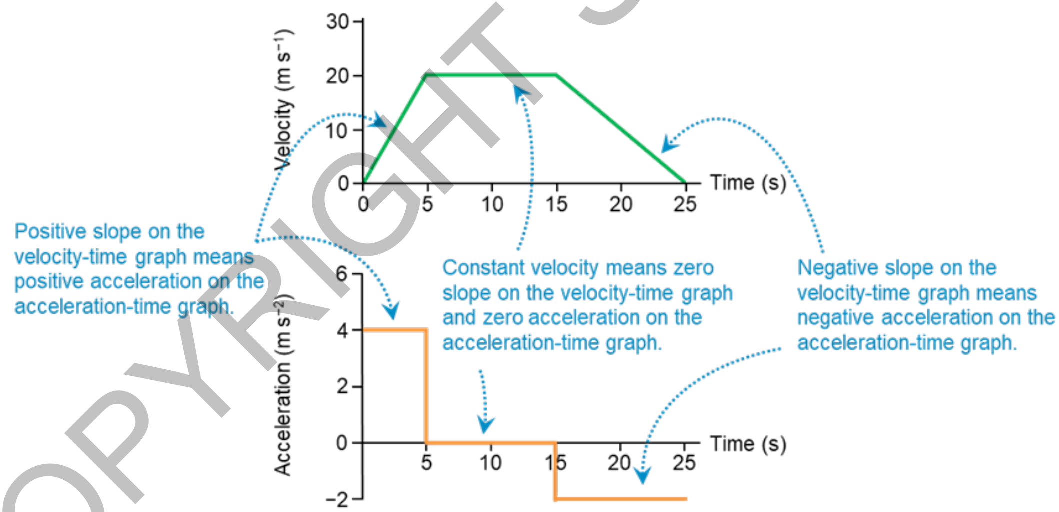


Figure 1.33: Deducing a velocity-time graph from an acceleration-time graph.

You may have noted that the process of deducing an acceleration-time graph from a velocity-time graph is analogous to deducing a velocity-time graph from a position-time graph. Therefore, it is possible to deduce a position-time graph from an acceleration-time graph by producing a velocity-time graph from the acceleration-time graph and then using the information to construct a position-time graph. Combining the three types of graphs provides a complete description of a particle's motion, allowing us to deduce the distance travelled, displacement, average speed, average velocity, instantaneous velocity, average acceleration, instantaneous acceleration, and change in velocity.

Equations of motion quantitatively describe and predict aspects of linear motion.

- Solve and interpret problems using the equations of motion:
  $v = v_0 + at$
  $s = v_0 t + \frac{1}{2}at^2$
  $v^2 = {v_0}^2 + 2as$

In this section, we will begin using a set of equations that describe the motion of particles moving with constant acceleration. These **"equations of motion"** are used to describe a wide range of everyday phenomena, including the motion of free-falling objects. As mentioned in the previous section, if a particle has a constant acceleration, its instantaneous acceleration is equal to its average acceleration, calculated using the formula below.

$$a = \frac{\Delta v}{\Delta t} = \frac{v - v_0}{t - t_0}$$

The initial and final times may be chosen arbitrarily in this formula, but the initial velocity is often given the symbol v_0 to denote the velocity measured at time zero, t_0. This formula is rearranged to yield our first equation of motion, which predicts or calculates a particle's velocity at time, t.

Formula	$v = v_0 + at$

Symbol	Variable	SI unit
v	velocity at time, t	m s^{-1}
v_0	initial velocity	m s^{-1}
a	acceleration	m s^{-2}
t	time interval	s

The formula above describes a straight line on a velocity-time graph, as shown in Figure 1.34. The line crosses the velocity axis at the value v_0 and has a slope a, which agrees with the concepts discussed in the previous section.

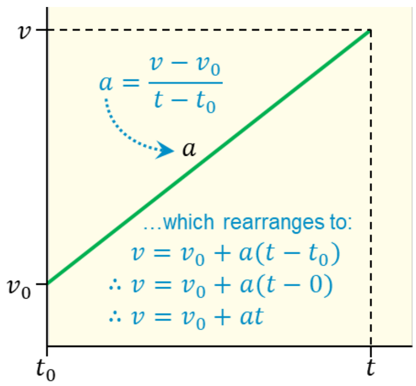


Figure 1.34: Deducing the first equation of motion: velocity as a function of time.

This equation may be rearranged to determine the initial velocity or time when the velocity and acceleration are known, as demonstrated in the following examples.

Example 1.05

A runner accelerates from rest at 1.9 m s^{-2}.

Calculate the speed of the runner after 5.2 s.

v	=	$v_0 + at$
v	=	0 + (1.9 x 5.2)
v	=	9.9 m s^{-1}

Example 1.06

A boat moves with a constant speed of 1.80 m s^{-1} before accelerating at 2.60 m s^{-2}.

Calculate the speed of the boat after 4.50 s.

v	=	$v_0 + at$
v	=	1.80 + (2.60 x 4.50)
v	=	13.5 m s^{-1}

Example 1.07

A sailfish reaches its top speed of 26.4 m s^{-1} after accelerating at a constant rate of 11.3 m s^{-2} over a time interval of 1.85 seconds.

Calculate the initial speed of the sailfish.

v_0	=	$v - at$
v_0	=	26.4 + (11.3 x 1.85)
v_0	=	5.50 m s^{-1}

Example 1.08

A brown hare accelerates from 0.50 m s^{-1} to 18 m s^{-1} at a constant rate of 6.0 m s^{-2} as it runs away from a predator.

Calculate the time interval over which the speed of the hare changes.

t	=	$\frac{v - v_0}{a}$
t	=	$\frac{18 - 0.50}{6.0}$
t	=	2.9 s

Question 40

A person is driving a car on Victor Harbor Road at night at 24 m s^{-1} when a kangaroo leaps onto the road 50 m in front of them.

The person applies the brakes and decelerates in a straight line at 8.0 m s^{-2}.

(a) Calculate the time taken for the car to come to rest.

(2 marks) **KA4**

(b) Determine whether the person comes to rest before hitting the kangaroo.

(3 marks) **KA4**

Question 41

At rest, a small frog extends its legs and leaps with a take-off speed of 3.5 m s^{-1} in 0.05 s.

(a) Calculate the frog's acceleration during take-off.

(2 marks) **KA4**

(b) Calculate the extension of the frog's legs during take-off in cm.

(3 marks) **KA4**

Question 42

A *Helicobacter pylori* bacterium in the stomach accelerates from rest at 160 μm s^{-2}.

(a) Calculate the time taken for the bacterium to reach a speed of 15 μm s^{-1}.

(2 marks) **KA4**

(b) Calculate the bacterium's displacement over this time interval in μm.

(3 marks) **KA4**

Air resistance

By definition, the motion of an object in free-fall is affected by the force of gravity and is "free" from the influence of all other forces. Objects dropped or launched upwards near the Earth's surface are not in free-fall as their motion is affected by **air resistance**. Air resistance, also called **aerodynamic drag** (symbol F_D), is a force that opposes the motion and reduces the vertical speed of an object moving through air, as illustrated in Figure 1.40.

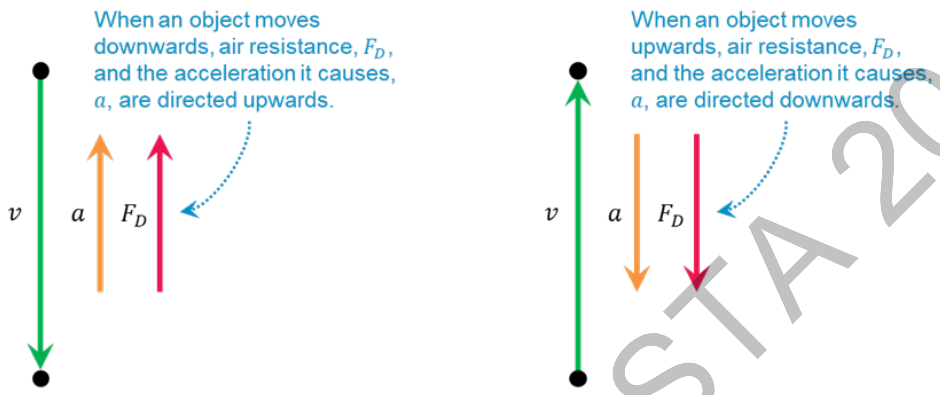


Figure 1.40: The effect of air resistance on an object's vertical motion.

Air resistance always acts in the opposite direction to the motion of an object moving through air. The amount of air resistance an object experiences is dependent on many factors, including its speed, cross-sectional area, and shape. To illustrate the effect of air resistance in simple terms, drop a sheet of paper and a ball from the same height, as shown in Figure 1.41. You will observe the paper drifting slowly to the ground, taking much more time to fall than the ball. This is because the paper has a large cross-sectional area and flat shape under which a mass of air can accumulate and apply a significant force on the paper as it falls. However, if you were to wad the sheet of paper into a tight ball and repeat the experiment, you would notice the paper and ball reach the ground at nearly the same time. This activity reveals the effect of cross-sectional area and shape on the amount of air resistance opposing the object's motion.

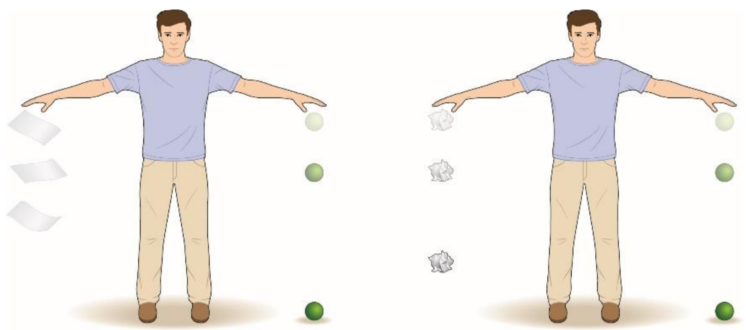


Figure 1.41: The effect of cross-sectional area and shape on air resistance.

Though free-fall is an idealisation that does not apply to many real-world situations, it is still a valid approximation. Therefore, in all the examples in this course, we will assume the effects of air resistance are negligible and that the vertical motion may be considered free-fall.

Despite the name, free-fall is not restricted to objects that are literally falling. Any object moving under the influence of gravity and no other forces is in free-fall. This includes dropped objects as well as those that have been tossed or shot straight up. We can visualise the motion of a free-falling object using motion diagrams and a velocity-time graph (Figure 1.42). The velocity-time graph reveals that the velocity of a free-falling object changes at a steady rate known as the **free-fall acceleration**, or the **acceleration due to gravity** (symbol g). The magnitude of the acceleration due to gravity varies slightly at different places on Earth, but we will use the average value of 9.8 m s^{-2} for calculations in this workbook. Since the acceleration due to gravity is the same for all objects, the motion diagram and velocity-time graph are the same for a low-mass object such as a falling tennis ball and a high-mass object such as a falling boulder. Furthermore, the acceleration due to gravity is always directed downwards, no matter what direction a free-falling object is moving.

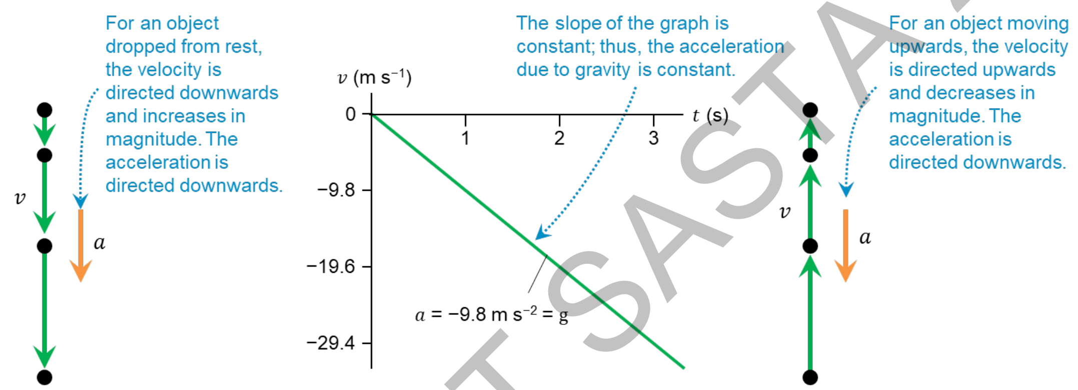


Figure 1.42: Motion diagrams and a velocity-time graph for free-falling objects.

The magnitude of the acceleration due to gravity on Earth indicates that a free-falling object's vertical speed changes by 9.8 m s^{-1} each second. This means that a descending object's speed increases by 9.8 m s^{-1} each second, and an ascending object's speed decreases by 9.8 m s^{-1} each second. Since free-fall is motion with constant acceleration, we can use the equations of motion to describe the motion of free-falling objects. In such cases, the symbol a in the equations is replaced with g. It is important to note that a coordinate system must be used whenever the object moves upwards as the velocity and acceleration have opposite directions. However, it is unnecessary to use a coordinate system when an object is dropped or descending towards the surface as the velocity and acceleration have the same direction.

Example 1.14

A lemon is at rest in a tree when it falls and contacts the ground after 0.8 s.

Calculate the lemon's vertical displacement.

$$s = v_0 t + \frac{1}{2} g t^2$$

$$s = (0 \text{ x } 0.8) + \frac{1}{2} 9.8 \text{ x } (0.8)^2$$

$$s = 3.1 \text{ m}$$

Balanced and unbalanced forces

Particles tend to have more than one force acting on them at a given time, and each of these is represented in a **force diagram**. A force diagram, also called a **free body diagram,** is a diagram of an isolated particle showing all the forces acting on it. Each force is represented by a vector, with the vector's length being proportional to the magnitude of the force on the particle (Figure 1.46).

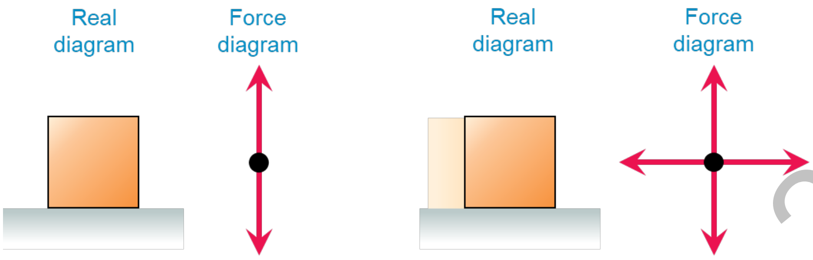


Figure 1.46: Force diagrams.

When analysing a force diagram, it is essential to first consider the forces acting along a single plane, such as the horizontal or vertical. The forces acting along a single plane are **balanced** when the force vectors acting in opposing directions have the same length (Figure 1.47).

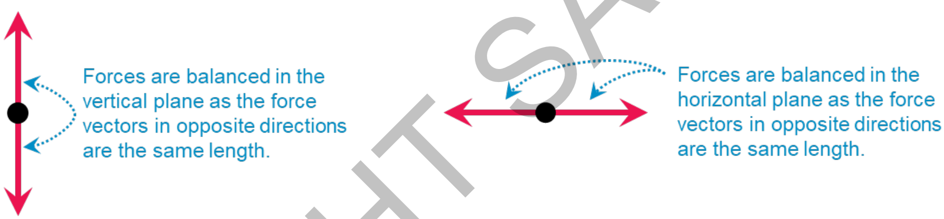


Figure 1.47: Balanced forces.

Conversely, the forces acting along a single plane are **unbalanced** when the force vectors acting in opposing directions have different lengths (Figure 1.48). It is important to note that the forces may be balanced in one plane and unbalanced in another plane.

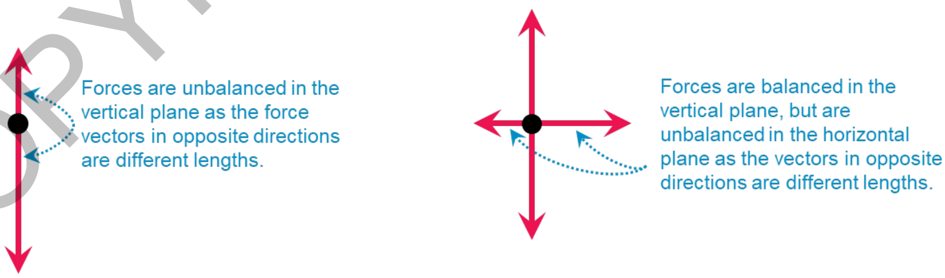


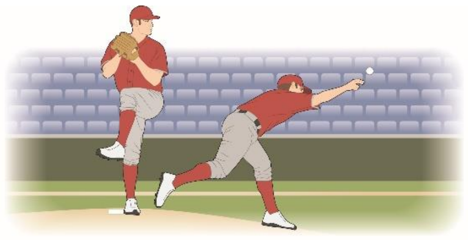
Figure 1.48: Unbalanced forces.

When the forces acting on a particle are unbalanced, there is an overall force on the particle that is equal to the vector sum of the original forces. This vector sum is often called the **resultant** of the forces or the **net force** (symbol $\vec{F}_{net}$). The net force acting on a particle in a given plane is calculated by adding the force vectors in that plane. Since the force vectors act in opposite directions, it is essential to use a coordinate system in which one direction is positive and the other negative. The SI unit of force is the **newton** (symbol N) and is named for Isaac Newton.

Example 1.26

A baseball pitcher exerts a net force on a 0.15 kg baseball that causes it to accelerate at 400 m s^{-2}.

Calculate the net force on the baseball.



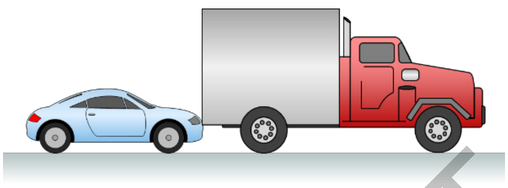
$\vec{F}$	=	$m\vec{a}$
$\vec{F}$	=	0.15 x 400
$\vec{F}$	=	60 N, right

Example 1.27

A car pushes a truck that has a flat battery.

The car exerts a net force of 1125 N on the truck, which accelerates at 0.25 m s^{-2}.

Calculate the mass of the truck.



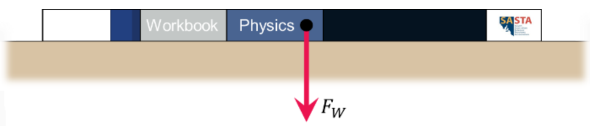
m	=	$\frac{\vec{F}}{\vec{a}}$
m	=	$\frac{1125}{0.25}$
m	=	4500 kg

Mass and weight

Mass and weight are similar but not identical physical quantities. A particle's mass is a measure of how difficult it is to change its velocity when a net force is applied. A particle's mass is proportional to its inertia and determines how hard it is to start an object moving if it is at rest, bring it to rest if it is moving, or change its direction of motion. For example, it is much easier to start an empty shopping trolley moving or change its direction than a trolley filled with groceries. It follows that the empty trolley has less mass than the filled trolley. In addition, mass can also be thought of as a measure of the quantity of matter in an object. In contrast, a particle's weight is a measure of the gravitational force exerted on it by a planet, moon, or star and is calculated as the product of a particle's mass and the acceleration due to gravity. For example, this workbook's weight is a measure of the gravitational force exerted on it by the Earth.

Example 1.28

Calculate the weight of a 1.5 kg physics workbook positioned at Earth's surface.



F_W	=	mg
F_W	=	1.5 x 9.8
F_W	=	14.7 N

Investigating Newton's Second Law

Newton's Second Law of Motion states that acceleration is directly proportional to force when mass is constant. This concept is explored experimentally using the apparatus shown in Figure 1.56. A cart is placed on an air track that provides a cushion of air on which a glider can ride with virtually no friction. A string attaches the glider to a set of slotted masses suspended from a pulley. An experimenter releases the slotted masses, allowing them to fall to the surface. The slotted masses' weight exerts a force on the glider that causes it to accelerate along the air track. The acceleration of the glider is typically measured by a light gate or motion sensor.

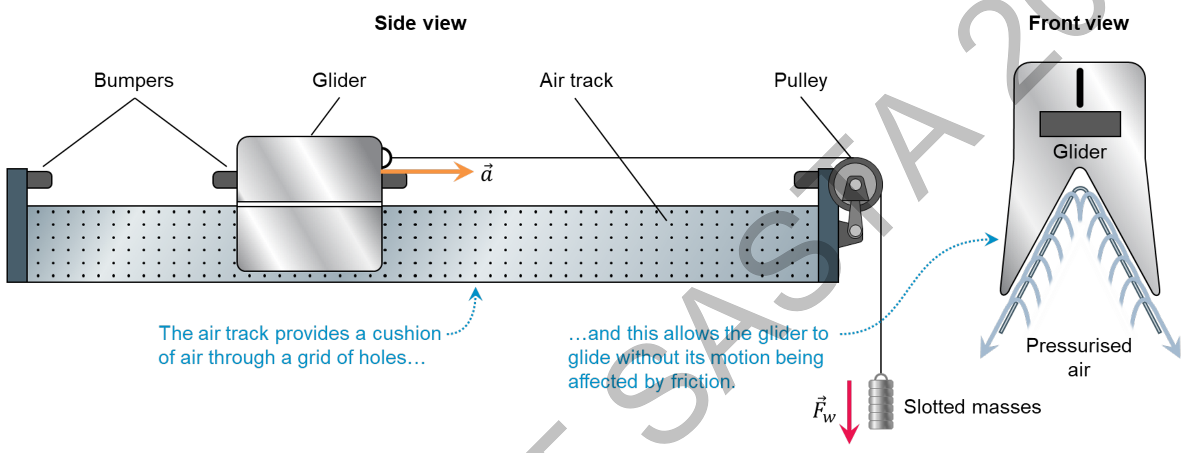


Figure 1.56: Apparatus used to verify Newton's Second Law of Motion.

The experiment is repeated several times by transferring slotted masses from the suspended assembly to the glider to ensure the system's mass remains constant. Each time the experiment is performed, the slotted masses' weight and the resulting acceleration of the glider are recorded and used to prepare a graph of force against acceleration. The slope of the line on the graph is equal to the mass of the system, which, as stated previously, is the sum of the masses of the glider and slotted masses (Figure 1.57).

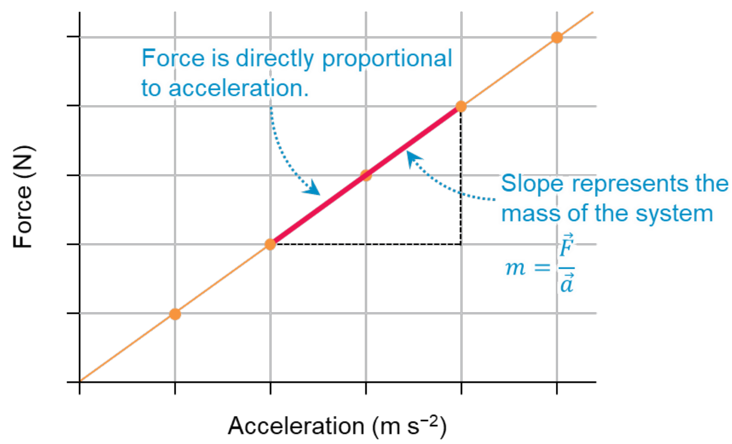
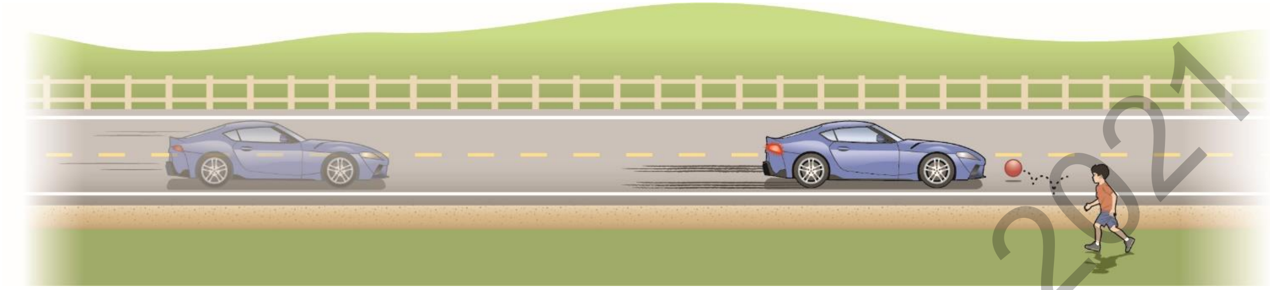


Figure 1.57: Graph of force ($\vec{F}$) against acceleration ($\vec{a}$).

Review Test 1

Question 1

The driver of a 1520 kg car moving at 16.0 m s^{-1} sees a child chasing a ball onto the street in front of them. The driver applies the brakes and decelerates to 4.00 m s^{-1} at a constant rate of 6.00 m s^{-2}.



(a) Calculate the time interval over which the car was decelerating.

(2 marks) **KA4**

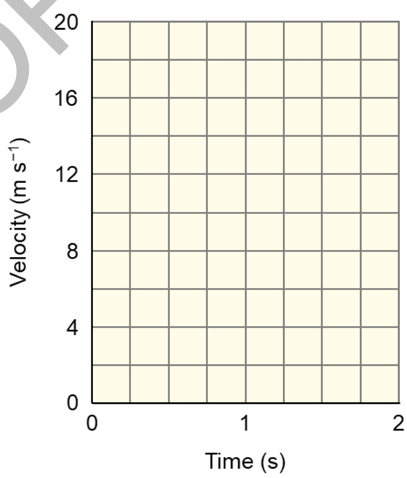
(b) Calculate the magnitude of the force exerted on the car while braking.

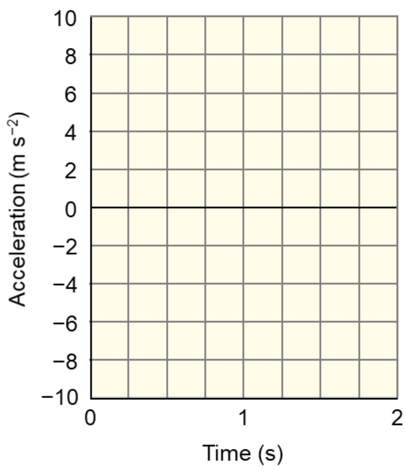
(2 marks) **KA4**

(c) Calculate the distance travelled by the car while braking.

(2 marks) **KA4**

(d) Sketch velocity-time and acceleration-time graphs for the car using the axes below.





(2 marks) **KA4**

Question 4

The diagram below shows a firefighter sliding down a pole.

(a) As they slide, the firefighter tightens their grip, increasing the force exerted on the pole.

Explain what happens when this force is equal in magnitude to their weight.

(2 marks) KA2

(b) A second firefighter of mass 87 kg slides from rest down the 4.0 m pole with constant acceleration and reaches the ground floor in 1.8 s.

(1) Calculate the firefighter's acceleration down the pole.

(2 marks) KA4

(2) Show that the pole exerts an upward force of 640 N on the firefighter.

(2 marks) KA4

(3) State the force exerted by the firefighter on the pole and give a reason.

(2 marks) KA2

(4) Firefighters need to move quickly in an emergency.

Explain how the firefighter could slide down the pole over a shorter time interval.

(2 marks) KA2

2.1: Potential difference and electric current

Atoms contain positively charged protons and negatively charged electrons.

Objects become charged when electrons are transferred from one object to another or redistributed on one object.

Two like charges exert repulsive forces on each other, whereas two opposite charges exert attractive forces on each other.

- Describe electric forces between like charges and between opposite charges.
- Explain various phenomena involving interactions of charge.
- Explain how electrical conductors allow charges to move freely through them, whereas insulators do not.

Suppose you have felt an unpleasant shock when touching a metal door handle, had bits of lint cling to your clothes, or observed a lightning storm. In that case, you are familiar with phenomena involving electric charge and electrical interactions, one of nature's fundamental classes of interactions. In this chapter, we will study electric charges and their interactions.

Electric charge

Electric charge is a fundamental property of matter and is responsible for the electrostatic interactions between electrically charged particles. The ancient Greeks discovered as early as 600 B.C. that amber, a solid, translucent material formed from the fossilised resin of extinct coniferous trees, would attract small, lightweight objects, including feathers (Figure 2.01) and straw when rubbed with wool or fur. Today we say that the amber has become **electrically charged**. The word electric is derived from the Greek word elektron, meaning "amber."

Figure 2.01: Amber

It was thought for some time that the ability to become "charged" was unique to amber. Much later, it was discovered that many other materials behave in this way. For example, a glass rod attracts small objects when rubbed with silk. In this respect, glass and amber have the same property. However, it turns out that these two materials have different types of charge. This property is observed by suspending a small, charged amber rod from a thread, as in Figure 2.02. If a second charged amber rod is brought nearby, the suspended rod rotates away, indicating **a repulsive force** between the two amber rods. We conclude from this observation that objects with the same charge, called "like charges", repel each other. On the other hand, if a piece of charged glass is brought near, the suspended amber rod rotates toward the glass, indicating an **attractive force**. We conclude from this observation that objects with different charges, called "opposite charges", attract one another as in the familiar expression "opposites attract".

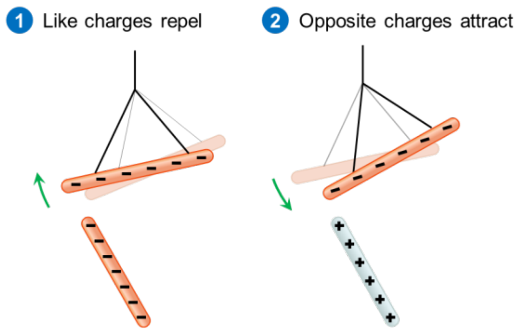


Figure 2.02: Attraction and repulsion

Electric charge

We have seen that amber becomes charged when rubbed with fur. But how exactly does the amber become charged? Initially, it was thought that the friction of rubbing created the observed charge. However, we now know that rubbing the fur across the amber results in a transfer of charge from the fur to the amber, with the total amount of charge being unchanged, as shown in Figure 2.06. Before charging, the fur and amber are both neutral. During the rubbing process, electrons are transferred from fur to amber, giving the amber a net negative charge and the fur a net positive charge. However, at no time during this process is charge ever created or destroyed. This is an example of the **law of conservation of charge**, a fundamental conservation law in physics, which states the total electric charge in the universe is constant. No physical process can increase or decrease the total amount of electric charge in the universe.

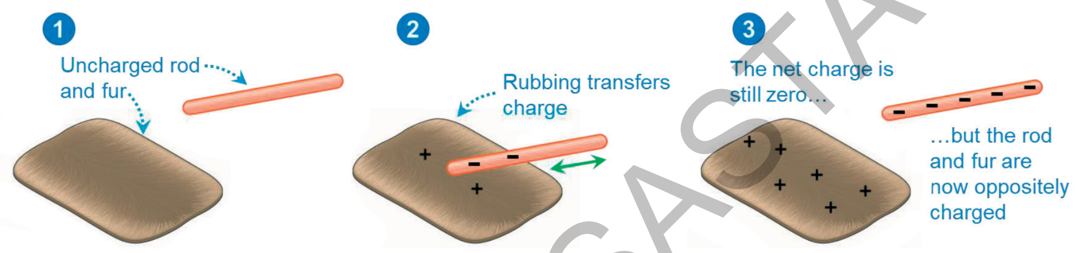


Figure 2.06: Charge transfer between fur and amber.

The transfer of charge between objects such as the amber and fur is caused by the movement of electrons. In a typical solid, the nuclei of atoms occupy a fixed position, but the outer electrons are often weakly bound and are separated relatively easily. As fur is rubbed across amber, some of the outer electrons that were initially part of the fur are separated from their atoms and transferred to the amber. The atoms in the fur lose electrons and are now positively charged, and the atoms in the amber receive extra electrons and become negatively charged. This is an example of electrostatic charging by **separation**.

Triboelectric Charging

When two materials are rubbed together, the magnitude and sign of the charge acquired by each material depend on how strongly it holds onto its electrons. For example, if silk is rubbed against glass, the glass acquires a positive charge. It follows that electrons have been transferred from the glass to the silk, giving the silk a negative charge. However, if silk is rubbed against amber, the silk becomes positively charged as electrons pass from the silk to the amber. These results are understood by referring to Figure 2.07, which shows the relative charging due to rubbing, known as **triboelectric charging**, for different materials.

Material	Relative charge with rubbing
Fur	++++++
Glass	+++++
Human hair	++++
Nylon	+++
Silk	++
Paper	+
Cotton	–
Wood	– –
Amber	– – –
Rubber	– – – –
PVC	– – – – –
Teflon	– – – – – –

Figure 2.07: Triboelectric charging

Charge polarisation

We know that opposite charges attract, but it is also possible for a charged object to attract small objects with zero net charge through a mechanism called **polarisation**. Polarisation is the separation of charge in an object, forming distinct regions of positive and negative charge called "poles". To see how polarisation works, consider Figure 2.10, in which a negatively charged rod is held close to an enlarged view of a neutral object. Atoms near the neutral object's surface become elongated because the negative electrons are repelled from the rod while the positive protons are attracted. As a result, a net positive charge develops near the rod's surface as the atoms' positive and negative charge has become polarised.

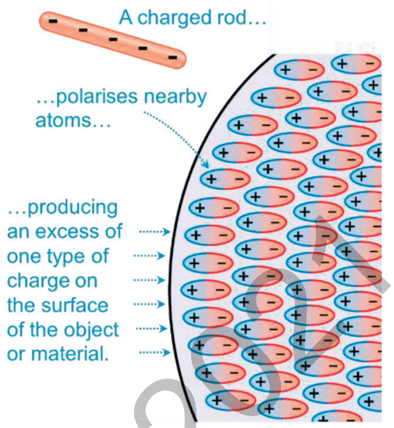


Figure 2.10: Polarisation of charge on neutral atoms.

The effect of polarisation is observed by rubbing a balloon on your hair and holding the balloon near a stream of water. In this case, electrons are transferred from your hair to the balloon. The negatively charged balloon then polarises water molecules in the uncharged water stream leading to an attractive force between the water and the balloon, as seen in Figure 2.11.

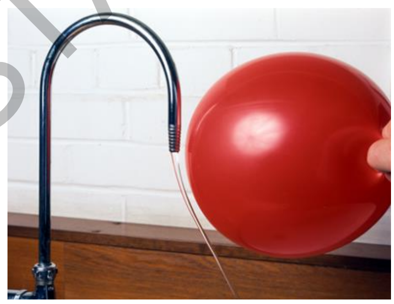


Figure 2.11: Polarisation of water

The force produced between the charged and neutral objects is always attractive, as illustrated in Figure 2.12. When a positively charged rod is brought near a neutral metal sphere, the negative charges at the top of the sphere are more strongly attracted to the rod than the more distant positive charges, which are repelled. The result is a net attractive force between the rod and the sphere. This polarisation force arises because the charges in the metal are slightly separated, not because the rod and metal are oppositely charged. Had the rod been negatively charged, the positive charge would move to the sphere's upper side and negative charge to the bottom. This would again lead to an attractive force between the rod and the sphere. Thus, the polarisation force between a charged object and a neutral one is always attractive.

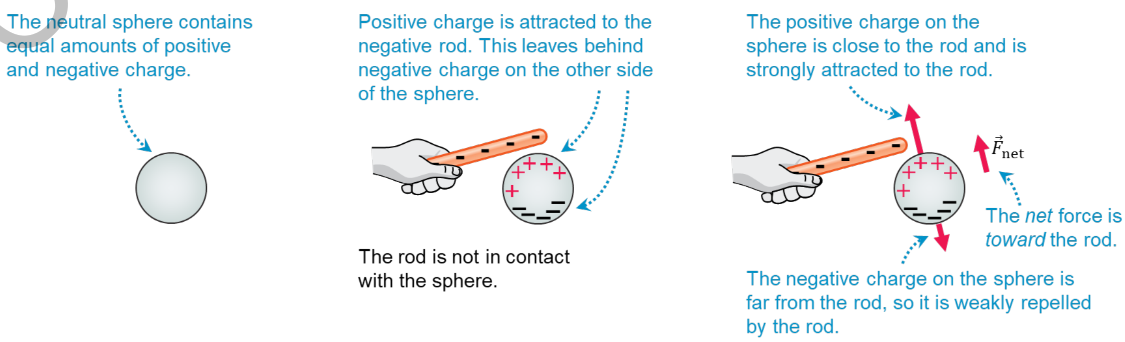


Figure 2.12: The polarisation force is always attractive.

Electric potential difference

Although electrons move freely in metal wires, they do not flow unless the wires are connected to a source of **electric potential difference** such as a battery, wall-outlet, power supply, generator, or solar cell. These devices use energy to separate positive and negative charges, and this charge separation produces an electrical potential difference that drives current flow in circuits. Charge separation produces two distinct regions in the circuit where the charges have different amounts of potential energy. The charges flow through the circuit from the higher potential region to the lower potential region. A close analogy is water flow in a garden hose. Imagine that you and a friend each hold one end of a garden hose filled with water, as depicted in Figure 2.20. If the two ends of the hose are held at the same level, the water does not flow as the two ends have the same potential energy. However, if one end is raised above the other, water flows from the high end, where the potential energy is higher, to the low end, where potential energy is lower.

Figure 2.20: Water flow as an analogy for electric current.

A source of electric potential difference performs a similar function in an electric circuit by producing a difference in potential energy between its two ends or **terminals**. The terminal corresponding to a high electric potential is denoted by a +, and the terminal corresponding to a low electric potential is denoted by a −. When the source of electric potential difference is connected to a circuit, electrons move in a closed path from the negative terminal, through the circuit, and back to the positive terminal. An example of a simple electric circuit is shown in Figure 2.21, in which wires connect a power supply to a switch and lightbulb.

When the switch is "closed", as in Figure 2.21, a closed path is produced through which the electrons flow from the power supply's negative terminal, through the circuit and light bulb, and return to the positive terminal. The electrons do work as they pass through the light bulb, causing it to glow. When the switch is "open", the path is open, and the electrons cannot flow into the light bulb, preventing it from glowing.

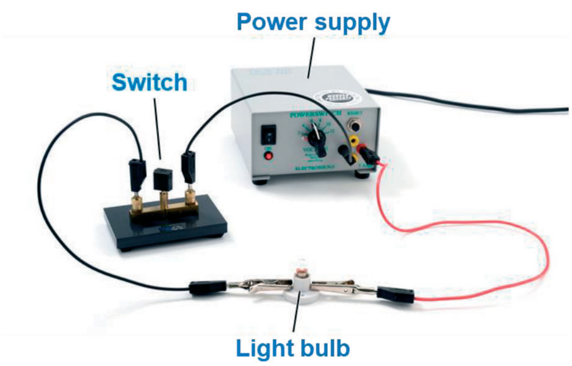


Figure 2.21: Simple electric circuit.

A mechanical analogue to the circuit in Figure 2.21 is shown in Figure 2.22. In this system, the person raising the water is analogous to the power supply, the paddle wheel is analogous to the lightbulb, and the water is analogous to the electric charge. Like the power supply, the person does work in raising the potential energy of the water. As the water falls back to its original level, it does work by turning the paddle wheel.

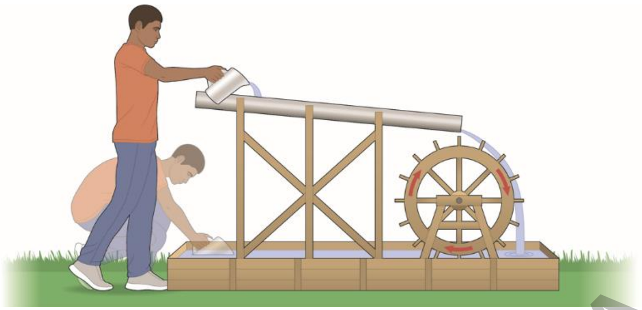


Figure 2.22: A mechanical analogue to a simple electric circuit.

When a battery or power supply is disconnected from a circuit and carries no current, the difference in electric potential between its terminals is called its **potential difference** or **voltage** (symbol ΔV). The potential difference determines the amount of work a battery or power supply does to move a certain amount of charge around a circuit. To be specific, the work done by the source of electric potential difference is the product of its potential difference, and the quantity of charge moved between its two terminals. Thus, the work done is equal to the change in potential energy of a charge when moved between the two terminals, and its magnitude is calculated using the formula below.

Formula	$W = \Delta V q$

Symbol	Variable	SI unit
W	work done	J
ΔV	potential difference	V
q	charge	C

Figure 2.23: Alessandro Volta

The SI unit of potential difference, the **volt** (symbol V), is named for the Italian physicist Alessandro Volta (Figure 2.23) and is defined as 1 joule per coulomb.

Example 2.02

A 1.5 V battery supplies 26 C of charge to a light bulb in a torch.

Calculate the work done by the battery.

W	=	$\Delta V q$
W	=	1.5 x 26
W	=	39 J

Safety features in household electric circuits

Household electric circuits pose potential dangers to homes and their occupants. For example, when several electrical devices are plugged into a single outlet, a high current flows through the wires connected to that outlet, and the corresponding power dissipation can turn them red hot and lead to a fire (Figure 2.26). In Australia, 40% of residential fires are caused by electrical faults in household circuits. To protect against this type of danger, household circuits use fuses and circuit breakers. **Fuses** are devices containing a thin metal strip (Figure 2.27) that melts and breaks open the circuit when the current exceeds a specified limit (typically 15 A in household circuits). **Circuit breakers** provide similar protection using a switch that incorporates a bimetallic strip (Figure 2.27). When the bimetallic strip is cool, the contacts are connected, and the current flows through the circuit. However, when a large current heats the strip, it bends enough to separate the contacts and prevent current flow. Unlike the fuse, which cannot be used after the wire melts, a circuit breaker can be reset when the bimetallic strip cools and returns to its original shape.

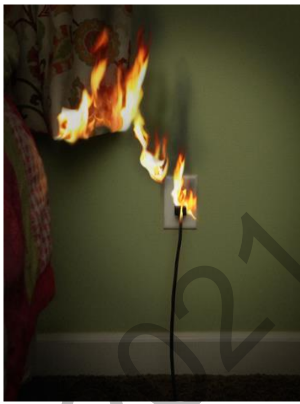


Figure 2.26: Electrical fire

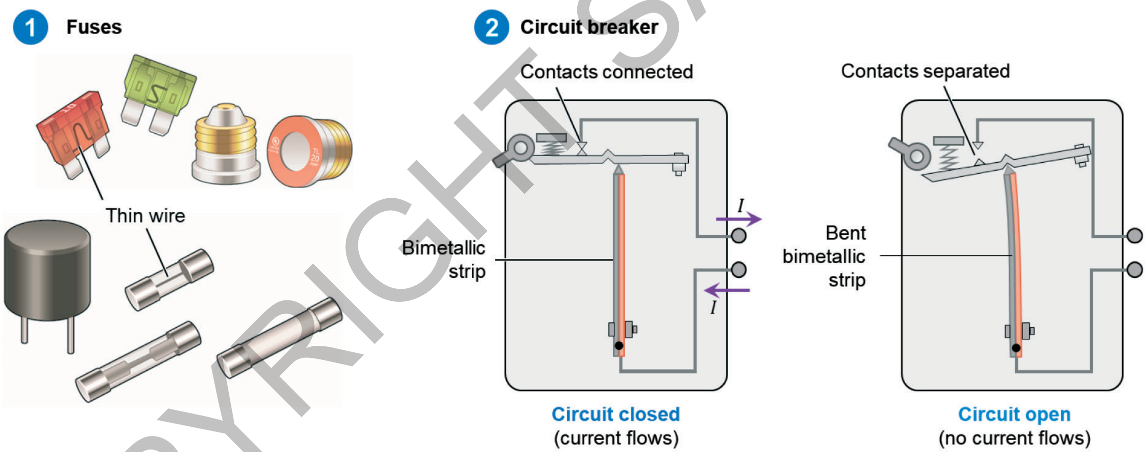


Figure 2.27: Fuses and circuit breaker.

Household circuits also pose a shock hazard to the occupants and at much lower current levels than those required to trigger a fuse or a circuit breaker. For example, it only takes a current of 1 mA to give a person a tingling sensation. Currents in the range of 10 mA to 20 mA cause respiratory arrest and produce muscle spasms that make it difficult to let go of the conductor, as in Figure 2.28. When currents reach 100 mA to 200 mA, the heartbeat is interrupted by an uncoordinated twitching referred to as ventricular fibrillation. As a result, currents in this range can prove to be fatal in a matter of seconds.

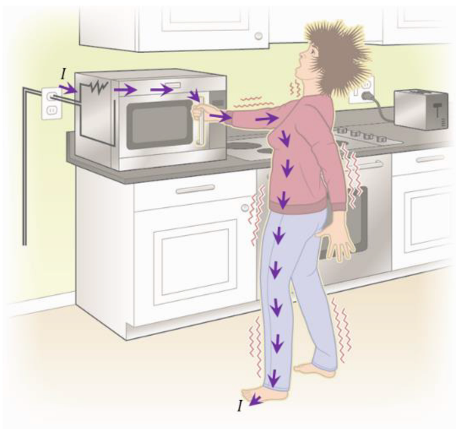


Figure 2.28: Electric shock

Several strategies are employed to reduce the danger of electric shock. The first line of defence is the three-prong grounded plug, shown in Figure 2.29. The third prong, called the earth pin, is connected directly to the ground when plugged into a three-prong receptacle of the power outlet. In addition, the third prong is wired to the outer enclosure of an electrical appliance. Suppose something goes wrong within the appliance, and a high-potential wire comes into contact with the outer enclosure. In that case, the resulting current flows through the third prong rather than through the body of a person who happens to touch the case, as depicted in Figure 2.28. The third prong provides a low-resistance path to the ground that can be wired to the case of an appliance. If a "hot" wire touches the case, the current flows through the grounded wire rather than the user. For example, if a malfunctioning electric drill is connected to a wall socket via a two-prong plug, a person may receive a shock, as shown in Figure 2.30. When the drill malfunctions when connected via a three-prong plug, a person touching it receives no shock since electric charge flows through the third prong and into the ground rather than through the person's body. If the ground current is appreciable, the circuit fuse blows.

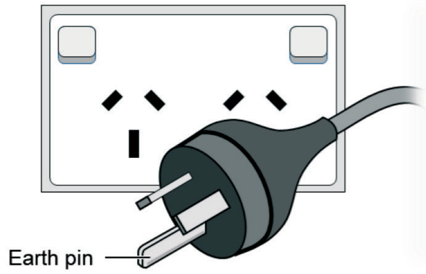


Figure 2.29: Grounded plug

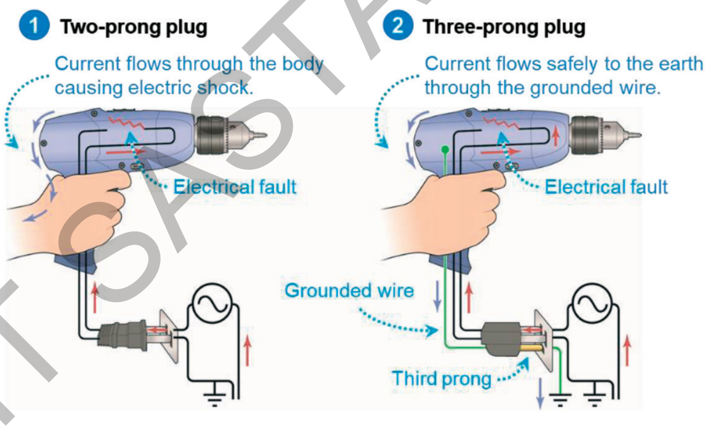


Figure 2.30: Malfunctioning drill.

A greater level of protection is provided by a **residual-current device (RCD)** (Figure 2.31). The wires carrying a current to the appliance pass through a small iron ring. When the appliance functions normally, the two wires carry equal currents in opposite directions, producing opposing magnetic fields that cancel out. Suppose a malfunction occurs in the appliance, such as a frayed wire contacting the appliance's case. In that case, the current that would ordinarily return through the power cord may pass through the user's body instead and into the ground. In such a situation, the two wires' currents are different, and the wire carrying current to the appliance now produces a net magnetic field within the iron ring. The changing magnetic field in the ring induces a current in the sensing coil wrapped around the ring, and the induced current triggers a circuit breaker in the RCD. This cuts the current flow to the appliance within a millisecond, protecting the user from electric shock.

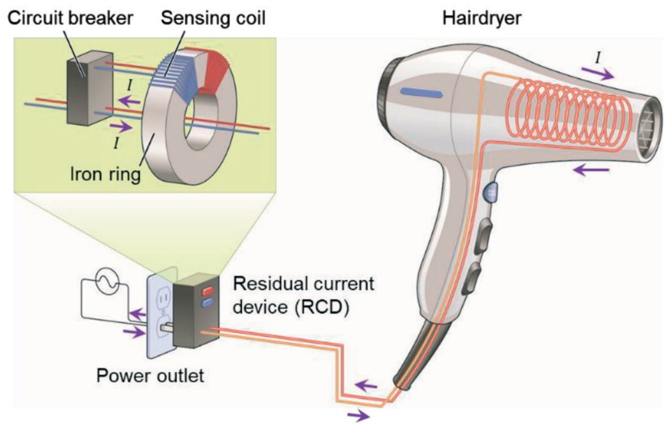


Figure 2.31: Residual current device

Kirchhoff's Laws

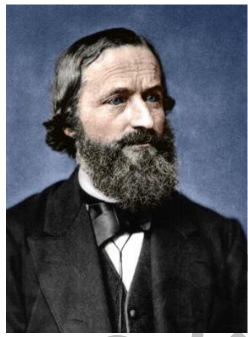


Figure 2.43: Gustav Kirchhoff

A circuit diagram is an essential tool for analysing the function of an electric circuit. Our techniques for analysing circuits are based on the physical principles of potential differences and currents. To find the currents and potential differences in a circuit, we use two laws introduced by the German physicist Gustav Kirchhoff (Figure 2.43). Kirchhoff's laws express charge conservation (the junction law) and energy conservation (the loop law) in a closed circuit.

In general, a **junction** is any point in a circuit where three or more wires meet. **Kirchhoff's junction law** states that the current entering any junction in a circuit must equal the current leaving that junction. If this were not the case, charge would either build up or disappear from a circuit. As an example, consider the circuit shown in Figure 2.44. At point A, three wires join to form a junction. In this example, the current entering the junction, I_1; is equal to the sum of the currents leaving the junction $I_2 + I_3$.

$$I_1 = I_2 + I_3$$

This is Kirchhoff's junction law applied to the junction at point A.

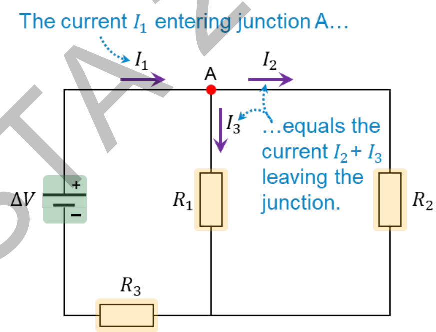


Figure 2.44: Junction law

Kirchhoff's junction law is an application of the law of conservation of charge. We can also apply the law of conservation of energy to circuits. A charge has potential energy due to its position within the circuit. A positive charge near the positive terminal of the power supply or battery has high potential energy, and the same charge positioned next to the negative terminal has low potential energy. If a charged particle moves around a closed-loop and returns to its starting point, there is no net change in its electric potential energy: $\Delta E_p = 0$. Since $\Delta V = \frac{W}{q} = \frac{\Delta E_p}{q}$, the net change in potential difference around any loop or closed path must also be zero. Figure 2.45 shows a circuit consisting of a battery and two resistors. If we start at point A in the lower-left corner, at the battery's negative terminal, and plot the potential around the loop, we get the graph shown in Figure 2.45. The potential increases as charges move "uphill" through the battery, then decreases in the two "downhill" steps, one for each resistor. If we add all potential differences around the loop formed by the circuit, the sum must be zero. This result is known as **Kirchhoff's loop law**:

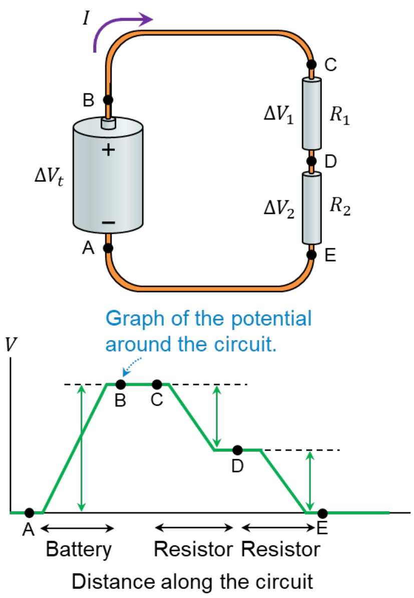


Figure 2.45: Loop law

$$\Delta V_t = \Delta V_1 + \Delta V_2$$

Temperature

Consider a simple gas in a container, as in Figure 3.02. We have defined thermal energy as the energy associated with the motion of atoms that make up an object. Because there are no bonds, the atoms in the gas have only kinetic energy due to their motion. Thus, the thermal energy of the gas is equal to the total kinetic energy of its atoms. If you take a container of gas and place it over a flame, as in Figure 3.03, heat flows from the hot flame to the cooler gas. As Figure 3.03 shows, heating causes the atoms to move faster, increasing the gas' kinetic and thermal energy. Heating the gas also increases its temperature, and this observation suggests that thermal energy and temperature are related quantities. But how? We get an important hint from the fact that a system's temperature does not depend on its size. If you mix two glasses of water, each at 20°C, you have a larger volume of water at the same temperature. The combined volume has more atoms, and therefore a greater total kinetic and total thermal energy, but each atom is moving about at the same speed it had before, and so the average kinetic energy per atom is unchanged. We conclude from this that temperature (symbol T) is a measure of the average kinetic energy of the atoms in the gas.

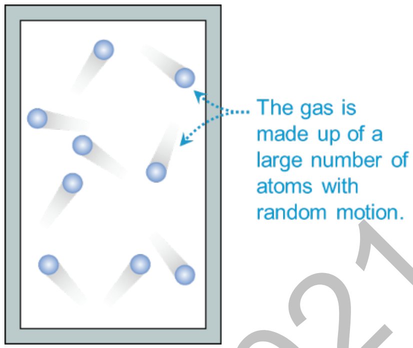


Figure 3.02: Simple gas in a container

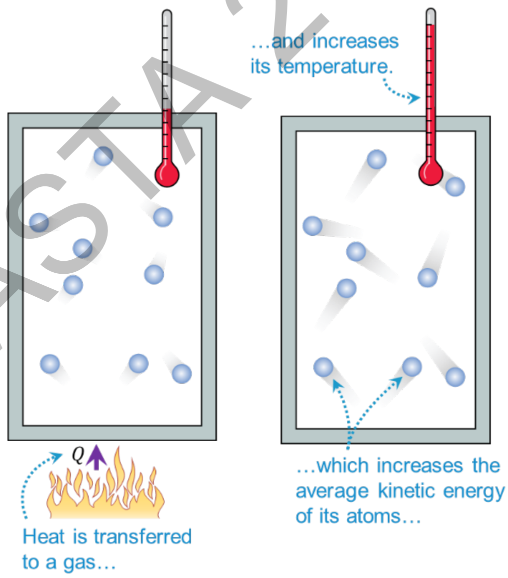


Figure 3.03: Simple gas in a container

Thermal equilibrium

Two objects are in thermal contact if heat can flow between them. In general, when a hot object is brought into thermal contact with a cold object, heat will be exchanged. The hot object cools off, and its atoms move more slowly, while the cold object warms up, and its atoms move more rapidly. After some time in thermal contact, the transfer of heat ceases. At this point, we say that the objects are in **thermal equilibrium**. Two objects in contact are in thermal equilibrium when they have the same temperature. The process of thermal equilibrium is illustrated in Figure 3.04.

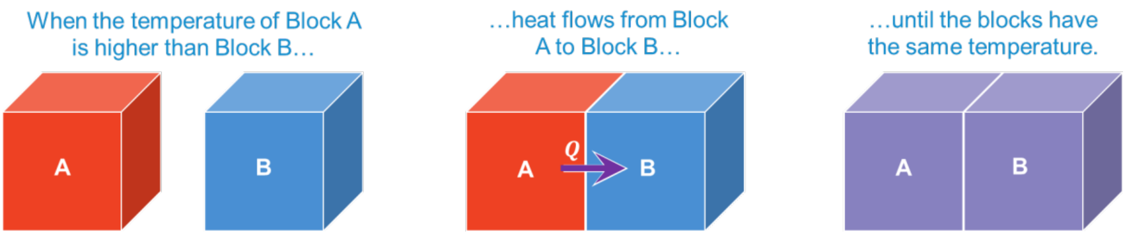


Figure 3.04: Two objects coming to thermal equilibrium.

Heat transfer

We have learned that heat is the flow of energy between two objects due to a temperature difference. Heat is transferred between objects in a variety of ways. The Sun, for example, warms the Earth from across 150 million kilometres of empty space by a process known as radiation. As the sunlight strikes the ground and raises its temperature, the air at ground level gets warmer and begins to rise, producing a further exchange of heat through convection. Finally, if you walk across the ground with bare feet, you feel the warming effect of heat entering your body by conduction. In this section, we consider each of these three mechanisms of heat transfer in detail.

Conduction

Perhaps the most familiar form of heat transfer is **conduction**, which is heat flow directly through a physical material. For example, if you hold one end of a metal rod and put the other end into a fire, it does not take long before you feel the warmth on your end. The heat you feel is transported along the rod by conduction. Let us consider this observation from a microscopic point of view. When you placed one end of the rod into the fire, the high temperature at that location caused the atoms to vibrate at higher frequencies with an increased amplitude. These atoms collide with their neighbours and cause them to vibrate with a greater amplitude as well. Eventually, the effect travels from atom to atom across the rod's length, resulting in the macroscopic phenomenon of conduction. Figure 3.20 shows a metal rod placed between a hot reservoir (a fire) and a cold reservoir (a block of ice). In this example, heat is transferred along the rod by collisions between fast-moving atoms at the hot end and slower-moving atoms at the cold end.

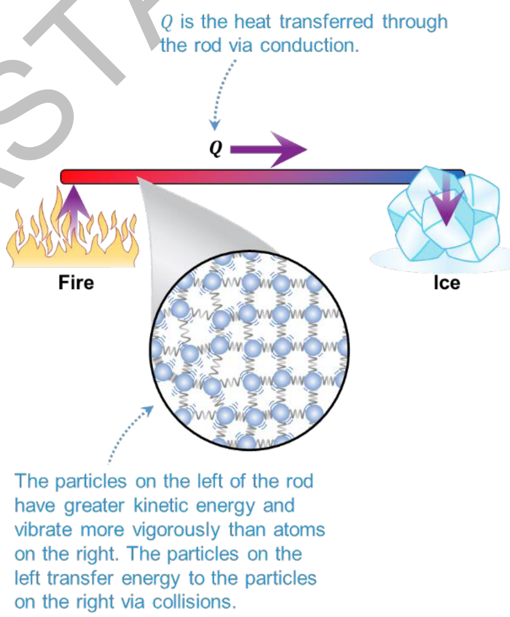


Figure 3.20: Conduction

The rate at which heat flows through a material by conduction is dependent on the temperature difference between the two materials, with heat flowing more rapidly when the temperature difference is greater. In addition, some materials, called **conductors**, conduct heat very well, whereas other materials, called **insulators**, conduct heat poorly. The quantity that characterises whether the material is a good conductor of heat or a poor conductor is called the material's **thermal conductivity** (symbol k). Values of k for some common materials are listed in Figure 3.21; a larger k value means a material is a better conductor of heat.

Material	k (W m^{-1} K^{-1})
Diamond	1000
Copper	400
Aluminium	235
Iron	72
Stainless steel	14
Ice	1.7
Glass	0.90
Concrete	0.80
Skin	0.50
Muscle	0.46
Fat	0.21
Wood	0.15
Fur, feathers, wool	0.02–0.06
Air	0.025

Figure 3.21: Thermal conductivity

Solids tend to have higher thermal conductivities when compared with liquids and gases. Thermal conductivity is greater in solids as the particles are closer together, allowing energy to be transmitted more rapidly through collisions. Thermal conductivity is lower in liquids and gases as the particles are more separated so that collisions do not occur frequently enough to enable efficient energy transfer through the material. The low thermal conductivity of liquids is demonstrated by placing an ice cube at the base of a test tube containing liquid water, as in Figure 3.22. The water can be heated to its boiling point, but the ice cube does not melt as heat flows too slowly through the water to melt the ice cube.

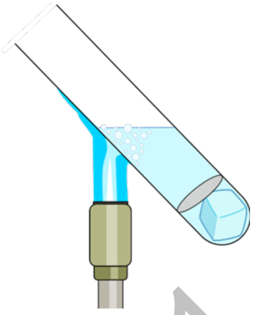


Figure 3.22: Conductivity in liquids

The low thermal conductivity of air is demonstrated by placing a matchhead a short distance from a burner's flame, as in Figure 3.23. The match-head contains flammable chemicals that ignite when sufficient heat is transferred. However, since the air is a poor conductor, sufficient heat is not transferred to the matchhead, and the match does not ignite.

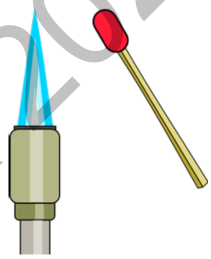


Figure 3.23: Conductivity in gases

An application of thermal conductivity is the insulated window. Most homes today have double-glazed windows as a means of increasing their energy efficiency. If you look closely at one of these windows, you will see that it is constructed from two panes of glass separated by a gap filled with argon or krypton gas, as in Figure 3.24. Thus, heat flows through three different materials in series as it passes into or out of a home. The fact that the argon or krypton gas' thermal conductivity is about 40 times smaller than that of glass means that the insulated window significantly reduces heat flow compared with a single pane of glass.

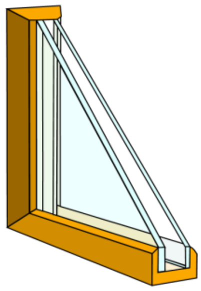


Figure 3.24: Double-glazed window.

As a final example of conduction, many animals transfer heat by a mechanism known as **countercurrent exchange** (Figure 3.25). As warm blood flows through the arteries, it passes through constricted regions where the arteries and veins are packed closely together. The warmer arterial blood flowing into the legs transfers heat to the cooler venous blood returning to the body. Thus, the counter-flowing streams of blood serve to maintain the core body temperature of the animal while at the same time keeping the legs and feet at much cooler temperatures. The feet still receive the oxygen and nutrients carried by the blood, but they stay at a relatively low temperature to reduce the amount of heat lost to the surroundings.

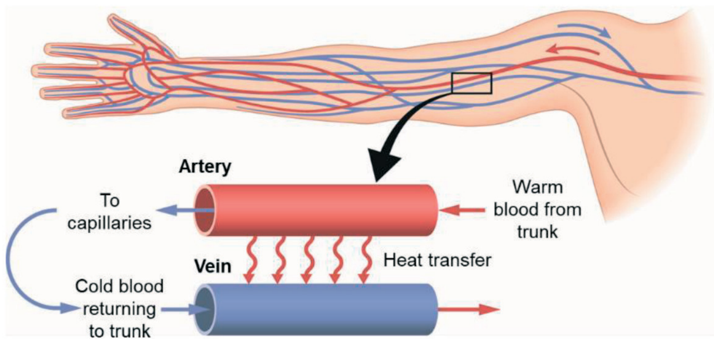


Figure 3.25: Countercurrent exchange

Work

When we push a trolley in a supermarket or pull a suitcase through an airport, we do work. In physics, **work** (symbol W) is the process of transferring energy from the environment to an object, or from an object to the environment, by applying forces. Work is done when a force acts on an object while the object undergoes a displacement. The work done on or by the object is proportional to the magnitudes of the force (F) and the resulting displacement (s). To be specific, suppose we push a box with a constant force, as shown in Figure 4.01. If the box is moved in the direction of the constant force, the work done is the product of the force and box's displacement and is calculated using the formula below.

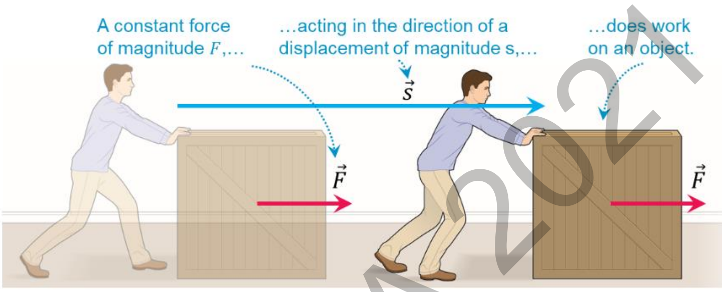


Figure 4.01: Work done by a constant force

Formula	$W = Fs$	
Symbol	**Variable**	**SI unit**
W	work	J
F	constant force	N
s	displacement	m

Example	W (J)
Volcanic eruption	10^{20}
Burning one litre of petrol	10^{7}
Human daily food intake	10^{7}
Melting an ice cube	10^{4}
Heartbeat	0.5
Turning the page of this book	10^{-3}
A flea hopping	10^{-7}
Breaking a hydrogen bond in a DNA molecule	10^{-20}

Figure 4.02: Typical values of work

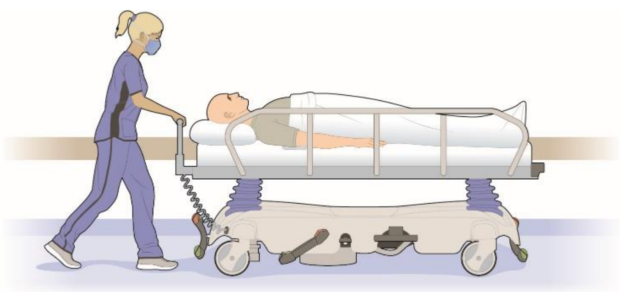
The SI unit of work is the **joule** for James Joule, who was discussed in Chapter 3.2. One joule of work is done in lifting an apple one metre, lighting a 100-watt lightbulb for 0.01 second and heating 0.2 mL of water by 1.0 degree Celsius. Some additional examples are listed in Figure 4.02.

Example 4.01

An intern pushes a patient on a gurney through the emergency room with a constant force of 60 N.

(a) Calculate the work done by the intern in pushing the patient and gurney 15 m.

$$W = Fs$$
$$W = 60 \times 15$$
$$W = 900 \text{ J}$$



(b) Calculate the distance the intern must push the gurney to do 450 J of work.

$$s = \frac{W}{F}$$
$$s = \frac{450}{60}$$
$$s = 7.5 \text{ m}$$

We have seen that work is an energy transfer process that occurs when a force is exerted on or by an object through a displacement. It is important to note three interesting points about our definition of work. The first point is that only the component of the force in the direction of the object's displacement does work. The maximum work is done when the force is parallel to the displacement, and forces perpendicular to a displacement do no work. For example, a person holding a briefcase while walking horizontally at a constant speed, as in Figure 4.03, does no work on the briefcase and transfers no energy to it, as the force on the briefcase is perpendicular to its displacement.

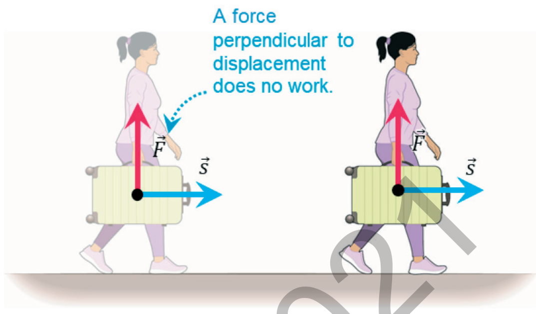


Figure 4.03: Force perpendicular to displacement

The second point is that the work done on or by an object can be positive or negative depending on the directions of the force and displacement. Work is *positive* when the force and displacement have the *same* direction and is *negative* when the force and displacement have *opposite* directions. Figure 4.04 shows that positive work is done when an apple falls as the force and displacement are parallel and negative work is done when the apple is thrown upwards as the force and displacement are opposite.

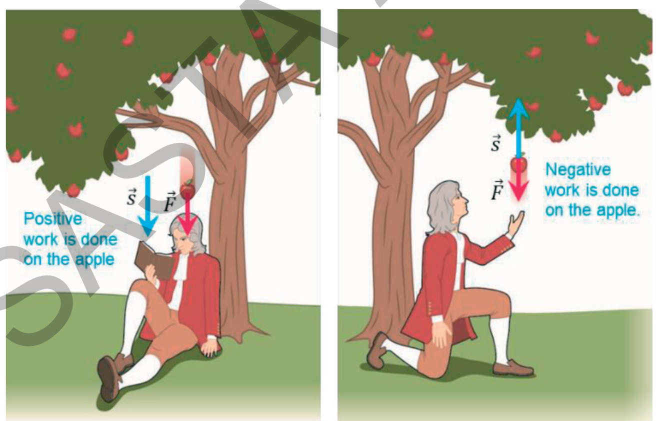


Figure 4.04: Positive and negative work

The third point is that no work is done when the displacement is zero, and this is true regardless of how great the applied force. Energy is transferred as work only when an object moves while the force acts through a displacement. A force applied to a stationary object transfers no energy to the object and does no work. For example, the weightlifter in Figure 4.05 struggles to hold the barbell over his head. But during the time the barbell remains stationary, he does no work on it because its displacement is zero. Why then is it so hard for him to hold it there? The repeated contraction and expansion of individual muscle cells uses stored chemical energy, tiring us out. Thus, even when the bar is "at rest," his muscles are doing mechanical work on a microscopic level.

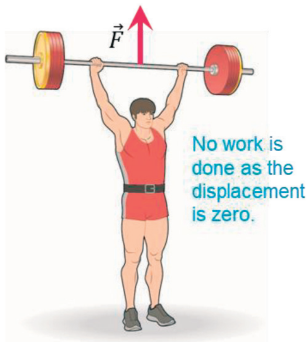


Figure 4.05: Weightlifter

Similarly, if the part of the object on which the force acts undergoes no displacement, no work is done. For example, the skater in Figure 4.06 pushes against the wall with her hands. Even though the wall pushes on the skater with a normal force, the wall does no work on her because her body undergoes no displacement.

Figure 4.06: Pushing a wall

Energy transfers

In physics, a **system** is an object or group of objects chosen for studying the changes that result from varying physical conditions. A system may be complex such as a planet, or relatively simple, as the liquid in a container. Systems transfer energy from one another in different ways. We have seen how energy is transferred when work is done on or by a system, but energy can also be transferred as heat, radiation and electricity.

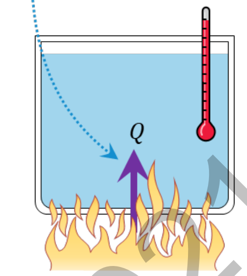


Figure 4.09: Energy transfer as hea

We learned in Chapter 3 that energy flows as heat within a system or between systems when there is a temperature difference. For example, heat is transferred from a flame to a mass of water in Figure 4.09. Energy transfer also occurs by radiation when electromagnetic waves are transferred from a higher temperature system to a lower temperature system.

We learned in Chapter 2 that energy is transferred through a complete electric circuit. In Figure 4.10, the charges transfer energy between the battery and circuit components. In addition, the battery transfers energy to the charges when it moves them between its two terminals.

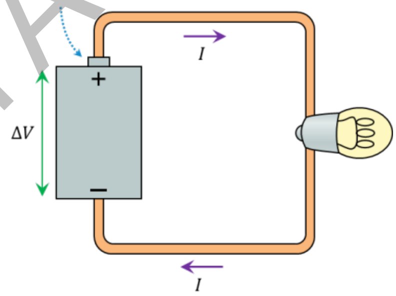


Figure 4.10: Energy transfer in a circuit.

Energy transformations

We have seen that objects contain different forms of energy. Interestingly, one form of energy can be **transformed** into another form. For example, a roller coaster's gravitational potential energy at the top of the track is transformed into kinetic energy as the coaster descends; the chemical energy of petrol is transformed into a moving car's kinetic energy, and electrical energy is transformed into light and heat in a light bulb's filament. In all the energy transformations described, no energy is lost or gained; the energy is transformed. Figure 4.11 conveys a sense of energy transformation. A tiny amount of the Sun's nuclear energy is transformed into light, which is then transformed into chemical energy in plant cells. This chemical energy is transferred to a human through digestion and is then transformed into the weights' gravitational potential energy as they are lifted.

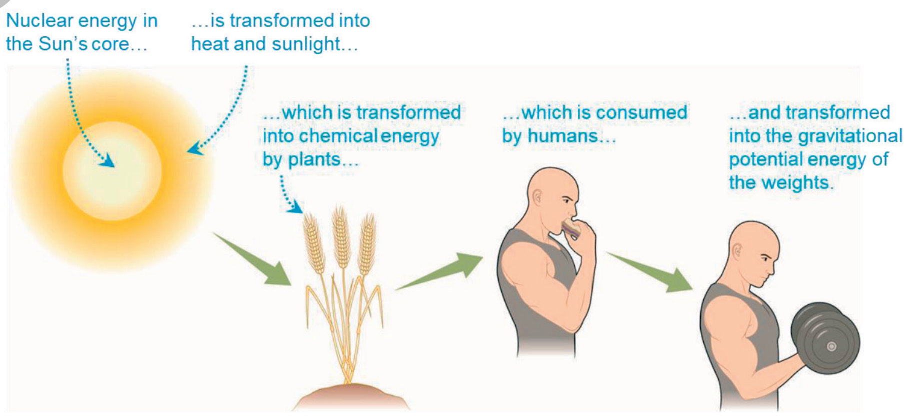


Figure 4.11: Energy transformation.

Conservation of Energy

We have seen that energy can be transferred from one system to another through heat transfer or work and transformed from one form to another. The heat transferred or work done on a system represents energy transferred into or out of the system. This transferred energy changes the system's energy by precisely the amount of heat transferred or the amount of work done. Writing the change in the system's energy as ΔE, we can represent these ideas mathematically as:

$$\Delta E = Q$$
$$\Delta E = W$$

Suppose now we have an **isolated system**, one that is separated from its surrounding environment so that no energy is transferred into or out of the system. This means that no heat is transferred, and no work is done on the system. The energy within the system may be transformed from one form into another, but the total energy of an isolated system, the sum of all the individual kinds of energy, remains constant. We say that an isolated system's total energy is conserved such that the final energy equals the initial energy. This is the **law of conservation of energy**.

The law of conservation of energy is a powerful tool in solving various problems and gaining greater insight into the workings of physical systems. To do so, we begin by defining the **mechanical energy**, E, as the sum of the potential and kinetic energies of an object:

$$E = E_P + E_K$$

Mechanical energy is conserved in isolated systems as they are unaffected by external forces* such as friction. The sum of the potential and kinetic energies of an isolated system never changes; E = constant. To show that the mechanical energy E is conserved in an isolated system, consider the example of the skateboarder descending a ramp, as in Figure 4.12. As the skateboarder descends, gravitational potential energy is transformed into kinetic energy, such that the decrease in gravitational potential energy is equal to the increase in kinetic energy.

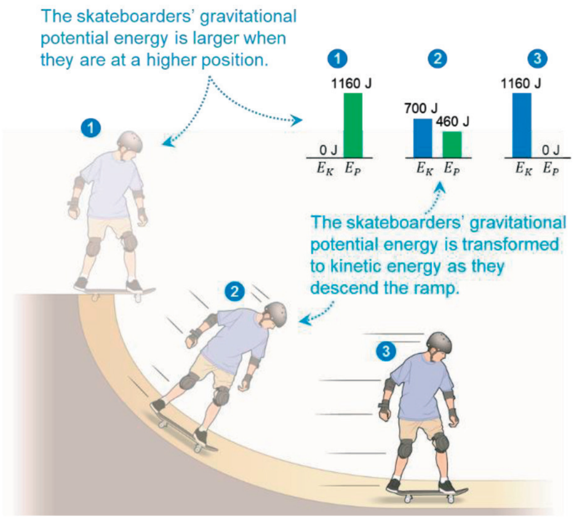


Figure 4.12: Skateboarder descending.

$$-\Delta E_P = \Delta E_K$$
$$E_{P_0} - E_P = E_K - E_{K_0}$$

With a slight rearrangement, we find:

$$E_P + E_K = E_{P_0} + E_{K_0}$$

Recalling that $E = E_P + E_K$, we have:

$$E = E_0$$

The derived formula shows that the final mechanical energy is equal to the initial mechanical energy, indicating that mechanical energy is constant.

*In situations where external forces such as friction are involved, the mechanical energy can change.

Impulse

A **collision** is a short-duration interaction between two objects. The sequence of high-speed photos of a soccer kick shown in Figure 4.20 reveals that the ball is compressed as the foot begins its contact. It takes time to compress the ball and more time for the ball to decompress as it leaves the foot.

Figure 4.20: A sequence of high-speed photos of a soccer ball being kicked.

The duration of a collision is when the two objects are in contact and depends on the materials from which the objects are made. A collision between two hard objects such as billiard balls lasts less than 1 ms, while that between your foot and a soccer ball might last 50 ms. As the foot and ball come into contact, as shown in the left frame of Figure 4.20, the ball is just beginning to compress. By the middle frame, the ball has sped up and become greatly compressed. Finally, as shown in the right frame, the ball, now moving very fast, is again only slightly compressed. The amount by which the ball is compressed is a measure of the magnitude of the force the foot exerts on the ball; more compression indicates a greater force. If we graph this **force versus time**, it will look something like Figure 4.21. The force is zero until the foot first contacts the ball, rises quickly to a maximum value, and then falls back to zero as the ball leaves the foot. Thus there is a well-defined duration (Δt) of the force. A large force like this exerted during a short interval of time is called an **impulsive force**. A golf club striking a ball and a hammer striking a nail are other examples of impulsive forces. A harder kick or a kick of longer duration produces a taller or wider force-versus-time curve with a larger area between the curve and the axis. Therefore, the effect of an impulsive force is proportional to the area under the force-versus-time curve. This area, shown in Figure 4.22, is called the force's **impulse** (symbol J). Impulsive forces can be complex, and the shape of the force-

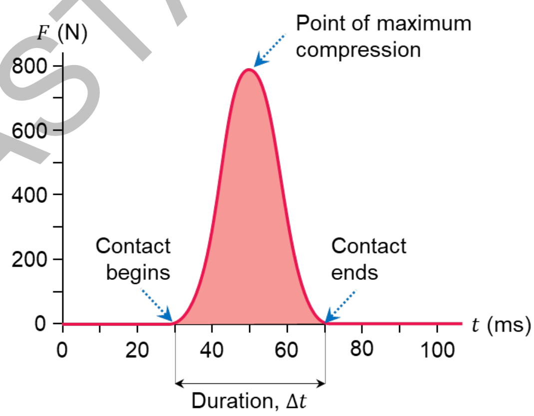


Figure 4.21: Force on the soccer ball

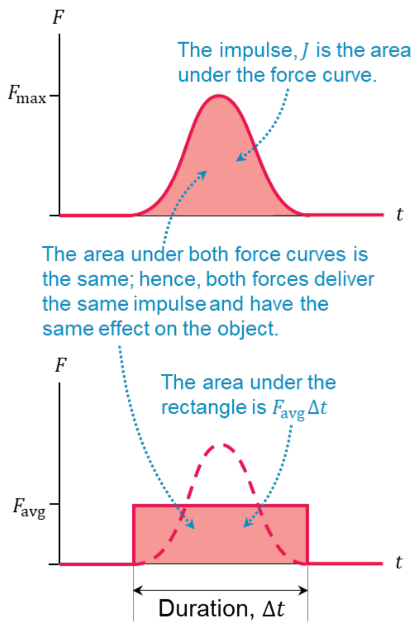


Figure 4.22: Force vs time graphs

Wave properties

We have seen that a wave is a regular, rhythmic disturbance that travels from one point to another, repeating itself both in space and time. We now explore some wave properties and see that the repeat length and the repeat time of a wave are directly related to its speed. We begin by considering the snapshots of a wave shown in Figure 5.11. It is helpful to use some terms to describe different components of a wave. Points on the wave corresponding to maximum upward displacement are referred to as **crests**, and points corresponding to maximum downward displacement are called **troughs**. The distance from one crest to the next, or from one trough to the next, is the repeat length—or **wavelength** (symbol λ)—of the wave. In this way, one wavelength is defined as the distance over which the wave repeats. Similarly, the repeat time—or **period** (symbol T)—of a wave is the time required for one wavelength to pass a given point, as illustrated in Figure 5.11. Closely related to the period of a wave is its frequency (symbol f), which is defined as the inverse of the period:

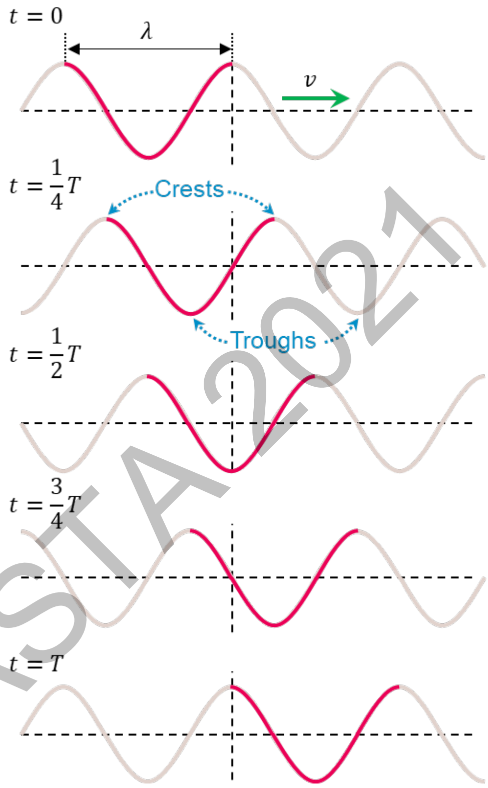


Figure 5.11: Snapshots of a wave.

$$f = \frac{1}{T}$$

Combining these observations, we see that a wave travels a distance λ in the time T. If we apply the definition of speed—distance divided by time—it follows that the speed of a wave is:

$$v = \frac{\lambda}{T} = \frac{1}{T}\lambda = f\lambda$$

Hence: a wave's speed is the product of its frequency and wavelength and is calculated using the formula below.

Formula	$v = f\lambda$

Symbol	Variable	SI unit
v	wave speed	$m\ s^{-1}$
f	frequency	Hz
λ	wavelength	m

Figure 5.12: Heinrich Hertz.

The SI unit of frequency, the **hertz** (symbol Hz), is named for the German physicist Heinrich Hertz (Figure 5.12) and is defined as one wave cycle passing a given point in one second.

The frequency range of human hearing extends well beyond the range of a piano, however. Humans can hear sounds with frequencies as low as 20 Hz and as high as 20,000 Hz. Sounds with frequencies above this range are referred to as **ultrasonic**, while those with frequencies lower than 20 Hz are classified as **infrasonic**. Though we cannot hear ultrasound and infrasound, these frequencies occur commonly in nature and are used in many technological applications.

Bats and dolphins produce ultrasound almost continuously as they go about their daily lives. By listening to the echoes of their calls—that is, by using **echolocation**—they can navigate their environment and detect their prey. Figure 5.23 shows a bat using ultrasound to locate a grasshopper. Some of the insects preyed upon by bats can hear the hunting bat's ultrasonic frequency and take evasive action as a defence mechanism. For example, the praying mantis has a specialised ultrasound receptor on its abdomen that allows it to detect an approaching bat. In addition, certain moths detect ultrasound emitted by approaching bats and respond by folding their wings in flight and dropping into a steep dive toward the ground.

Figure 5.23: Bat echolocation

Ultrasound is also used in medicine. An ultrasound scan, or **sonogram**, is a technique used to image a foetus in the womb, as in Figure 5.24. The technique works by sending bursts of ultrasound into the body and measuring the time delay of the resulting echoes. The information is used to map out the location of structures hidden beneath the skin.

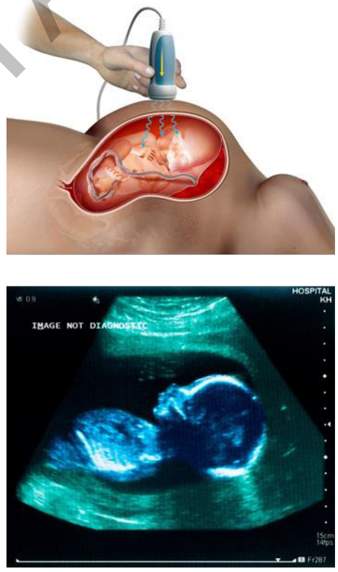


Figure 5.24: Ultrasound scan

Ultrasound can also produce changes within the body that would otherwise require surgery. For example, shock wave lithotripsy (SWL) is a technique in which a high-intensity beam of ultrasound is concentrated onto a kidney stone that must be removed. Such a procedure is shown in Figure 5.25. After being hit with as many as 1000 to 3000 pulses of sound, the stone is fractured into small pieces that the body can eliminate.

Figure 5.25: Shock wave lithotripsy

As for infrasound, it has been discovered in recent years that elephants (Figure 5.26) and some whales can communicate with one another using sounds with infrasonic frequencies as low as 5 Hz. These sounds, which humans feel as vibration rather than hear as sound, can travel over an area of about 30 km^2 on the dry African Savannah. Similarly, some whale species, including blue whales, produce powerful infrasonic calls heard by others of their species over thousands of kilometres.

Figure 5.26: African elephants

Natural frequency

The medium through which a mechanical wave travels is composed of particles that oscillate as the wave passes. The particles oscillate at certain frequencies and with certain amplitudes. The frequency of oscillation refers to the time taken for a particle to complete one full oscillation about its fixed position in the material, and the amplitude of oscillation refers to the displacement of the particle as it oscillates about its fixed position. The frequency and amplitude of oscillation can be altered by adding or removing energy from the object or material. Energy is added by applying an external force that does work on the system. Suppose, for example, that you hold the end of a string from which a particle is suspended, as in Figure 5.29. If the particle is set in motion and you hold your hand still, it will soon stop oscillating. However, if you move your hand back and forth in a horizontal direction, you can keep the particle oscillating indefinitely. The motion of your hand is said to be "driving" the particle, leading to **driven oscillations** or **forced vibrations**. The response of the particle in this example depends on the frequency of your hand's back-and-forth motion. For instance, if you move your hand very slowly, the particle will track the motion of your hand. Similarly, if you oscillate your hand very rapidly, the particle will exhibit only small oscillations. Oscillating your hand at an intermediate frequency, however, can result in large amplitude oscillations. To achieve a large response, your hand should drive the particle at the frequency at which it oscillates when not being driven. This is referred to as the **natural frequency**, f_0, of the system. All solids have one or more natural frequencies at which the system tends to oscillate when a force is applied, and these vibrations will persist in the absence of any driving or damping force. In general, driving any system at a frequency near its natural frequency results in large oscillations.

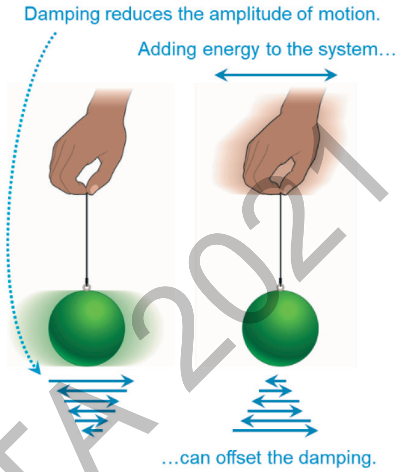


Figure 5.29: Oscillating particle.

Consider an oscillating system that is set vibrating by a force. When disturbed by an external force, the system oscillates at its natural frequency. Suppose that this system is now subjected to forced vibrations with a frequency called the **driving frequency,** f_{ext}. Somebody or something in the environment selects the driving frequency of the forced vibration, causing the force to push on the system f_{ext} times each second. The external force now causes the system to oscillate at f_{ext}, rather than its natural frequency, f_0. Suppose the system has a natural frequency f_0 = 5 Hz. We can use a forced vibration to push and pull on the system at a frequency f_{ext}, measure the amplitude of the resulting oscillation, and then repeat this for many different driving frequencies. Figure 5.30 shows a graph of amplitude versus driving frequency, called the oscillator's **response curve**.

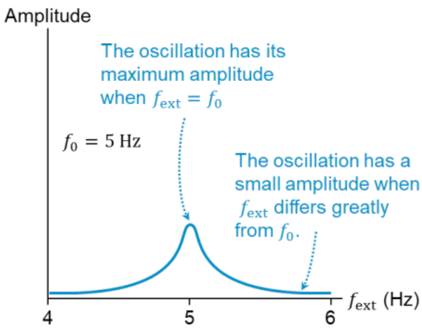


Figure 5.30: Response curve

Resonance

At the left and right edges of Figure 5.30, the driving frequency is substantially different from the oscillator's natural frequency. The system oscillates, but its amplitude is tiny as it does not respond well to a driving frequency that differs much from f_0. As the driving frequency gets closer and closer to the natural frequency, the amplitude of the oscillation rises dramatically. After all, f_0 is the frequency at which the system prefers to oscillate, so it is quite happy to respond to a driving frequency near f_0. Hence, the amplitude reaches a maximum when the driving frequency matches the system's natural frequency: $f_{ext} = f_0$. This large-amplitude response to a forced vibration whose frequency matches the system's natural frequency is called **resonance**. Within the context of driven oscillations, the natural frequency f_0 is called the **resonance frequency.** The amplitude can become exceedingly large when the frequencies match, especially if there is minimal **damping**, which refers to any action that reduces the amplitude of oscillation. Figure 5.31 shows the response curve of the oscillator of Figure 5.31 with different amounts of damping. Three different graphs are plotted, each with a different time constant for damping. The three graphs have damping ranging from $t = 50T$ (minimal damping) to $t = 5T$ (significant damping).

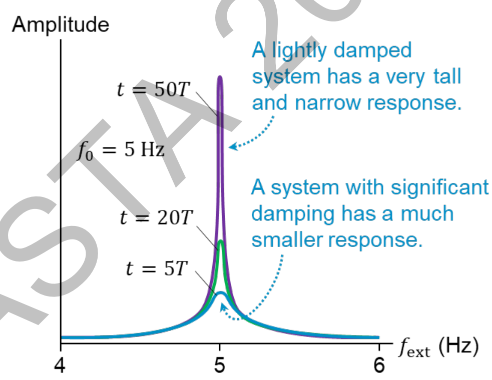


Figure 5.31: Response curve with damping

Resonance plays an essential role in various physical systems, from pendulums to atoms in a laser to a tuner in a radio or TV. For example, adjusting the tuning knob on a radio changes the electric circuit's resonance frequency in the tuner. A radio station is picked up when its resonance frequency matches the frequency being broadcast by a station. To change stations, we change the tuner's resonance frequency to that of another station. A good tuner will have little damping, so stations that are even slightly off-resonance will have a small response and hence will not be heard.

Human-made structures can show resonance effects as well. One of the most dramatic and famous examples of mechanical resonance is the collapse of Washington's Tacoma Narrows Bridge in November 1940. High winds through the narrows had often set the bridge into a gentle swaying motion (oscillation). However, during one particular windstorm, the bridge experienced a resonance-like effect, and the amplitude of its swaying motion began to increase. Alarmed officials closed the bridge to traffic, and a short time later, the swaying motion became so great that the bridge broke apart and fell into the water below, as shown in Figure 5.32. Since that time, bridges have been designed to prevent such catastrophic oscillations, which has proven successful with a few exceptions.

Figure 5.32: Tacoma Narrows Bridge

Interference pattern

Interference is a property exhibited by all types of waves. In general, when waves combine, they form interference patterns that include regions of both constructive and destructive interference. An example is shown in Figure 5.38, where two circular waves are interfering. Notice the regions of constructive interference separated by regions of destructive interference. To understand the formation of such patterns, consider a system of two identical sources, as in Figure 5.39. Each source sends out waves consisting of alternating crests and troughs. In this example, sources one and two have been set up so that when one source emits a crest, the other emits a crest as well. Wave sources that are synchronised like this are said to be **in phase**. At point A, the distance to each source is the same. Thus, if the wave from one source produces a crest at point A, so too does the wave from the other source. As a result, with crest combining with crest, the interference at A is constructive, as shown in Figure 5.40 (1).

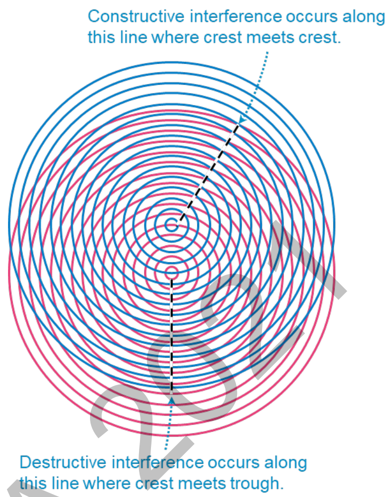


Figure 5.38: Interference of circular wave

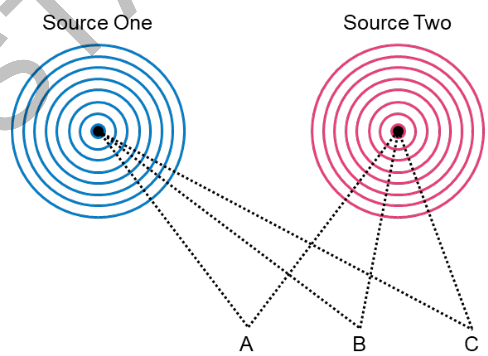


Figure 5.39: Two-source interference

At point B, the wave from source one must travel a greater distance than the wave from source two. If the extra distance is half a wavelength, the wave from source one produces a trough at B when the wave from source two produces a crest at B. As a result, the waves combine to give destructive interference at B, as shown in Figure 5.40 (2).

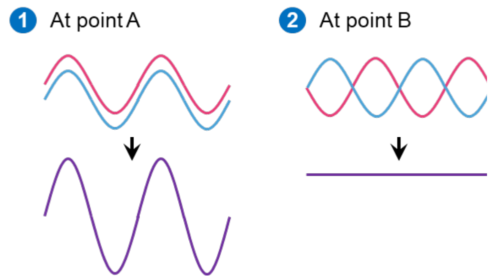


Figure 5.40: Interference of waves

At point C, the distance from source one is one wavelength greater than the distance from source two. Hence the waves are in phase again at C, with crest meeting crest for constructive interference.

In general, then, we can say that constructive and destructive interference occurs under the following conditions for two wave sources that are in phase:

- Constructive interference occurs when the path length from two in-phase sources differs by $0, \lambda, 2\lambda, 3\lambda \ldots$
- Destructive interference occurs when the path length from two in-phase sources differs by $\frac{1}{2}\lambda, \frac{3}{2}\lambda, \frac{5}{2}\lambda \ldots$

Other path length differences result in intermediate degrees of interference between the extremes of destructive and constructive interference.

Beats

Suppose two waves are travelling toward your ear, such as the red and blue waves shown in Figure 5.41. The two waves have the same amplitude but slightly different frequencies: the blue wave has a slightly higher frequency and a slightly shorter wavelength than the red wave. This slight difference causes the waves to combine in a manner that alternates between constructive and destructive interference. Their superposition, drawn in purple below the two waves, is a wave whose amplitude varies periodically. When the waves reach your ear, you will hear a single tone whose intensity is modulated. The sound volume increases and then decreases periodically, producing a distinctive sound pattern called **beats**.

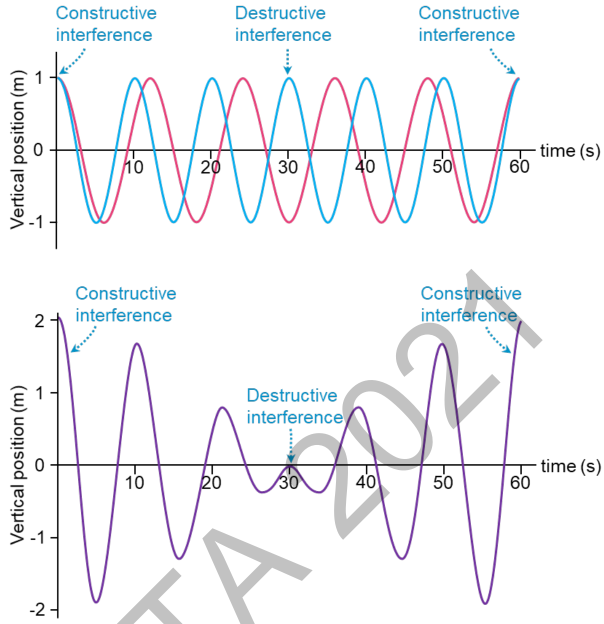


Figure 5.41: Interference of two waves with slightly different frequencies.

To be specific, imagine plucking two guitar strings that have slightly different frequencies. If you listen carefully, you notice that the sound produced by the strings is not constant in time; the intensity increases and decreases with a definite period. These intensity fluctuations are the beats, and the frequency of successive maximum intensities is the **beat frequency**. The beat frequency is equal to the difference between the two individual frequencies.

$$f_{\text{beat}} = f_1 - f_2$$

Figure 5.42 is a history graph of the wave at the position of your ear. You can see both the sound wave oscillation at a frequency f_{osc} and the much slower intensity oscillation at a frequency f_{beat}. Frequency f_{osc} determines the pitch you hear, while f_{beat} determines the frequency of the loud-soft-loud modulations of the sound intensity.

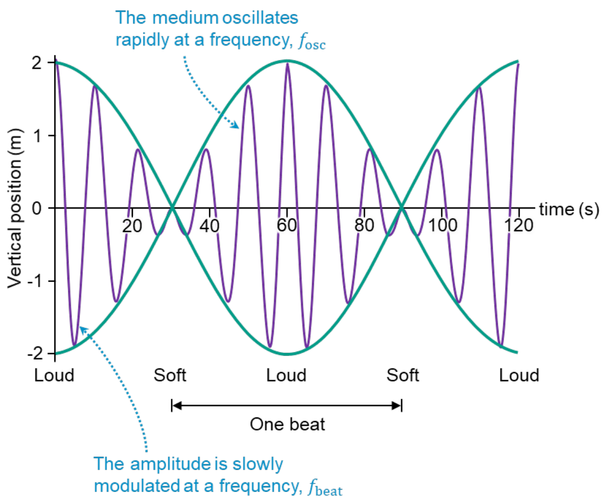


Figure 5.42: Beats

Musicians use beats to tune their instruments. If one flute is tuned adequately at 440 Hz, but another plays 438 Hz, the flautists will hear two loud-soft-loud beats per second. The second flautist is "flat" and needs to shorten her flute slightly to bring the frequency up to 440 Hz.

Many measurement devices use beats to determine an unknown frequency by comparing it to a known frequency. For example, a Doppler blood flowmeter uses ultrasound reflected from moving blood to determine its speed. The meter determines this tiny frequency shift by combining the emitted wave and the reflected wave and measuring the resulting beat frequency.

Light

The nature of light is elusive. Under some circumstances, light behaves like a stream of particles travelling in straight lines, while in others, it shows the same kinds of wave-like behaviour as sound or water waves. Rather than exploring an all-encompassing "theory of light," it will be better to develop **models of light**, with each explaining the behaviour of light within a specific range of physical situations. The first model of light we will explore is the **wave model,** which is the most widely applicable model, which describes light as being composed of electromagnetic waves with properties and behaviours similar to sound and water waves. The wave model will be used to explore wave behaviours of light, including diffraction and polarisation. The second model we will explore is the **ray model**, which describes light as being composed of rays that travel in a straight line. The ray model will be used to explore the ray behaviours of light, including reflection, refraction and total internal reflection. Unfortunately, it is difficult to reconcile the statement "light is a wave" with the statement "light travels in a straight line". For the most part, waves and rays are mutually exclusive models of light. An important task will be to learn when each model is appropriate.

The Wave Model of Light

In the wave model, light is composed of electromagnetic waves that travel outwards from a source in all directions. The outwards propagation of the wave is commonly described using **wavefronts**, which are points on the wave at which the phase of vibration is the same. That is, at any instant, all points on a wavefront are at the same part of the cycle of their periodic variation. One way to think of wavefronts is to imagine taking a photograph of ripples spreading on a pond and marking the crests' location on the photo, as in Figure 5.68 (1). The lines that locate the crests are the wavefronts, and they are spaced precisely one wavelength apart. During wave propagation, the wavefronts all move at the same speed in the direction of propagation of the wave, as in Figure 5.68 (1). Although the wavefronts are circles, you would hardly notice the curvature if you observed a small section of the wavefront very far away. The wavefronts would appear to be parallel lines, still spaced one wavelength apart and travelling at speed v as in Figure 5.68 (2). When observing a circular wave far from its source, the wavefronts appear as planes, with each representing a crest of the propagating wave, as in Figure 5.68 (3). The propagating wave is often called a **plane wave** when observed from a distance as the circular wavefronts appear as straight lines.

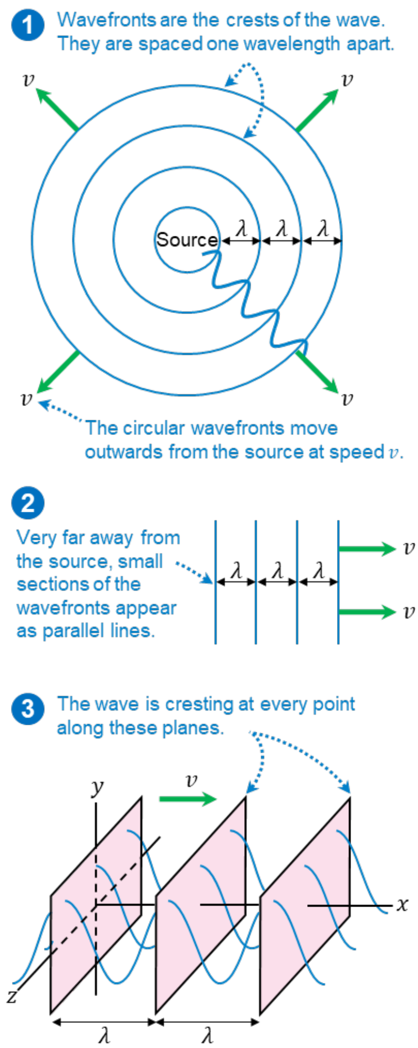


Figure 5.68: Wavefronts

Polarisation

Polarisation is a property of all transverse waves, including electromagnetic waves. This chapter is primarily about light, but to introduce basic polarisation concepts, we can use the ideas presented in Chapter 5.2 about transverse waves on a string. For example, for a string whose equilibrium position is along the x-axis, the displacements can be along the y-direction, as in Figure 5.72 (1). In this case, the string always vibrates in the x-y plane. But the displacements might instead be along the z-axis, as in Figure 5.72 (2); then, the string vibrates in the x-z plane. When a wave oscillates along the y-direction only, we say that it is polarised in the y-direction. A wave oscillating along the z-direction is polarised in the z-direction.

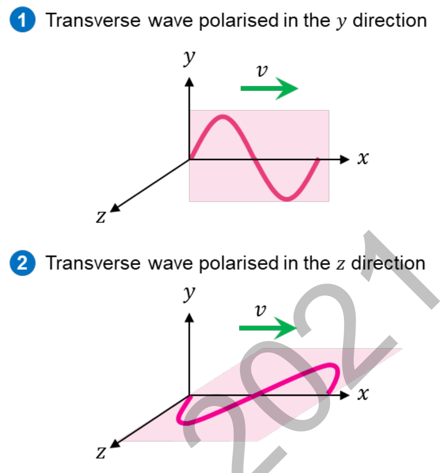


Figure 5.72: Polarisation of waves

This same concept is applied to electromagnetic waves, which also have polarisation. Recall that the electric and magnetic fields oscillate perpendicular to each other and the wave propagation. We define the plane of polarisation of an electromagnetic wave as the plane of the electric field, as depicted in Figure 5.73. The electric field defines the plane of polarisation as most electromagnetic wave detectors, including the human eye, respond to the interactions with the electric field, not the magnetic field.

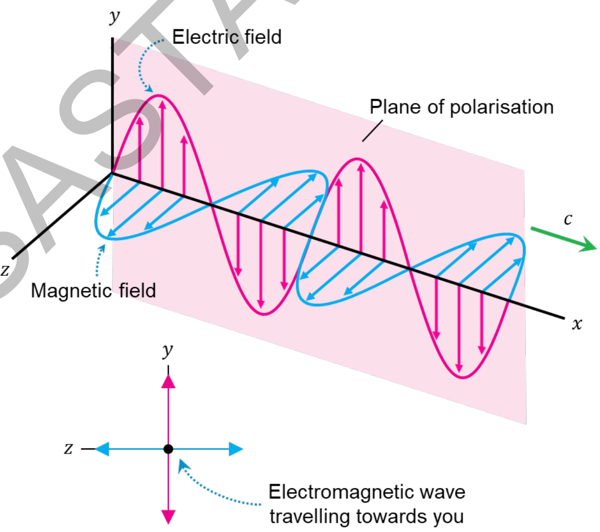


Figure 5.73: Polarisation of an EM wave

Light sources emit light that is either **plane-polarised** or **unpolarised**. Light is plane-polarised when the electric fields of the electromagnetic waves are confined to a single plane. For example, in Figure 5.74 (1), the light is vertically plane-polarised as the oscillations of the electric field are confined to the vertical plane. In contrast, light is unpolarised when the electromagnetic waves have polarisations in different, random directions, as in Figure 5.74 (2). Examples of unpolarised light include sunlight and light from incandescent light globes. An unpolarised light beam can be polarised using a **polariser** which is a material that is composed of long, thin, electrically conductive molecules oriented in a specific

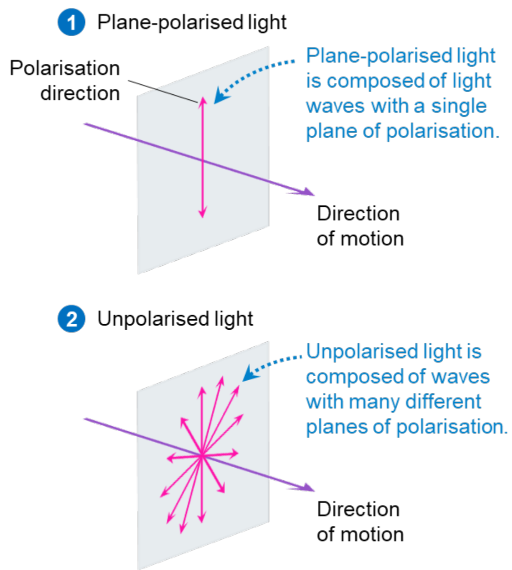


Figure 5.74: Polarised and unpolarised light

direction. When a beam of light strikes a polariser, it is readily absorbed if its electric field is parallel to the molecules. In contrast, light whose electric field is perpendicular to the molecules passes through the material with little absorption. As a result, the light that passes through a polariser is preferentially polarised along a specific direction. A simple mechanical analogue of a polariser is shown in Figure 5.75. Here we see a wave that oscillates along the string in the vertical direction as it propagates toward a slit cut into a block of wood. If the slit is oriented vertically, as in Figure 5.75 (1), the wave passes unaffected. Conversely, when the slit is oriented horizontally, it stops the wave, as in Figure 5.75 (2). A polariser performs a similar function on a beam of light.

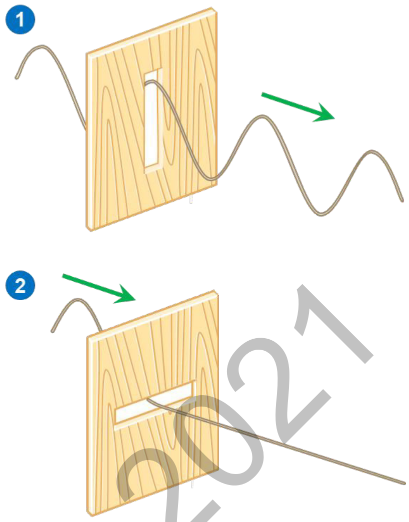


Figure 5.75: Mechanical polariser

The most common polarising filter for light is a material named Polaroid™, which is widely used in sunglasses and polarising filters for camera lenses. Polaroid™ incorporates substances that exhibit **dichroism**, a property of some materials in which one of two plane-polarised components of light is absorbed more strongly than the other, as in Figure 5.76.

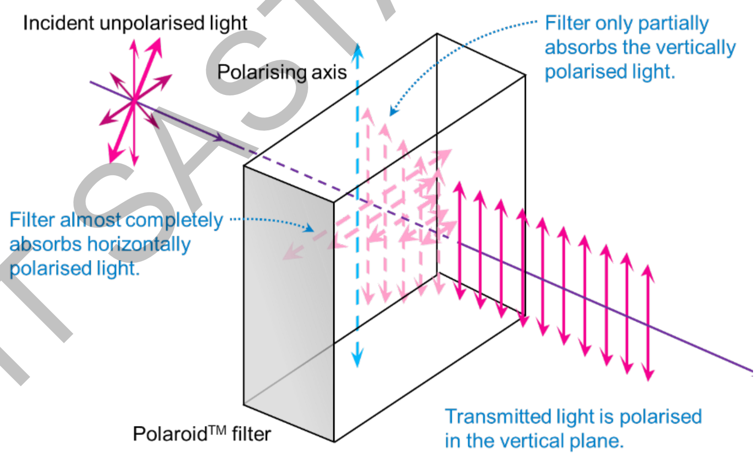


Figure 5.76: How a Polaroid™ filter produces polarised light.

An ideal polariser passes 100% of the incident light polarised in the direction of the filter's polarising axis but blocks all light polarised perpendicular to that axis. Such a device is an unattainable idealisation. A Polaroid™ filter, for example, transmits 80% or more of the waves polarised parallel to the polarising axis, but only 1% or less of waves polarised perpendicular to this axis. In this way, a polaroid successfully minimises the intensity of light, and this property is utilised in sunglass lenses used to reduce glare, as in Figure 5.77. Now suppose we insert a second polariser between the first polariser. Light is transmitted if the polarising axes of the lenses on the two sunglasses are parallel, as in the centre of Figure 5.78 and is not transmitted if the polarising axes are perpendicular, as at the top left of Figure 5.78.


Figure 5.77: Polaroid lenses

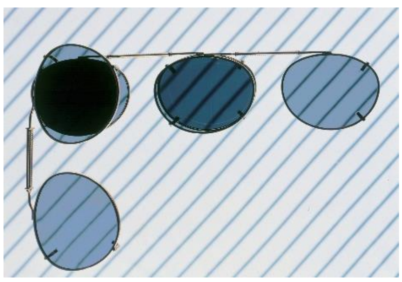


Figure 5.78: Polarising sunglasses

The speed of a light wave in a given medium is calculated using the formula below.

Formula	$v = \frac{c}{n}$

Symbol	Variable	SI unit
v	light speed in medium	m s^{-1}
c	light speed in a vacuum	m s^{-1}
n	index of refraction	

Example 5.13

The photograph below shows a beam of light moving from air into water.

Calculate the speed of light in water which has a refractive index of 1.33.

v	=	$\frac{c}{n}$
v	=	$\frac{3 \times 10^8}{1.33}$
v	=	2.26×10^8 m s^{-1}

Figure 5.86 shows the refraction of a single ray at a boundary between medium 1 and medium 2. Let the angle between the ray and the normal be θ_1 in medium 1 and θ_2 in medium 2. Just as for reflection, the angle between the incident ray and the normal is the angle of incidence. The angle on the transmitted side, measured from the normal, is called the **angle of refraction**. In Figure 5.86 (1), the light ray bends toward the normal, whereas, in Figure 5.86 (2), the refracted ray bends toward the normal. The property that determines whether the refracted ray bends towards or away from the normal when entering medium 2 is the index of refraction. When a ray is transmitted into a material with a higher index of refraction, it bends towards the normal. When transmitted into a material with a lower index of refraction, it bends away from the normal.

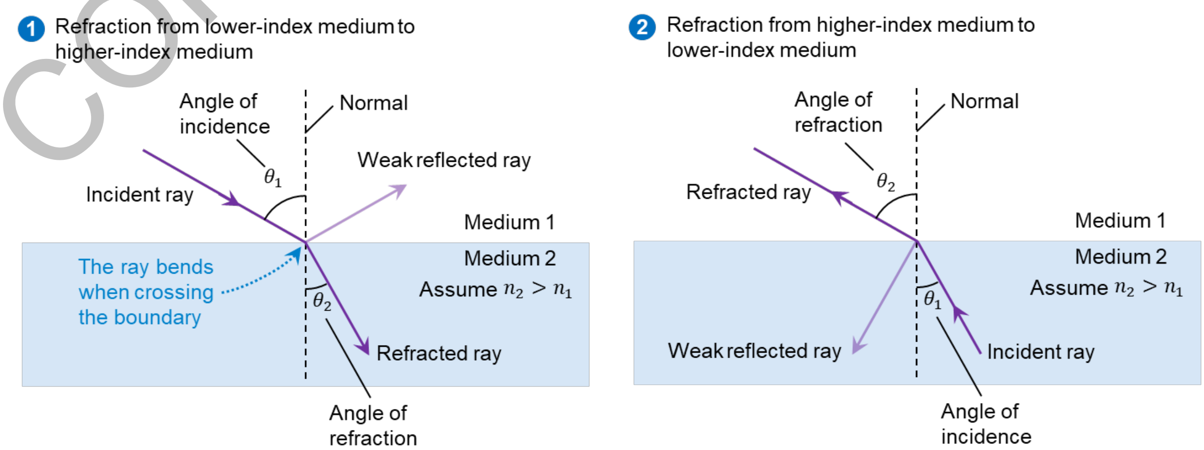


Figure 5.86: Refraction of light rays.

Total Internal Reflection

Figure 5.88 shows three light rays emitted by a light source positioned inside a tank of water. The three light beams strike the surface of the water at increasing angles of incidence. The two beams with the smallest angles of incidence refract from the water, but the beam with the largest angle of incidence cannot refract through the boundary. Instead, 100% of the light reflects from the boundary back into the water. This process is called **total internal reflection** (TIR).

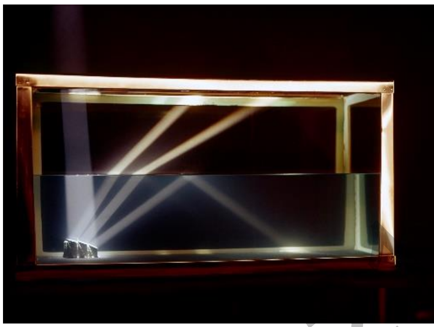


Figure 5.88: Total internal reflection

Figure 5.89 shows several rays leaving a point source in a medium with an index of refraction, n_1. The medium on the other side of the boundary has a lower refractive index such that $n_2 > n_1$. As we have seen, rays bend away from the normal when crossing a boundary into a material with a lower index of refraction. Two things happen as the angle of incidence θ_1 increases. First, the angle of refraction θ_2 approaches 90°. Second, the fraction of the transmitted light decreases while the fraction of reflected light increases. A **critical angle,** θ_c is reached when θ_2 = 90°, and this is calculated below.

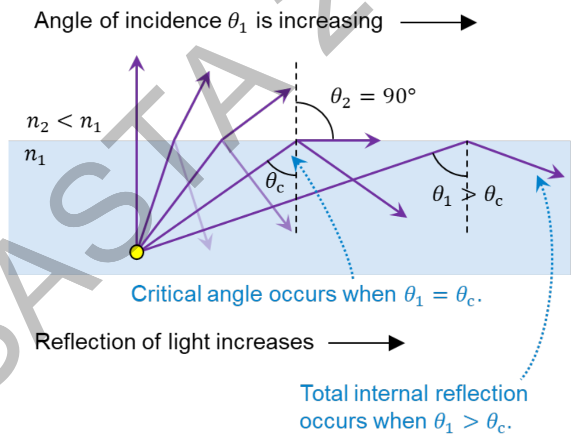


Figure 5.89: Critical angle

$$\theta_C = sin^{-1}\left(\frac{n_2}{n_1}\right)$$

The refracted light vanishes at the critical angle, and the reflection becomes 100% for any angle of incidence greater than or equal to the critical angle, $\theta_1 \geq \theta_C$. We can compute the critical angle of the water-air boundary in Figure 5.89.

θ_C	=	$sin^{-1}\left(\frac{n_2}{n_1}\right)$
θ_C	=	$sin^{-1}\left(\frac{1.00}{1.33}\right)$
θ_C	=	48.8°

Many technologies use total internal reflection. For example, Figure 5.90 shows a pair of binoculars. The lenses are much farther apart than your eyes, so the light rays need to be brought together before exiting the eyepieces. Rather than using mirrors, which scratch easily and require alignment, binoculars use a pair of prisms on each side, and their arrangement ensures each light ray undergoes two TIRs before emerging from the eyepiece.

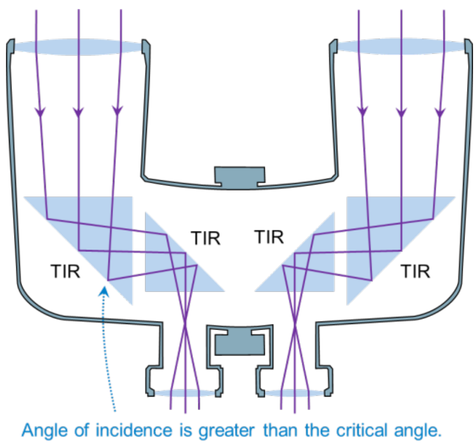
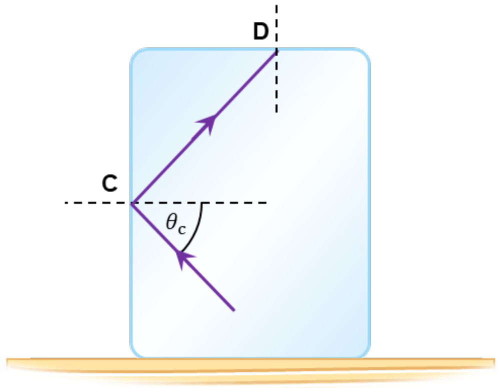


Figure 5.90: Binoculars

Question 361

A light ray travels inside a magnesium fluoride crystal with an index of refraction of 1.38.

The ray strikes C at the critical angle, totally reflects, and then emerges into the air at D.



(a) Calculate the critical angle for the magnesium fluoride crystal.

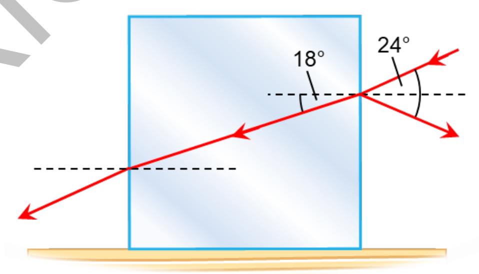
(2 marks) **KA4**

(b) Calculate the angle of refraction at D.

(3 marks) **KA4**

Question 362

Light from a red laser (650 nm) is passed through a material and follows the path shown below.



(a) Calculate the refractive index of the material.

(2 marks) **KA4**

(b) Calculate the wavelength of the light inside the material.

(2 marks) **KA4**

emitting particles and electromagnetic radiation. The time scale of these decay processes ranges from a small fraction of a microsecond to billions of years. The stable nuclides are plotted on the graph in Figure 6.06, where the neutron number N is plotted against the atomic number Z for each nuclide. Stable nuclei are represented by blue diamonds and unstable, radioactive nuclei by pink dots. The graph contains two black lines. The first represents nuclides with equal numbers of protons and neutrons and is called the N vs Z line. The second is a curved line representing stable nuclides and is called the **line of stability**. Stable nuclides are located on or close to the line of stability. In contrast, unstable nuclides are in bands along both sides of the line of stability.

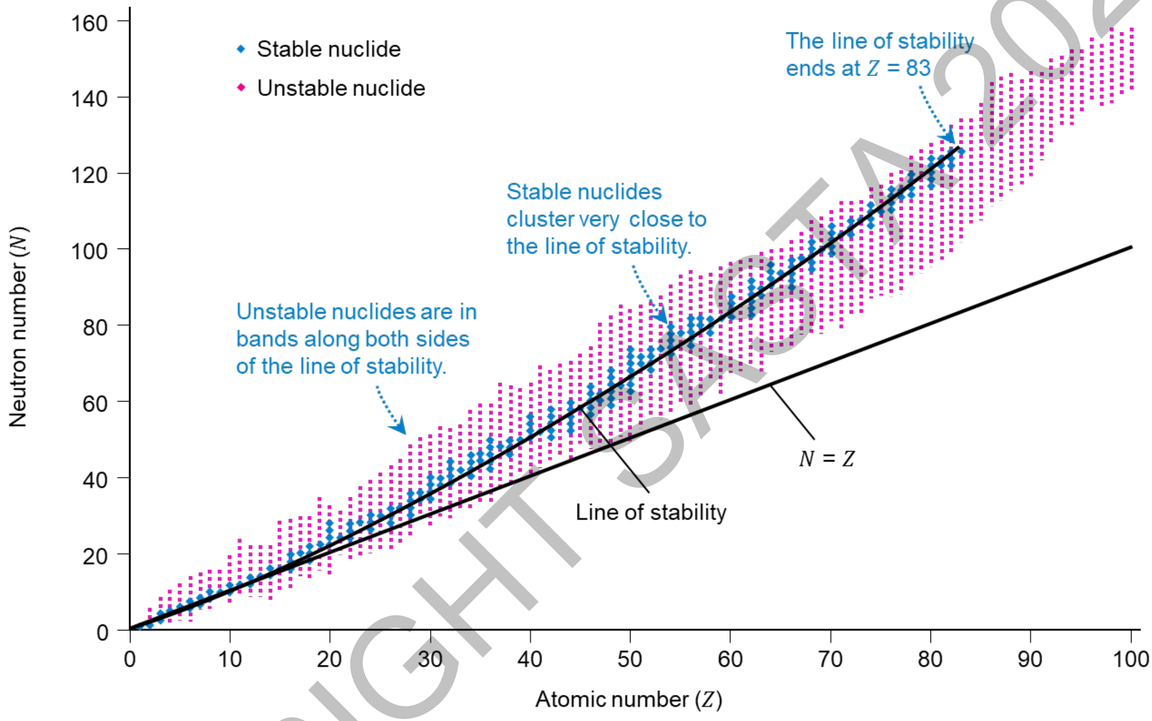


Figure 6.06: Stable and unstable nuclides shown on an N vs Z graph.

The graph shows that nuclides with $Z < 20$ have approximately equal numbers of protons and neutrons, $N = Z$. As the atomic number increases, the number of neutrons needed for stability grows increasingly larger than the number of protons such that $N > Z$ for nuclides with $Z > 20$. The N/Z ratio is ≈1.2 at $Z = 40$ and increases to ≈1.5 at $Z = 80$. The increasing N/Z ratio results from neutrons increasing the strong nuclear force while exerting no electrostatic forces, thereby providing the extra "glue" that holds larger nuclides together. However, regardless of neutron number, there are no stable nuclides with a mass number greater than 209 or an atomic number greater than 83.

The stability or instability of a nucleus is determined primarily by the competition between the attractive strong nuclear force and the repulsive electrostatic force. Nuclides with small atomic numbers are more stable as the attractive strong nuclear forces outweigh the repulsive electrostatic forces. Nuclides with higher atomic numbers are less stable as the repulsive electrostatic forces overcome the attractive strong nuclear forces. As the nucleus grows, a point is reached where the repulsive electrostatic force increases faster than the binding energy, and stability is impossible.

Alpha decay

Nuclides with atomic numbers greater than 83 and mass numbers greater than 209 are unstable and typically undergo radioactive decay through the emission of an alpha particle, ${}^{4}_{2}\alpha$. An alpha particle is identical to a helium–4 nucleus containing two protons and two neutrons bound together. When an unstable nuclide decays by giving off an alpha particle, its atomic number, Z, decreases by 2, and its mass number, A decreases by 4. Symbolically, we can write this process as follows:

$$ {}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha $$

In this expression, X is referred to as the **parent nucleus**, and Y is the **daughter nucleus**. Notice that the atomic and mass numbers are conserved as the sum of the atomic or mass numbers on the right side of the arrow is equal to the atomic or mass numbers on the left side. For example, radium–226 decays radioactively to radon–222 through the emission of an alpha particle. The decay is illustrated in Figure 6.07 and described in the equation below.

$$ {}^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\alpha $$

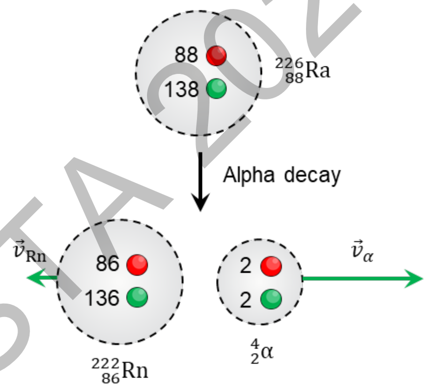


Figure 6.07: Alpha decay

When a nucleus emits an alpha particle, its N and Z values decrease by two such that the daughter nucleus is closer to the line of stability on the N vs Z graph than the parent nucleus.

Alpha particles are typically emitted at speeds approximately 5% of the speed of light and travel several centimetres in air or a few tenths or hundredths of a millimetre through solids before they are brought to rest by collisions. The daughter nucleus, which is much more massive than an alpha particle, undergoes only a slight recoil, as shown in Figure 6.07. Consequently, the energy released in an alpha decay ends up mainly as the kinetic energy of the alpha particle.

You may not realise it, but there is a source of alpha decay in your home. Australian homes must have a smoke detector, like the one shown in Figure 6.08, that uses the alpha decay of a human-made radioactive isotope named americium–241, ${}^{241}_{95}$Am.

$$ {}^{241}_{95}\text{Am} \rightarrow {}^{237}_{93}\text{Np} + {}^{4}_{2}\alpha $$

In this type of smoke detector, a minute quantity of ${}^{241}_{95}$Am is placed between two metal plates connected to a battery. The ${}^{4}_{2}\alpha$ particles emitted by the radioactive source ionise the air, allowing a measurable electric current to flow between the plates. As long as this current flows, the siren is disengaged, and the smoke detector remains silent. However, when smoke enters the detector, the ionised air molecules stick to the smoke particles and become neutralised, reducing the current and triggering the siren to sound the alarm.

Figure 6.08: Smoke detector

Beta minus decay

Nuclides with a high neutron-to-proton ratio have too many neutrons to be stable. and typically undergo radioactive decay through the conversion of a neutron to a proton and an electron, ${}_{-1}^{0}e$. The emission of an electron is necessary to conserve charge by creating a negative charge to balance the positive charge produced in converting a neutron to a proton.

$$ {}_{0}^{1}n \rightarrow {}_{+1}^{1}p + {}_{-1}^{0}e $$

This type of decay is termed **beta minus decay** after the term beta minus particle, the original term for an electron. The proton remains in the nucleus while the electron is emitted from the nucleus at high speeds ranging up to 99.95% of the speed of light. If the only two particles involved were the electron and the recoiling nucleus, conservation of momentum and energy would require each to have a definite momentum and kinetic energy. However, early observations of beta decay revealed that the electrons are emitted with a continuous range of kinetic energies, as shown in Figure 6.09. Specifically, we find that all electrons emitted in beta decay have energies that are less than would be predicted by energy conservation. On closer examination, it is found that beta decay seems to violate momentum conservation also. This observation led Austrian theoretical physicist Wolfgang Pauli, in 1930, to propose that the "missing" energy and momentum were carried off by a third particle that was not observed in the experiments. For this particle to have been unobserved, it must have zero charge and little or no mass. Italian physicist Enrico Fermi dubbed Pauli's hypothetical particle the **neutrino**, meaning "little neutral one." The neutrino evaded detection until 1956 due to its low mass and weak interaction with matter. Today, the particle emitted in beta minus decay is called the **electron antineutrino**, $\bar{\nu}_e$ with atomic and mass numbers equal to zero. The beta minus decay of a neutron is summarised in the equation below.

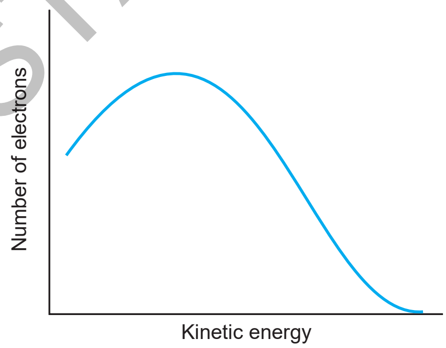


Figure 6.09: Electron kinetic energies

$$ {}_{0}^{1}n \rightarrow {}_{+1}^{1}p + {}_{-1}^{0}e + {}_{0}^{0}\bar{\nu}_e $$

When an unstable nuclide undergoes beta minus decay, its atomic number, Z, increases by 1, and its mass number remains constant. Symbolically, we can write this process as follows:

$$ {}_{Z}^{A}X \rightarrow {}_{Z+1}^{A}Y + {}_{-1}^{0}e + {}_{0}^{0}\bar{\nu}_e $$

For example, carbon–14 decays radioactively to nitrogen–14 through the emission of an electron. The decay is illustrated in Figure 6.10 and described in the equation below.

$$ {}_{6}^{14}\mathrm{C} \rightarrow {}_{7}^{14}\mathrm{N} + {}_{-1}^{0}e + {}_{0}^{0}\bar{\nu}_e $$

When a nucleus emits an electron, its neutron-to-proton ratio decreases such that the daughter nucleus is closer to the line of stability on the N vs Z graph than the parent nucleus.

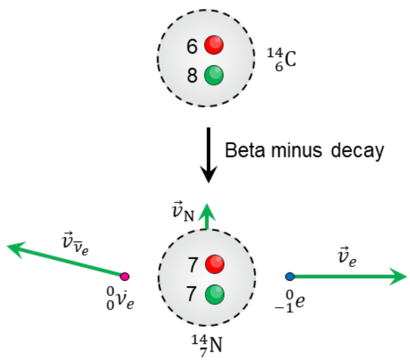


Figure 6.10: Beta minus decay

Uses of radiation

Radioactive isotopes have a broad range of uses in many industries, including **nuclear medicine**, to diagnose certain conditions and selectively destroy tissues. The hazards associated with such treatment are not negligible, but any hazard may be preferable if the disease is fatal without treatment. Artificially produced isotopes are often used as sources of radiation treatment. Such artificial sources have several advantages over naturally radioactive isotopes, including shorter half-lives and greater activity. In addition, the location and concentration of radioactive isotopes can be detected by measuring the radiation they emit.

A familiar example is the use of iodine–131 for thyroid studies. A small quantity of iodine–131 is fed or injected into the patient, and the speed with which it is absorbed in the thyroid provides a measure of thyroid function. In addition, the radiation emitted by the isotope can be detected and measured to produce an image of the thyroid, like in Figure 6.31, which shows enlargement and other abnormalities. If cancerous thyroid nodules are detected, they can be destroyed through treatment with much larger doses of iodine–131. The half-life of iodine–131 is eight days, so there are no long-lasting radiation hazards as nearly all iodine is eliminated or stored in the thyroid.

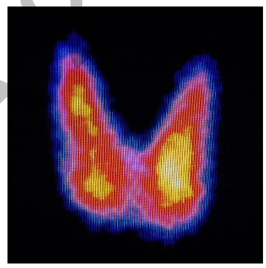


Figure 6.31: Thyroid scan

Positron emitting isotopes are used in **positron emission tomography (PET)**, which uses gamma-rays produced following positron emission to form an image. For example, images of the brain may be produced through PET using fluorine–18 with a half-life of 110 minutes. The decay of fluorine–18 releases a positron which produces gamma-rays by annihilation. The emitted gamma rays are captured and used to form an image like Figure 6.32 to diagnose a stroke or Alzheimer's disease.

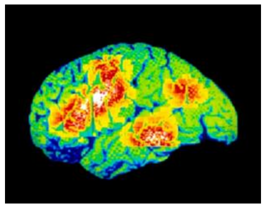


Figure 6.32: Brain scan

Similar techniques use gamma-rays to visualise other tissues and organs in the body. A useful isotope for such purposes is technetium–99 which emits gamma rays and is readily attached to organic molecules taken up by various tissues and organs. A small quantity of technetium-bearing molecules is injected into a patient, and a detector is used to produce an image, like Figure 6.33, that reveals the parts of the body that have taken up these molecules. In this way, technetium–99 acts as a radioactive tracer that locates abnormalities. The half-life of technetium–99 is only six hours, which is long enough to monitor metabolic processes in the body but short enough to disappear quickly afterwards.

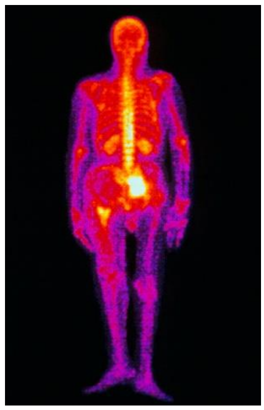


Figure 6.33: Body scan

Tracer techniques have many other applications. For example, tritium, a radioactive isotope of hydrogen, is used to tag molecules in complex organic reactions and isotopes of sulfur, chlorine and phosphorus are tagged to pesticide molecules to trace their passage through food chains. In addition, mechanics and engineers use isotopes of iron to study piston ring wear in machinery, and laundry detergent manufacturers use dirt and oils containing radioactive carbon and iron isotopes to test the effectiveness of their products.

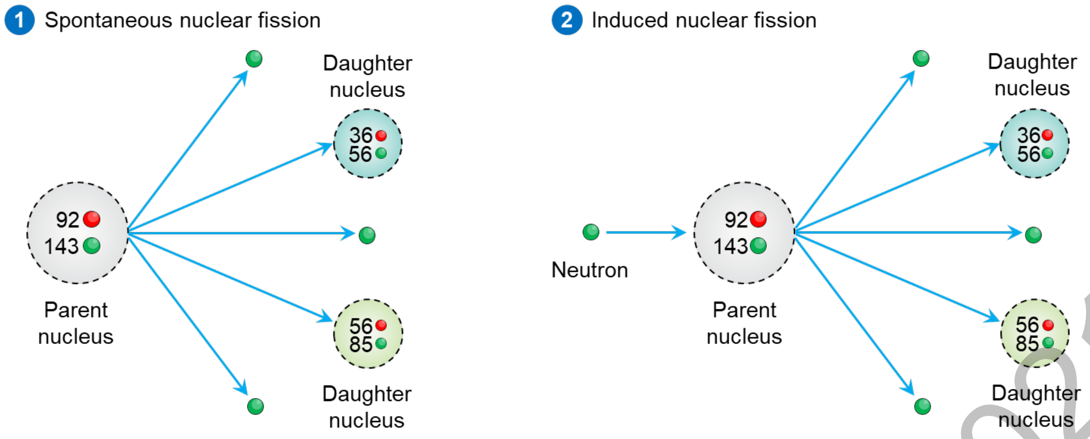


Figure 6.34: Spontaneous and induced nuclear fission.

An induced fission reaction begins when a heavy unstable nucleus like uranium–235 captures a neutron. This process increases the mass number by one and leaves the uranium–236 nucleus in an excited state:

$$^{1}_{0}n + ^{235}_{92}\text{U} \rightarrow ^{236}_{92}\text{U}^{*}$$

The excited uranium–236 nucleus oscillates wildly and becomes highly distorted, as in Figure 6.35. The oscillations cause the nucleus to elongate, increasing the separation of nucleons and weakening the strong nuclear force without significantly reducing the electrostatic force of repulsion. The electrostatic force dominates and causes the parent nucleus to fission into two daughter nuclei. The fission fragments are highly variable. For example, there are about 90 different ways in which the uranium–235 nucleus can fission, and these are depicted in Figure 6.36. The equations below show the different fission fragments produced in the three induced nuclear fission reactions of uranium–235.

$$^{1}_{0}n + ^{235}_{92}\text{U} \rightarrow ^{141}_{56}\text{Ba} + ^{92}_{36}\text{Kr} + 3^{1}_{0}n$$

$$^{1}_{0}n + ^{235}_{92}\text{U} \rightarrow ^{140}_{54}\text{Xe} + ^{94}_{38}\text{Sr} + 2^{1}_{0}n$$

$$^{1}_{0}n + ^{235}_{92}\text{U} \rightarrow ^{101}_{42}\text{Mo} + ^{132}_{50}\text{Sn} + 3^{1}_{0}n$$

The daughter nuclei each have a higher binding energy per nucleon and are more stable than the parent nucleus. However, each daughter nucleus has a high neutron to proton ratio, resulting in beta minus decay. The energy released in the beta decay of the daughter nuclei accounts for around 10% of the energy released in nuclear fission.

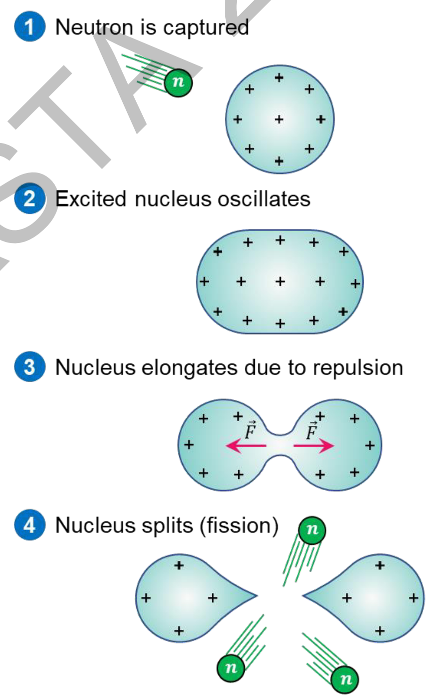


Figure 6.35: Induced nuclear fission

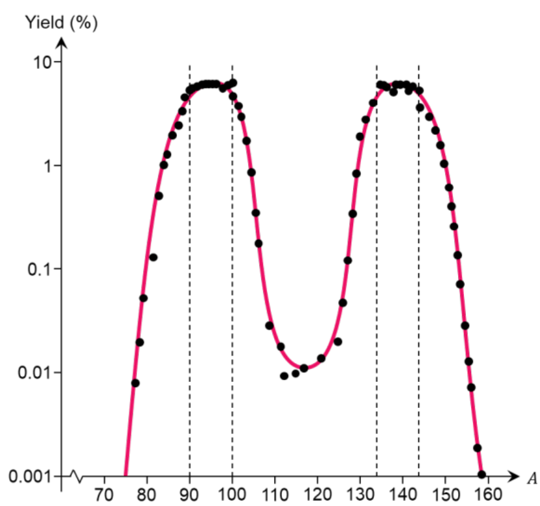


Figure 6.36: $^{235}_{92}\text{U}$ fission fragments

On average, more than one neutron is emitted in nuclear fission. This leads to the possibility that these neutrons will induce further fissions, resulting in a chain reaction.

Relate the starting, normal operation, and stopping of a nuclear reactor to the nature of the chain reaction.

The neutrons emitted as a result of nuclear fission have high speeds.

$^{235}_{92}U$ undergoes fission with slow neutrons. Hence to induce fission in these nuclei, the neutrons must be slowed down.

Many neutrons are absorbed by surrounding nuclei or escape and cause no further fissions.

- Explain why neutrons have to be slowed down to produce fission in $^{235}_{92}U$.

Enrichment increases the proportion of $^{235}_{92}U$ in uranium fuel.

- Describe how enrichment enables a chain reaction to proceed.
- Use a diagram of a reactor to locate and discuss the function of the principal components of a water-moderated fission power reactor.

The fact that fission reactions release more than one neutron on average has significant implications. For the sake of discussion, suppose that a fission reaction gives off two neutrons, called **fission neutrons,** and each induces additional fission reactions. These nuclei, in turn, give off two fission neutrons. Thus, starting with one nucleus to begin the chain reaction, we have two nuclei in the second generation of the chain, four nuclei in the third generation, and so on, as in Figure 6.37. Thus, after only 100 generations, the number of nuclei undergoing fission is 1.3 x 10^{30}. Furthermore, suppose each of these reactions gives off 32 pJ of energy. In that case, the total energy release after just 100 generations is 4.1 x 10^{19} J, which is enough energy to supply Australia for six years.

A nuclear chain reaction is self-sustaining when one fission neutron from every fission reaction induces a reaction in surrounding nuclei. A material that can sustain a nuclear chain reaction is described as **fissile**. Examples of fissile materials are uranium–235, uranium–233, thorium–232 and plutonium-239. The minimum mass of a fissile material required to achieve a self-sustaining chain reaction is called the **critical mass**. A nuclear chain reaction can proceed slowly and in a controlled manner, as in a nuclear reactor, or explosively, as in a bomb.

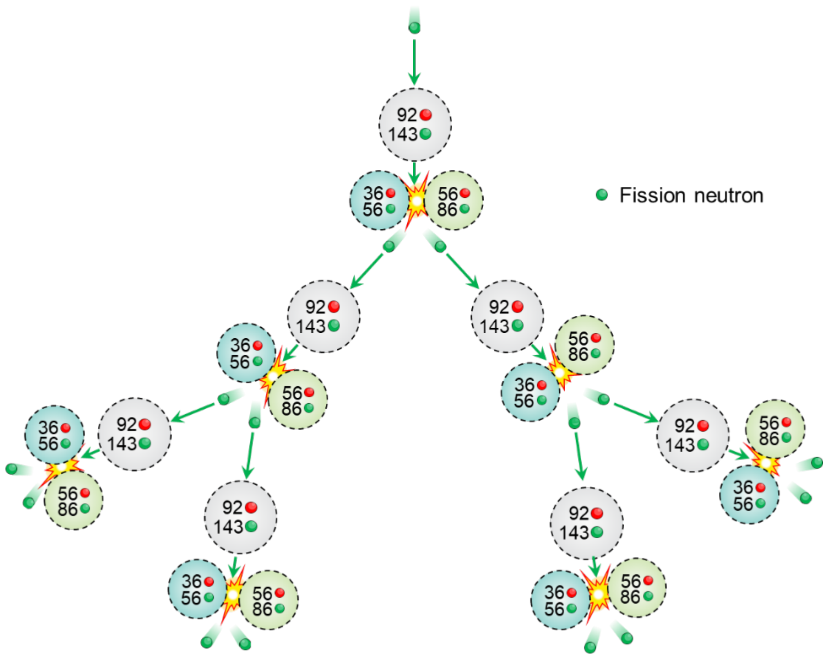


Figure 6.37: Nuclear chain reaction

Nuclear Reactor

We have seen that a nuclear chain reaction releases an enormous amount of energy. This energy can be released in a controlled manner in a **nuclear reactor**. A nuclear reactor is a system in which a controlled nuclear chain reaction is used to liberate energy. In a nuclear power plant, this energy is used to generate steam, which operates a turbine and turns an electrical generator. There are many different types of nuclear reactors, including the pressurised water reactor (PWR), boiling water reactor (BWR), and the pressurised heavy-water reactor (PHWR). The most common type in nuclear power stations is the PWR, shown in Figure 6.38.

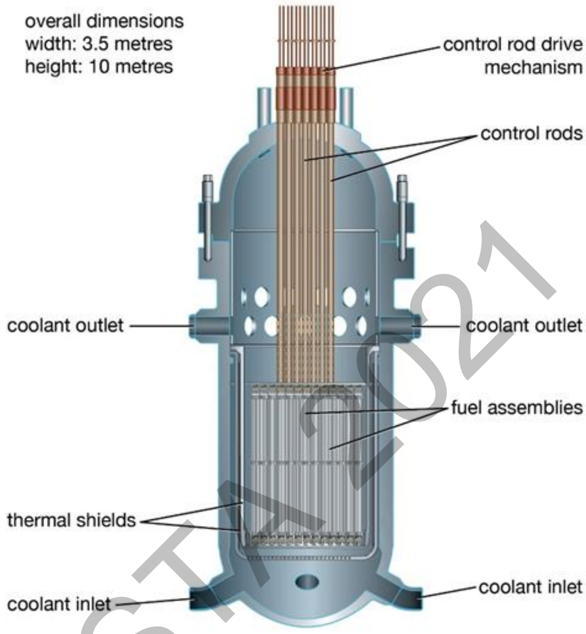


Figure 6.38: Pressurised water reactor.

The fuel assemblies are composed of hundreds of **fuel rods**, long thin cylinders filled with tiny pellets of fissile material. A typical nuclear reactor contains 150 assemblies, each containing 200 rods (Figure 6.39). The nuclear chain reaction in the fuel rods is initiated by a **start-up neutron source** which is a material that emits neutrons (^1_0n) such as californium–252 ($^{252}_{98}$Cf) which emits neutrons through spontaneous fission.

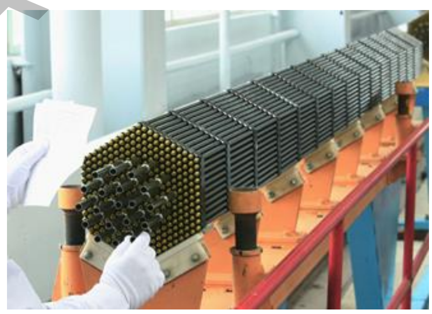


Figure 6.39: Fuel rod assembly.

The chain reaction rate is controlled by inserting or withdrawing **control rods** (Figure 6.40) made of elements (such as cadmium) whose nuclei absorb neutrons efficiently without undergoing any additional nuclear reaction. With the control rods fully inserted into the pile, any reaction quickly fizzles out because neutrons are absorbed rather than allowed to cause additional fissions. As the control rods are pulled partway out, more neutrons become available to induce reactions. The reactor is critical when, on average, one neutron given off by any fission reaction produces an additional reaction. Nuclear reactors are operated near their critical condition by continuous adjustment of the placement of the control rods.

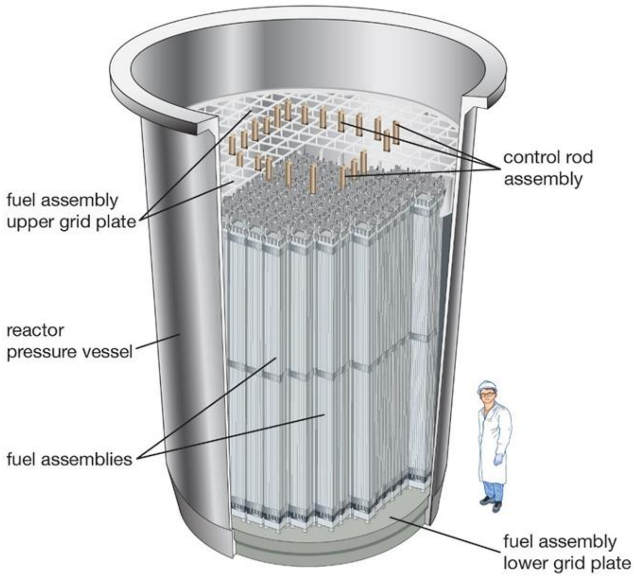


Figure 6.40: Control rod assembly.

On average, each fission of fissile uranium-235 releases between two and three free neutrons, so 40% of the neutrons are needed to sustain a chain reaction. The probability of neutron absorption by a nucleus is much greater for low-energy neutrons than for higher-energy neutrons liberated during fission. In a nuclear reactor, fission neutrons are slowed by collisions with nuclei in the surrounding material, called the **moderator**, to cause further fissions. In nuclear power plants, the moderator is often water, occasionally graphite. The moderator is positioned around the fuel rods such that fission neutrons pass through the moderator as they move between fuel rods, as illustrated in Figure 6.41.

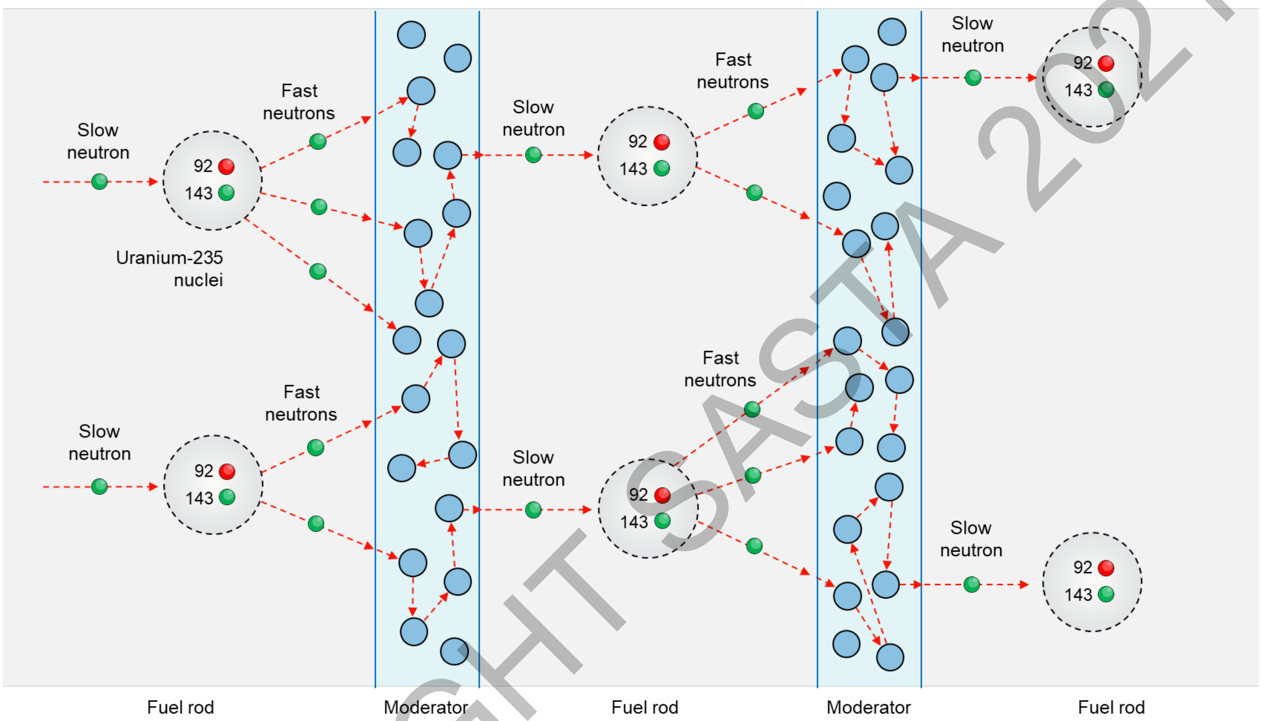


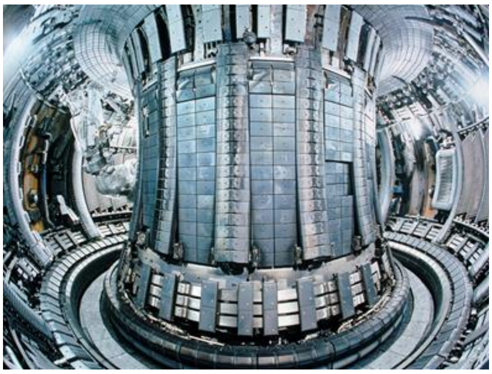
Figure 6.41: Position of a moderator in a nuclear reactor.

Fission neutrons that the moderator has slowed are called **thermal neutrons.** Thermal neutrons are produced when a fast-moving fission neutron collides and transfers energy to the moderator. The most effective moderators have two physical properties. The first is low neutron absorption, as neutron absorption would reduce the reactor's power output. The second is a similar mass to a neutron, which ensures that elastic collisions between neutrons and the moderator produce the maximum reduction in neutron speed.

Uranium–235 is the most widely-used fissile isotope in a nuclear reactor. However, naturally occurring uranium ore contains a uranium–235 concentration which is below the critical mass. Therefore, after mining and processing, the resulting uranium ore undergoes a process called **enrichment** designed to increase the proportion of fissile uranium–235. The uranium that is mined and processed contains atoms of uranium–235 and uranium–238. The enrichment process involves separating the uranium isotopes and isolating the uranium–235 atoms to increase the concentration from <1% to between 2 and 4%. Two techniques used to enrich uranium on a large scale are gaseous diffusion and gas centrifugation that separate the isotopes by mass.

Question 416

The Joint European Torus, or JET, is a nuclear fusion reactor located in Great Britain.



Scientists at JET use energy from the fusion of hydrogen isotopes in electrical power generation.

The most common type of fusion reaction involves deuterium, ${}^{2}_{1}\mathrm{H}$ and tritium, ${}^{3}_{1}\mathrm{H}$.

$$ {}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} $$

Each reaction releases 2.82 pJ.

(a) Calculate the mass of tritium given the data below.

Reactant	Mass (kg)
${}^{2}_{1}\mathrm{H}$	3.3436×10^{-27}
${}^{3}_{1}\mathrm{H}$	?

Product	Mass (kg)
${}^{4}_{2}\mathrm{He}$	6.6447×10^{-27}
${}^{1}_{0}n$	1.675×10^{-27}

(4 marks) **KA4**

(b) Suggest two advantages of using nuclear fusion rather than fission to produce electricity.

(2 marks) **KA2**

(c) Tritium occurs only in trace amounts in nature, and it decays quickly.

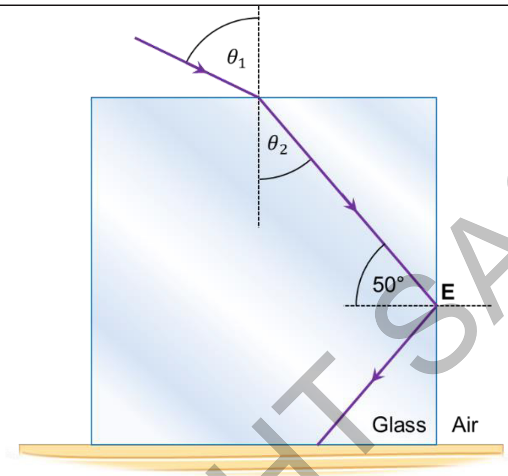
Explain how these properties limit the effectiveness of tritium as a fuel source.

(2 marks) **KA2**

SOLUTIONS

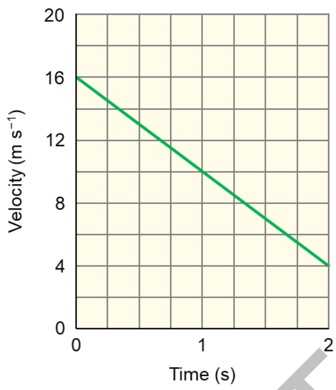
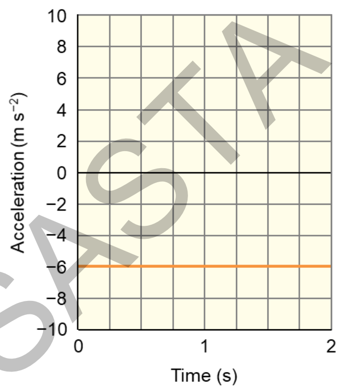
SOLUTIONS TO CHAPTER QUESTIONS

1	(a)	$s = 18 + 8 + 18$	1
		$s = 44$ m	1
	(b)	$\vec{s} = 10 - 2$	1
		$\vec{s} = 8$ m, south	1
2		Coordinate system: east is positive, west is negative	
	(a)	$\vec{s} = 15 - 6$	1
		$\vec{s} = +9$ m **or** 9 m, east	1
	(b)	$\vec{s} = 15 - 21$	1
		$\vec{s} = -6$ m **or** 6 m, west	1
3		Coordinate system: east is positive, west is negative	
	(a)	$s = 400 + 350 + 600$	1
		$s = 1350$ m	1
	(b)	$\vec{s} = 400 + (-350) + 600$	1
		$\vec{s} = +650$ m **or** 650 m, east	1
4	(a)	$v = \frac{s}{t}$	
		$v = \frac{100}{9.58}$	1
		$v = 10.44 \text{ m s}^{-1}$	1
	(b)	$t = \frac{s}{v}$	
		$t = \frac{100}{9.53}$	1
		$t = 10.49$ s	1
5	(a)	$s = vt$	
		$s = 12 \text{ x } 80$	1
		$s = 960$ m	1
	(b)	$t = \frac{s}{v}$	
		$t = \frac{2460}{12}$	1
		$t = 205$ s	1
6	(a) (1)	$\vec{v} = \frac{s}{t}$	
		$\vec{v} = \frac{50}{5}$	1
		$\vec{v} = 10 \text{ m s}^{-1}$, south	1
	(a) (2)	The velocity calculated in (1) is the horse's average velocity between A and B, whereas the velocity midway between A and B is the instantaneous velocity.	1
	(b)	Between D and E	1
		The ratio of displacement to time is slightly greater between D and E.	1
	(c)	$v = \frac{s}{t}$	
		$v = \frac{600}{36}$	1
		$v = 16.7 \text{ m s}^{-1}$	1

362	(a)		$n_2 = \frac{n_1 sin\theta_1}{sin\theta_2}$	
			$n_2 = \frac{1.00 \text{ x } sin24}{sin18}$	1
			$n_2 = 1.32$	1
	(b)		$\lambda = \frac{\lambda_0}{n}$	
			$\lambda = \frac{650}{1.32}$	1
			$\lambda = 494 \; nm$	1
363	(a)	(1)	$n_1 = \frac{n_2 sin90}{sin\theta_c}$	
			$n_1 = \frac{1.00 \text{ x } 1.00}{sin45}$	1
			$n_1 = 1.4$	1
		(2)		1
	(b)		$\theta_1 = sin^{-1}\left(\frac{n_2 sin\theta_2}{n_1}\right)$	
			$\theta_1 = sin^{-1}\left(\frac{1.4 \text{ x } sin(180-90-50)}{1.00}\right)$	1+1
			$\theta_1 = 65.4°$	1
364	(a)		The light ray travels parallel to the prism surface at the glass-air boundary.	1
			This occurs when the angle of incidence is precisely equal to the critical angle.	1
	(b)		$\theta_c = sin^{-1}\left(\frac{n_2}{n_1}\right)$	
			$\theta_c = sin^{-1}\left(\frac{1.00}{1.50}\right)$	1
			$\theta_c = 41.8°$	1
365	(a)		$\theta_1 = sin^{-1}\left(\frac{n_2 sin\theta_2}{n_1}\right)$	
			$\theta_1 = sin^{-1}\left(\frac{1.33 \text{ x } sin34.0}{1.00}\right)$	1
			$\theta_1 = 48.0°$	1
	(b)		As the angle of incidence is greater than the critical angle for the water-air boundary.	1

SOLUTIONS

SOLUTIONS TO REVIEW TESTS

1	(a)		$t = \frac{v - v_0}{a}$	
			$t = \frac{4.00 - 16.0}{-6.00}$	1
			$t = 2.00$ s	1
	(b)		$F = ma$	
			$F = 1520 \times 6.00$	1
			$F = 9120$ N	1
	(c)		$s = \frac{v^2 - {v_0}^2}{2a}$	
			$s = \frac{4.00^2 - 16.0^2}{2 \times (-6.00)}$	1
			$s = 20$ m	1
	(d)		 	1+1
2	(a)		$v = \frac{65}{3.6} = 18.1$ m s^{-1}	1
	(b)	(1)	$s_D = s_P$	
			$v_D t = v_0 t + \frac{1}{2} a_P t^2$	
			$v_D t = \frac{1}{2} a_P t^2$	
			$2v_D = a_P t$	
			$t = \frac{2v_D}{a_P}$	1
			$t = \frac{2 \times 18.1}{4.5}$	1
			$t = 8.0$ s	
		(2)	$s_D = v_D t$	
			$s_D = 18.1 \times 8.0$	1
			$s_D = 144.9$ m	1
			OR:	
			$s_P = v_0 t + \frac{1}{2} a_P t^2$	
			$s_P = 0 + \frac{1}{2} 4.5 \times (8.0)^2$	
			$s_P = 144.9$ m	