ACADEMIC ASSOCIATES

WACE Study Guide

PHYSICS

YR 12 ATAR COURSE

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TO THE STUDENT

The purpose of this guide is to assist students in their preparation for tests and examinations in the new ATAR Physics course for Units 3 and 4. The structure of the topics will allow students to use the book throughout the year.

The guide closely adheres to the W.A. School Curriculum and Standards Authority ATAR syllabus. Essential theory is interwoven with revision exercises so that students will be able to actively review core theory and concepts.

Science Understanding

Essential core theory for each topic of Science Understanding is covered clearly and in detail. Illustrations and worked examples are used extensively to assist students in their learning. Throughout each chapter, questions and exercises are integrated with theory to help students clarify and consolidate their understanding of new concepts.

Review questions at the end of each chapter provide a wide range of problems. All questions and review exercises have detailed answers to provide students with immediate feedback and a means of enhancing their progress.

Trial Tests

Trial tests for each major topic provide an ideal means of self assessment. The style and structure of these tests is similar to that proposed for the WACE examination. They include sections on short response, problem solving and comprehension. The marks allocated for each of these sections also reflect the weightings proposed by the SCSA for the examinations.

Physics is a most interesting and an enjoyable science to study. The practical work, in particular, holds a fascination for students. I hope that this study guide will help students to better understand the concepts they will encounter and to achieve greater success in the subject.

Michael Lucarelli

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UNIT 4 – REVOLUTIONS IN MODERN PHYSICS

PHYSICS
UNIT 3

GRAVITY AND MOTION

1

SYLLABUS CHECKLIST

SCIENCE UNDERSTANDING – GRAVITY AND MOTION

- ☐ the movement of free-falling bodies in Earth's gravitational field is predictable.
- ☐ all objects with mass attract one another with a gravitational force; the magnitude of this force can be calculated using Newton's Law of Universal Gravitation.

  This includes applying the relationship:

  $$F_g = G\frac{m_1 m_2}{r^2}$$

- ☐ objects with mass produce a gravitational field in the space that surrounds them; field theory attributes the gravitational force on an object to the presence of a gravitational field.

  This includes applying the relationship:

  $$F_{weight} = m\,g$$

- ☐ when a mass moves or is moved from one point to another in a gravitational field and its potential energy changes, work is done on the mass by the field.

  This includes applying the relationships:

  $$E_p = m\,g\,\Delta h\ ,\ W = F\,s\ ,\ W = \Delta E\ ,\ E_k = \tfrac{1}{2}\,m\,v^2$$

- ☐ gravitational field strength is defined as the net force per unit mass at a particular point in the field.

  This includes applying the relationships:

  $$g = \frac{F_g}{m} = G\,\frac{M}{r^2}$$

- ☐ the vector nature of the gravitational force can be used to analyse motion on inclined planes by considering the components of the gravitational force (that is, weight) parallel and perpendicular to the plane.

- [ ] projectile motion can be analysed quantitatively by treating the horizontal and vertical components of the motion independently.

  This includes applying the relationships:

  $v_{av} \frac{s}{t}$, $a = \frac{v - u}{t}$, $v = u + at$, $s = ut + \frac{1}{2}at^2$, $v^2 = u^2 + 2as$, $E_k = \frac{1}{2} m v^2$

- [ ] when an object experiences a net force of constant magnitude perpendicular to its velocity, it will undergo uniform circular motion, including circular motion on a horizontal plane and around a banked track; and vertical circular motion.

  This includes applying the relationships:

  $v = \frac{2\pi r}{T}$, $a_c = \frac{v^2}{r}$ resultant $F = m a_c = \frac{mv^2}{r}$

- [ ] Newton's Law of Universal Gravitation is used to explain Kepler's laws of planetary motion and to describe the motion of planets and other satellites, modelled as uniform circular motion.

  This includes deriving and applying the relationship:

  $\frac{T^2}{r^3} = \frac{4\pi^2}{GM}$

- [ ] when an object experiences a net force at a distance from a pivot and at an angle to the lever arm, it will experience a torque or moment about that point.

  This includes applying the relationship:

  $\tau = r F \sin\theta$

- [ ] for a rigid body to be in equilibrium, the sum of the forces and the sum of the moments must be zero

  This includes applying the relationships:

  $\sum F = 0$, $\tau = r F \sin\theta$, $\sum \tau = 0$

1.1 GRAVITATION

Newton's Law of Universal Gravitation

We are all very familiar with the force of gravitation. It is the force that holds us to the surface of the Earth and the force that exists between all the bodies of the universe.

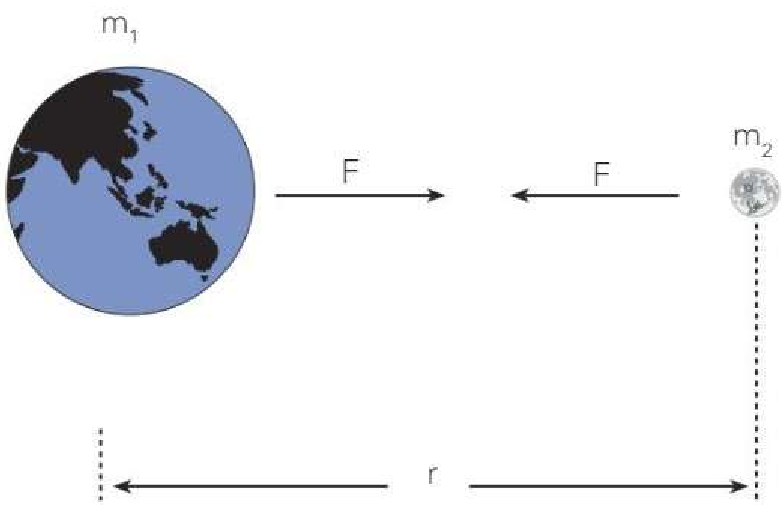


Figure 1.1 *Gravitational attraction is mutual. For example, the moon attracts the Earth with the same force that the Earth attracts the moon.*

Sir Isaac Newton was the first to develop a theory that explained how gravitational forces act. This theory is summarised in the Law of Universal Gravitation.

"Any two bodies attract each other with a force which is proportional to the product of their masses and inversely proportional to the square of their distance apart."

This Law is usually expressed mathematically as follows:

$$F = \frac{Gm_1m_2}{r^2}$$

F = force of attraction (N)
G = Universal Gravitational constant
= 6.67×10^{-11} N m^2 kg^{-2}
m_1, m_2 = masses of two bodies (kg)
r = distance between the centres of mass of the two bodies (m)

Worked Example 1.1

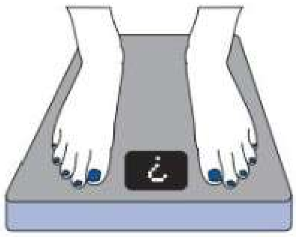
Calculate the force of attraction between you (say 65 kg) and the Earth. (Physical data is listed in the appendix).

F = ?
G = 6.67×10^{-11} N m^2 kg^{-2}
m_1 = 5.97×10^{24} kg
m_2 = 65 kg
r = 6.38×10^6 m

$$F = \frac{Gm_1m_2}{r^2} = \frac{(6.67 \times 10^{-11})(5.97 \times 10^{24})(65)}{(6.38 \times 10^6)^2} = 636 \text{ N}$$

Important Note!

- This force of attraction is mutual. You attract the Earth with the same force the Earth attracts you.
- This force is your weight.



Question 1.1

If it is true that you attract the Earth as much as it attracts you, then why does the Earth not appear to move towards you when you jump up in the air?

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Question 1.2

Suppose you jump 1.0 m in the air. Will this change your weight? Explain.

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Terms that matter

- **Mass:** Mass is the amount of matter in a body and is measured in kilograms. The mass of a body does not vary with position, e.g. a 2 kg hammer on earth will also have a 2 kg mass on the Moon.

- **Weight:** Weight is a force and is measured in Newtons. Your weight is a measure of the gravitational attraction between you and the Earth. It depends on where you are and the value of g at that point ($W = m\,g$). Your weight on the Moon would be approximately $\frac{1}{6}$ of what it is on Earth.

- **Centre of mass:** For ease of calculation it is convenient to think of a single point in a body about which mass is evenly distributed. For regular shaped objects of uniform density this is their geometrical centre. It is also the point about which objects will smoothly rotate.

- **Centre of gravity:** The centre of gravity of a body is the point at which all its weight may be considered to act. It is the point about which the body's weight is evenly distributed and in nearly all cases is the same as the centre of mass. Where bodies are very large or are in a non-uniform gravitational field, then the centre of gravity will be different to the centre of mass.

Question 1.3

(a) Is it possible for the centre of mass of a body to be located where no body exists? If so, give an example.

(b) The moon is a large body such that the gravitational field of the Earth is stronger on its near side compared to its far side. Where would you expect its centre of gravity to be in comparison to its centre of mass? Explain.

Gravitational fields

All masses exert forces on all other masses and so we can see that a gravitational force field exists in any region surrounding a body. Gravitational fields can act at a great distance and their force is not affected by objects in their path.

Gravitational fields exert a force on masses and hence they can be detected and measured by the influence they have on a unit mass. The strength of a gravitational field (g) is defined as the force (F) exterted on a unit mass (m).

That is $g = \dfrac{F}{m}$

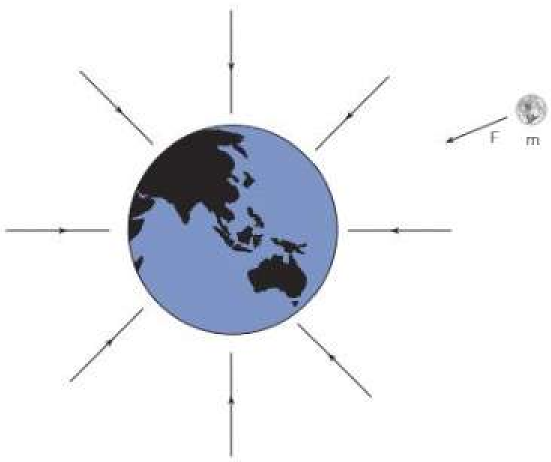


Figure 1.2 Gravitational fields. The gravitational force acting on a unit mass (g) decreases with distance from the centre of the Earth.

Using the previous expression for gravitational force we can show that:

$$g = \frac{Gm_E}{r_E^2}$$

g = gravitational field strength
G = Universal Gravitational constant
m_E = mass of Earth
r_E = radius of the Earth (distance to the centre of mass)

Worked Example 1.2

Calculate the value of g in a plane flying at an altitude of 9.5 km at a point on Earth where its radius is 6375 km. The Earth's mass is 5.97×10^{24} kg.

g = ?
G = 6.67×10^{-11} N m^2 kg^{-2}
m_E = 5.97×10^{24} kg
r_E = 6.375×10^6 m
r = $r_E + 9.5 \times 10^3$ m

$$g = \frac{Gm_E}{r_E^2}$$

$$= \frac{(6.67 \times 10^{-11})(5.97 \times 10^{24})}{(6.3845 \times 10^6)^2}$$

$$= 9.77 \text{ ms}^{-2}$$

Variations in the value of g

- **On the Earth's surface.**
  The value of g varies only slightly at the different points on the Earth's surface. The differences are due to the Earth's uneven shape (its diameter is 42 km greater at the equator) and variations in the density of its crust.

- **As we go into space.**
  As we leave the Earth's surface the value of g decreases in proportion to the square of the distance from its centre. We can show this graphically.

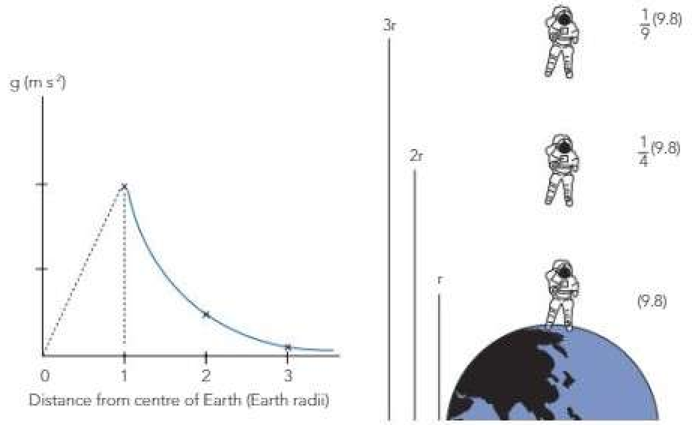


Figure 1.3 Variation of g with altitude.

Question 1.4

What would be the value of the Earth's gravitational field:

(a) 1000 km above the Earth's surface?

____

(b) halfway to the moon, if we assume that this is approximately 30 Earth radii from the Earth's centre?

____

Gravitational Potential Energy

The concepts of work and energy were covered in your year 11 physics course. You will recall that the work done on a body is the product of the applied net force multiplied by the displacement of the body in the direction of the force ($W = Fs$).

If a body is lifted in a gravitational field the force required to lift it is equal to its weight, mg. As the body is lifted it will gain gravitational potential energy, E_p. Hence if a mass m is lifted vertically, a height h, the work done and potential energy gained will be as follows:

$$\text{Work done} = Fs$$
$$W = mgh$$
$$E_p = mgh$$

W = work done, joules (J)
F = force, newtons (N) – in this case the weight mg
s = displacement, metres (m) – in this case the height
E_p = potential energy (J)

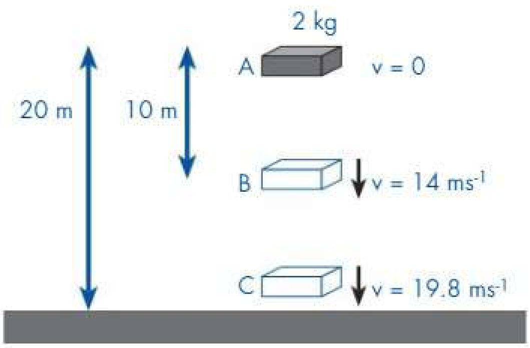
If the body is now allowed to fall freely it will accelerate due to the force of gravity acting on it. Its kinetic energy will increase as it falls. However, an equal decrease in the gravitational potential energy of the body will also occur. This is an example of the *Law of conservation of energy*. Energy is never lost or gained; just changed in form. In this case it is transformed from potential energy to kinetic energy.

At any point in the fall of the body we can say:

Loss in potential energy $E_p = E_k$ Gain in kinetic energy

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

Consider the energy of a 2.00 kg mass falling from a height of 20.0 m. (Assume air resistance is negligible.)



At position A: $E_p = 392$ J, $E_K = 0$, $E_T = 392$ J

At position B: $E_P = 196$ J, $E_K = 196$ J, $E_T = 392$ J

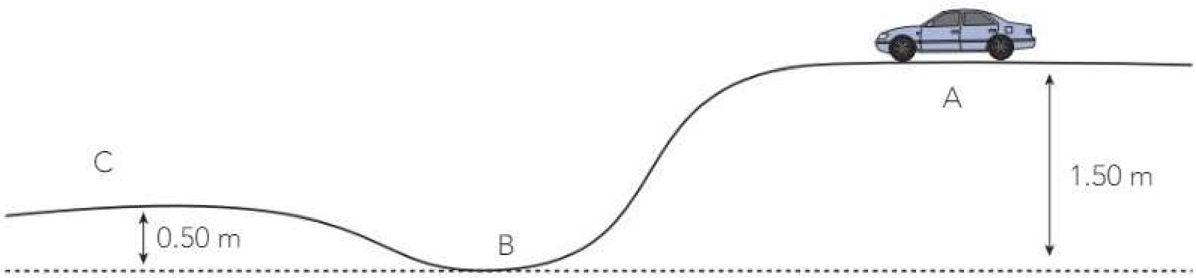
At position C: $E_P = 0$, $E_K = 392$ J, $E_T = 392$ J

Figure 1.4 *Conversion of potential energy to kinetic energy.*

Worked Example 1.3

A toy car of mass 200 g is at rest on the edge of a ramp as shown in the diagram on the next page. It begins to move freely down the slope past point B and eventually past point C.

Assuming no friction or air resistance determine the following.
(a) Potential energy of the toy car at point A
(b) Kinetic energy of the toy car when it reaches point B
(c) Velocity as it reaches point C.



(a) At point A $E_p = mgh = (0.200)(9.80)(1.50)$

$= 2.94\ \text{J}$

(b) E_k gained $=$ E_p lost

E_k at point B $= 2.94\ \text{J}$

Ep at point C $= mgh = (0.200)(9.80)(0.50)$
$= 0.980\ \text{J}$

E_k at point C $=$ Change in E_p from point A to point C
$= 2.94 - 0.980$
$= 1.96\ \text{J}$

Hence $\frac{1}{2}mv^2 = 1.96$
$v^2 = (1.96)(2)/(0.200)$
$v = 4.43\ \text{m s}^{-1}$ at point C

Question 1.5

The toy car in the worked example above is again allowed to run freely down the ramp from A to C. However the car is given an initial velocity of $4.00\ \text{m s}^{-1}$ as it leaves point A. Determine, assuming no friction or air resistance, the following:

(a) Potential, kinetic and total energy of the toy car at point A.

___

___

(b) Kinetic energy of the toy car when it reaches point B.

___

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(c) Velocity of the toy car when it reaches point C.

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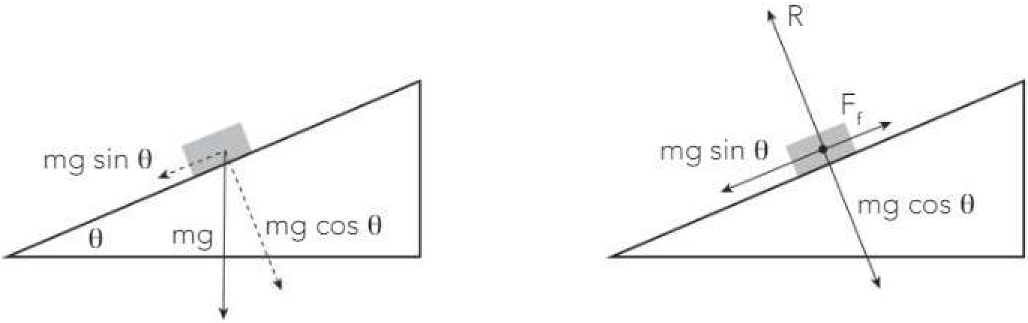
Motion on inclined planes

The direction of a gravitational force is always towards the centre of the earth, that is, vertically downwards. However bodies can also move down an inclined plane due to the effects of gravity. The gravitational force acting on a body, its weight, is vectorial in nature. Hence we can consider the components of the weight force that act parallel and perpendicular to an inclined plane as shown below.



(a) The components of weight force acting on a mass m, on an inclined plane of angle θ to the horizontal. The component force parallel to the plane is given by mgsinθ. The component force perpendicular to the plane is given by mgcosθ.

(b) The forces acting on a body moving down a rough plane. The normal reaction force R is equal and opposite to mgcosθ. The frictional forces F_f act in the opposite direction to mgsinθ. Hence the net force acting on mass m is mgsinθ - F_f (down the plane).

Figure 1.5 *Forces acting on a body on an inclined plane.*

Worked Example 1.4

A block of mass 2.70 kg is placed on an inclined plane whose incline is 22.5° to the horizontal.

(a) Determine the weight components acting parallel and perpendicular to the plane.

(b) The plank is slightly rough and the block remains at rest on the plank. What is the minimum force of friction needed for this to occur?

(c) Assuming that the force of friction is reduced to 10% of the weight force determine;
(i) the net force acting on the block,
(ii) the acceleration of the block down the plane.

(a) Parallel to the plane: $F = mg\sin\theta = (2.70)(9.80)(\sin 22.5°) = 10.1\ \text{N}$

Perpendicular to the plane: $F = mg\cos\theta = (2.70)(9.80)(\cos 22.5°) = 24.4\ \text{N}$

(b) The force of friction would need to be equal to the weight component down the plane.
Hence friction force $= 10.1\ \text{N}$

(i) Force of friction $Ff = (0.10)\ mg\sin\theta = (0.10)(10.1) = 1.01\ \text{N}$

Weight force parallel to plane $F = mg\sin(22.5°) = 10.1\ \text{N}$

Net force acting down the plane $F = 10.1 - 1.01 = 9.09\ \text{N}$

(ii) Acceleration $a = \dfrac{F}{m} = \dfrac{9.09}{2.70} = 3.37\ \text{m s}^{-2}$

1.2 PROJECTILE MOTION

Whenever an object is projected into the air with some horizontal velocity, it will move in a parabolic path if air resistance is considered negligible. The motion of any projectile is best analysed by considering its vertical and horizontal motion separately.

- **Vertical motion** – the body is under the influence of gravity with a constant downward acceleration of 9.80 m s^{-2}. This motion can be used to determine its *time of flight* and maximum height.

- **Horizontal motion** – assumed constant during the flight of the projectile. This motion can be used to determine *the range of the flight* (horizontal distance travelled). The angle of projection and initial velocity will determine the characteristics of the parabolic flight.

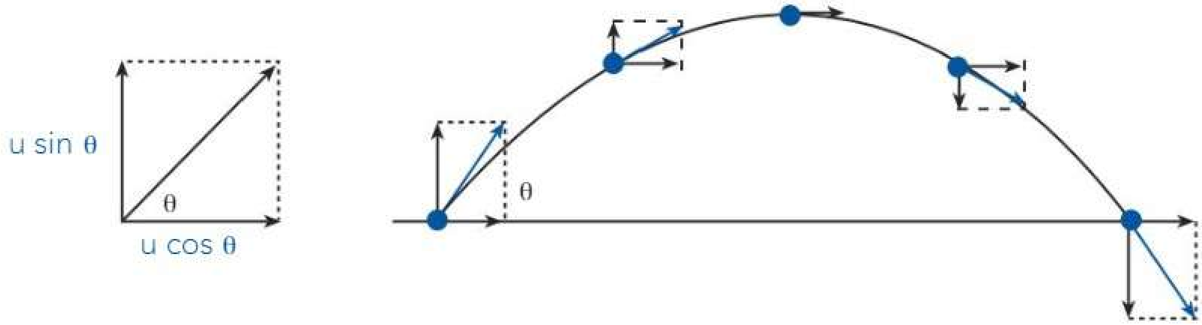
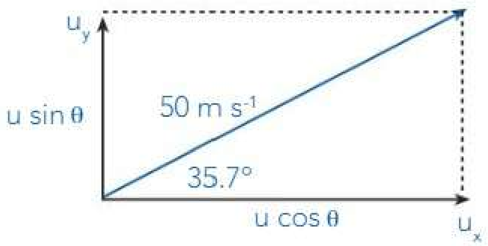


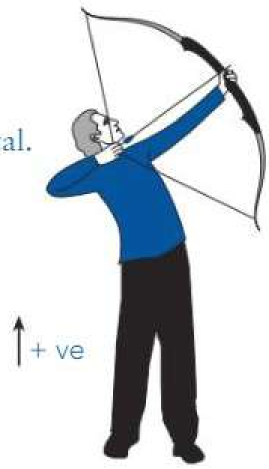
***Figure 1.6** Projectile motion. Note that the projectile's velocity is not zero at the top of its flight. The vertical component of the velocity changes but the horizontal component remains the same (assuming no air resistance).*

Worked Example 1.5

An arrow is fired into the air at 50.0 m s^{-1} at an angle 35.7° to the horizontal. Assuming no effects from air resistance determine:

(a) its maximum height
(b) its time of flight
(c) its range.





Determine horizontal and vertical components of initial velocity.

Horizontal u_x = u cos θ
= (50)(cos 35.7)
= 40.6 m s^{-1}

Vertical u_y = (50)(sin 35.7)
= 29.2 m s^{-1}

(a) Now - considering vertical motion only

u	=	29.2 m s^{-1}	v^2	=	$u^2 + 2as$
a	=	-9.80 m s^{-2}	s	=	$\frac{v^2 - u^2}{2a}$
s	=	?		=	$\frac{0 - (29.2)^2}{(2)(-9.80)}$

Maximum height = 43.4 m

(b) Consider vertical motion only - the whole flight

u	=	29.2 m s^{-1}	s	=	$ut + \frac{1}{2} a t^2$
a	=	-9.80 m s^{-2}	0	=	$(29.2)(t) + (0.5)(-9.8)(t^2)$
s	=	0		=	$29.2t - 4.9t^2$
t	=	?		=	$29.2 - 4.9t$
			t	=	5.95 s = flight time

(c) Consider horizontal motion only. Assume constant velocity:

v	=	40.6 m s^{-1}	s	=	vt
t	=	5.96 s		=	(40.6)(5.95)
s	=	?	Range	=	242 m

Question 1.6

(a) How could the range of the arrow (in the previous problem) be increased? Assume that the initial speed from the bow is the same.

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(b) Assuming no effect from air resistance, what angle would give maximum range?

____

____

(c) How could maximum height be increased?

____

Air Resistance Effects

The path of projectiles in a vacuum is parabolic. However, air resistance will cause the trajectory of a body moving in our normal atmosphere to be different.

Air resistance is a force which opposes the motion of the object through the air. It acts in the opposite direction to the movement of the object at any particular instant. Its effect on the projectile's path will:

- reduce its calculated range
- reduce its calculated maximum height
- increase its angle of descent.

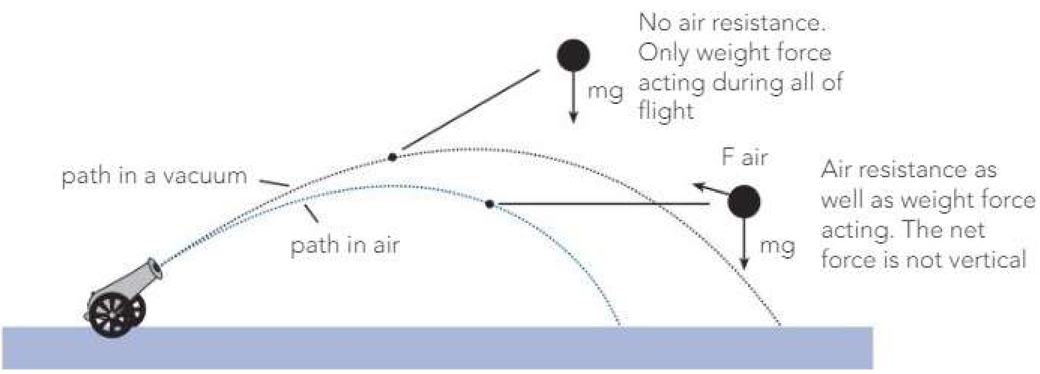
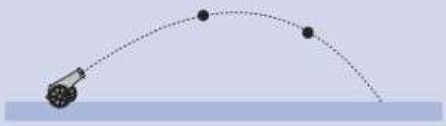


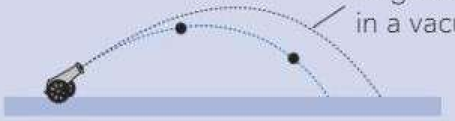
Figure 1.7 Effect of air resistance on projectile motion. The net force is not vertical. A non parabolic path results.

Question 1.7

In each of the following cases indicate the direction of the net force acting on the projectile at the different points shown.



(a) projectile moving in a vacuum



(b) projectile moving in air

Question 1.8

For a projectile moving in air:

(a) Why is the angle of descent greater than the angle of projection?

____

____

(b) Is the time taken to reach maximum height the same as that to return to Earth? Explain. (Hint: consider vertical forces acting on the way up and on the way down.)

____

____

Effect of angle on range

The range of a projectile depends on both its initial speed and the angle of projection. Assuming no air resistance the paths for different launch angles will all be parabolic as shown below. The maximum range will occur for a launch angle of 45°.

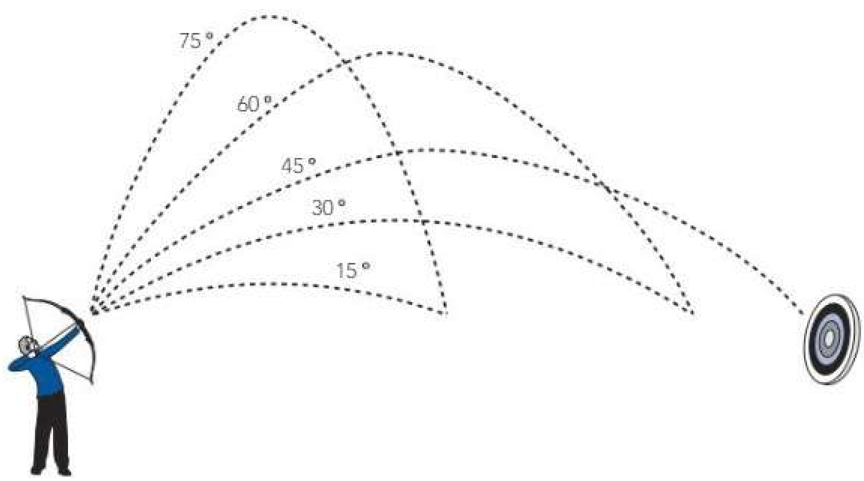


Figure 1.8 The trajectories of an object projected at different angles but with the same initial speed. The paths shown assume no air resistance. Maximum range occurs at 45°.

1.3 CIRCULAR MOTION

Circular Motion

The most interesting thing about circular motion is that bodies undergoing this movement are actually accelerating towards the centre. Their speed is constant but their velocity is constantly changing, since their direction is constantly changing (see Figure 1.9).

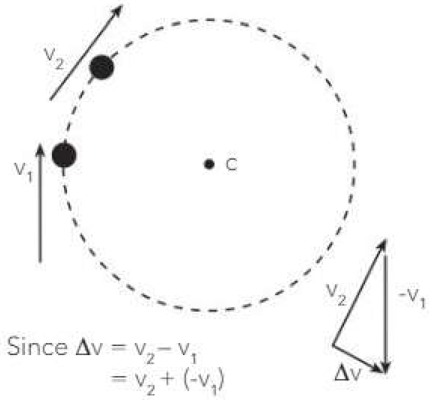


Figure 1.9 Circular motion. The change in velocity is always towards the centre.

This acceleration towards the centre of motion is called **centripetal acceleration**. Its magnitude can be calculated from the following formulae.

$$a_c = \frac{v^2}{r}$$

Since there is an acceleration there must be a force. The force required to keep the mass moving in a circular path is called the **centripetal force**.

From F = ma we can see that:

$$F_c = \frac{mv^2}{r}$$

F_c = centripetal force
m = mass
v = tangential velocity
r = radius of curvature

Describing circular motion

There are several terms which are often used to refer to the "speed" of an object in circular motion. These include velocity, revolutions per minute, frequency, period, angular velocity and so on. Each of these terms has a very specific meaning and it is important that they be distinguished.

- **Period (T):** Time taken for on complete revolution. Units are seconds (s).
- **Frequency (f):** The number of revolutions (or rotations) completed in one second. Units are hertz (Hz). Quite often, however, frequency may be given as revolutions per minute (rpm).
- **Speed (v):** This refers to the linear speed of a point moving in a circular path. Often just called the velocity. Units are ms^{-1}.
- **Rotational Speed:** This, like frequency, is simply the number of rotations or revolutions per second. Sometimes also called angular speed. Units are rpm or Hz.

Note also the following relationships.

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

$$v = \frac{2\pi r}{T}$$

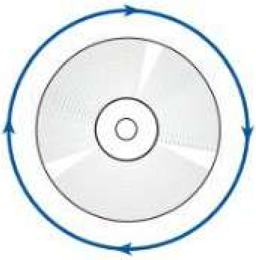
$$Hz = \frac{r.p.m.}{60}$$

Worked Example 1.6

A compact disc of 12.0 cm diameter spins at varying rates depending on which track it is playing. For inner tracks this is about 500 rpm and for outer tracks only about 200 rpm. This allows the laser beam to scan the CD at a constant linear speed.

Assume that a CD is spinning at a rate of 200 rpm and determine:

(a) its frequency of rotation in Hz;
(b) its period of rotation;
(c) the speed of a point on its outer edge;
(d) the acceleration of a point on its outer edge.



$r = 0.06$ m

$f = 200$ rpm $= ?$ Hz

$T = ?$

$v = ?$

$a = ?$

(a) $f = \dfrac{\text{rpm}}{60} = \dfrac{200}{60} = 3.33$ Hz

(b) $T = \dfrac{1}{f} = \dfrac{1}{3.33} = 0.300$ s

(c) $v = \dfrac{2\pi r}{T} = \dfrac{(2)(\pi)(0.060)}{0.300} = 1.26$ m s^{-1}

(d) $a = \dfrac{v^2}{r} = \dfrac{(1.26)^2}{0.06} = 26.5$ m s^{-2}

Question 1.9

(a) How does the acceleration at the edge of the CD compare to that due to Earth?

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(b) How does the acceleration at the edge of the CD compare with that at a point 3.0 cm from the centre?

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Centripetal force

As we have already stated, in order for a mass to move in a circular path, a centripetal force is required. This is a force that acts at right angles to the path of the body. Without it the body would simply travel in a straight line (Newton's 1st Law of Motion).

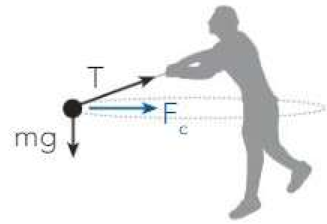


Figure 1.10 Centripetal force causes circular motion. The centripetal force shown (F_c) is the net force acting on the object. This net force is due to the combined effect of the tension force (T) and weight force (mg).

In the example illustrated at right (Figure 1.10) the net force acting on the mass is the centripetal force (F_c). This centripetal force is actually the result of two unbalanced forces acting on the mass (weight force downwards and the tension force from the string).

Some common examples of centripetal force are:

- The frictional force acting on a coin resting on a moving turntable. This force prevents the coin from sliding off the turntable.
- The reaction force between you and the side of your car door when rounding a bend. This force is directed towards the centre of the circular path taken by the car. It causes you to move in a circle (with the car) rather than go forward in a straight line (which would be out of the car). The frictional force between you and your seat also assists as a centripetal force.
- The reaction force between clothes and the inside wall of a spin dryer. This causes the clothes to move in a circle but not the water which has no reaction force exerted on it because there are holes.
- The gravitational force of attraction between the Earth and the Moon. This force keeps the Moon, which has a tangential velocity, in a circular path around the earth rather than moving off in a straight line into space.

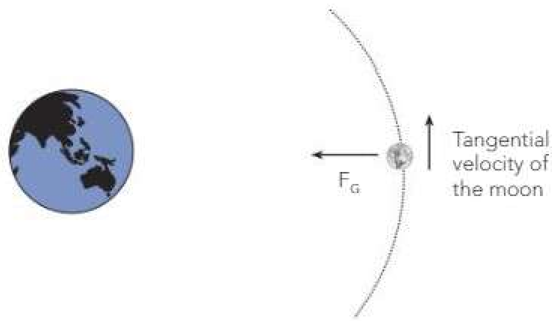


***Figure 1.11** The gravitational force between the Earth and the Moon provides the centripetal force necessary for circular motion.*

Question 1.10

Explain clearly how centripetal force is involved or applied in the following situations.

(a) A car is able to go around a corner on the road.

____

(b) A cyclist rides along a banked track at a velodrome.

____

(c) A pilot doing loop the loop (flying in a vertical circle) may experience large 'g' forces at the bottom of the loop.

____

Worked Example 1.7

Young Rachael is sitting on a horse on a merry-go-round which makes 4.2 revolutions per minute. The horse is 3.50 m from the centre. Rachael's mass is 25 kg.

(a) What is Rachael's period of rotation?
(b) What is her speed?
(c) What is the net force exerted on Rachael? How is it applied?

f = 4.2 rpm
= ? Hz
r = 3.50 m
m = 25 kg
T = ?
v = ?
F_c = ?

(a) $f = \dfrac{4.2}{60}$

$\therefore T = \dfrac{1}{f} = \dfrac{1}{0.07}$

$= 14.3$ s

(b) $v = \dfrac{2\pi r}{T} = \dfrac{(2\pi)(3.50)}{14.3}$

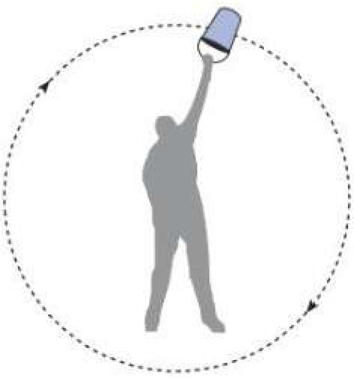
$= 1.54$ m s^{-1}

(c) $F_c = \dfrac{mv^2}{r} = \dfrac{(25)(1.54)^2}{3.5}$

$= 16.9$ N

This force is applied by the friction between her and the horse.

Vertical circular motion



In horizontal circular motion the force applied by, say, the tension on a string is always constant. However in vertical circular motion the force of gravity must also be considered.

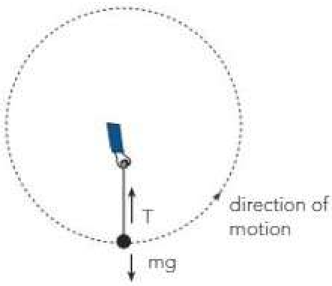
In the following typical examples of vertical circular motion (Worked Example 1.16) we can see that there are usually two forces acting with the net force being the centripetal force. Note the following:

- the weight force (mg) always acts downwards and is always the same magnitude.
- the tension force (T), or reaction force (R), are always greatest at the bottom. If they become zero at the top then 'apparent weightlessness' occurs.
- the centripetal force (F_c) in each case is not shown as it is actually the resultant of the other forces acting.

Remember for circular motion – **"the net force is always the centripetal force ".**

Worked Example 1.8

(a) Mass on the end of a string (bottom).
For circular motion the net force is always the centripetal force (F_c). Since the tension and weight force are acting in opposite directions we have:



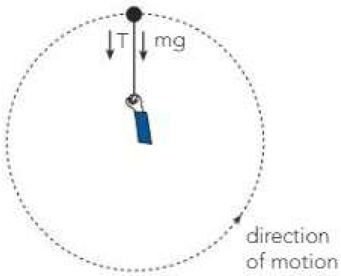
$$\text{Net force} = F_c = T - mg$$

$$\therefore \frac{mv^2}{r} = T - mg$$

$$\therefore \quad T = \frac{mv^2}{r} + mg$$

(b) Mass on the end of a string (top)

Again, the net force is F_c if the body is undergoing circular motion. However in this case both tension (if any) and weight force are acting downwards.

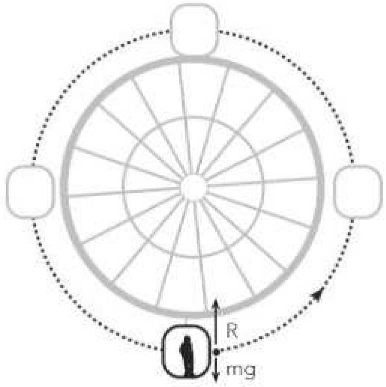


$$\text{net force} = F_c = T + mg$$

$$\therefore \frac{mv^2}{r} = T + mg$$

$$\therefore T = \frac{mv^2}{r} - mg$$

(c) Standing in a revolving Ferris wheel (bottom)



Net force acting on you is the centripetal force (F_c).

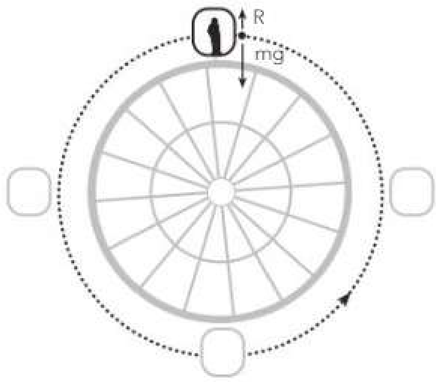
$$\text{net force} = F_c = R - mg$$

$$\therefore \frac{mv^2}{r} = R - mg$$

$$\therefore R = \frac{mv^2}{r} + mg$$

Note similarity to Example 1.8(a).

(d) Standing in a revolving Ferris wheel (top)



Net force acting on you is the centripetal force (F_c).

$$\text{net force} = F_c = mg - R$$

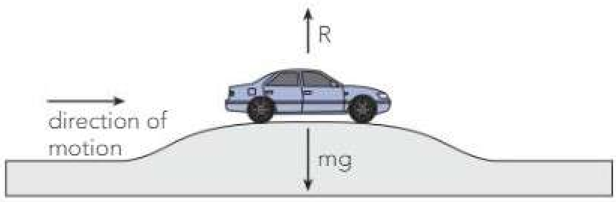
$$\therefore \frac{mv^2}{r} = mg - R$$

$$\therefore R = mg - \frac{mv^2}{r}$$

Note difference to Example 1.8(b).

(e) Travelling over a humped road

This situation is of course exactly the same as Example 1.8(d).



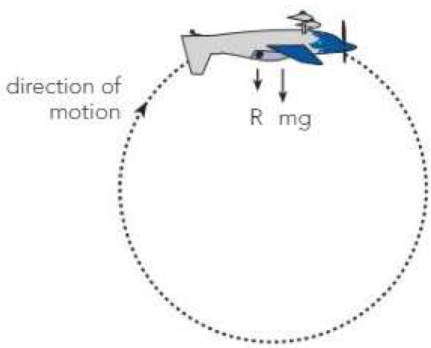
$$\text{net force} = F_c = mg - R$$

$$\therefore \frac{mv^2}{r} = mg - R$$

$$\therefore R = mg - \frac{mv^2}{r}$$

(f) A plane doing loop the loop

This situation is similar to Example 1.8(b) although we are dealing with a reaction force (R) rather than the tension (T) in a string.



$$\text{net force} = F_c = R + mg$$

$$\therefore \frac{mv^2}{r} = R + mg$$

$$\therefore R = \frac{mv^2}{r} - mg$$

Question 1.11

This question relates to Worked Example 1.8, examples (a) to (f).

(a) In this situation, at the bottom, the tension force (T) must be greater than the weight force (mg). Explain.

___

___

(b) In this situation, at the top, under what conditions would a body experience 'apparent weightlessness'?

___

___

(c) You feel heavier at the bottom of a revolving Ferris wheel. Explain.

___

___

(d) (i) Which force is your 'apparent weight' at the top of the Ferris wheel?

___

(ii) Can your 'apparent weight' be zero? Explain.

___

___

(e) If the reaction force (R) is zero, what will be the 'apparent weight' of the driver?

___

___

(f) If the reaction force (R) is equal to the weight force (mg), what will be the 'apparent weight' of the pilot? Explain.

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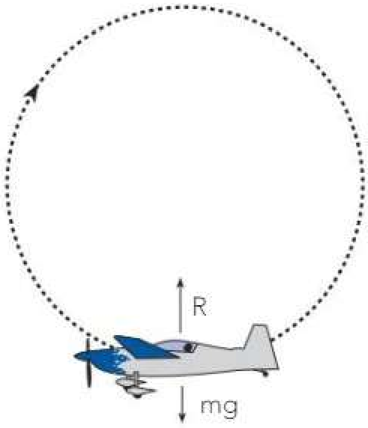
Worked Example 1.9

A pilot of mass 85 kg is flying in a vertical circle of radius 2.10 km at a constant speed of 176 m s^{-1}. Calculate the following.

(a) The maximum reaction force that his seat will exert on him.

(b) How does this force compare to the pilot's normal weight?

(c) The minimum speed he would need to travel at in order to feel weightless.



R = ?
m = 85 kg
v = 176 m s^{-1}
r = ?

(a) Maximum reaction force will occur at the bottom

$$R = \frac{mv^2}{r} + mg$$

$$= \frac{(85)(176)^2}{2100} + (85)(9.80) = 1254 + 833$$

$$= 2.09 \times 10^3 \text{ N}$$

(b) Ratio of $\frac{R}{mg} = \frac{2.087 \times 10^3}{833}$

$$= 2.51$$

i.e. the pilot feels approximately 2.5 times his usual weight (often referred to as 2½ g)

(c) Weightlessness will be experienced at the top of the loop if the reaction force is zero.

Since $R = 0$ then $\frac{mv^2}{r} = mg$

$$v = \sqrt{gr} = \sqrt{(9.80)(2100)}$$

minimum velocity = 143 m s^{-1}

Question 1.12

In the worked example above the pilot feels weightlessness (R = 0) at a speed of 143 m s^{-1}. What would happen to the reaction force if the speed was a little lower, say 130 m s^{-1}? Remember the pilot is upside down at this point of the flight.

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Banked tracks

When an athlete races around a bend or a car turns around a corner the reaction force with the ground provides the necessary centripetal force.

By banking a track or a road we can make use of the weight force and the reaction force with the ground to provide the centripetal force. This is particularly important at high speeds.

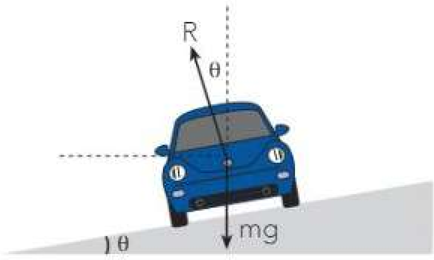


Figure 1.12 Banked track. The horizontal component of the reaction force provides the centripetal force.

Consider the car in Figure 1.12. If there is no friction force acting parallel to the bank, the only two external forces on the car will be:

- the weight force mg
- the reaction force R

If we look carefully at the reaction force (R) we note that:

(i) $R \cos \theta = m\,g$ since Σ vertical forces = 0
i.e. the vertical component of R balances the weight force mg.

(ii) $R \sin \theta = F_c$ (net force)
i.e. the horizontal component of R provides the centripetal force (F_c) towards the centre of motion.

Combining (i) and (ii) we can show that:

$$\tan \theta = \frac{v^2}{r\,g}$$

θ = angle of track (to horizontal)
v = optimum speed for banked track
r = radius of curvature
g = 9.80 m s^{-2}

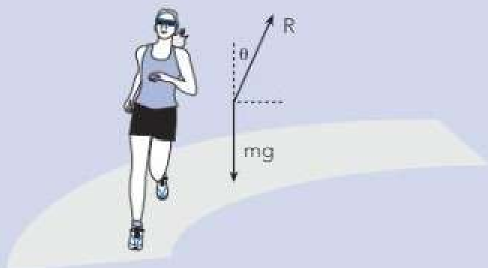
Question 1.13

In designing the bend on a freeway, engineers needed to calculate an appropriate slope for a curve of 400 m radius. If the slope was decided to be 10°, what would be the optimum speed for this curve? Is this reasonable?

____

Question 1.14

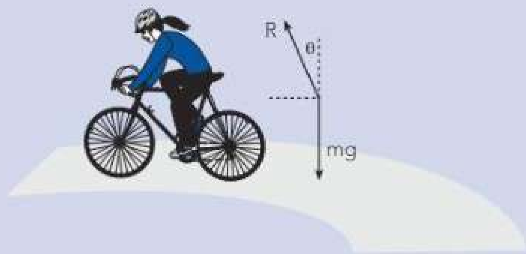
(a) An athlete leans in when running around a circular track. The only forces acting on the athlete are shown where R is the reaction force from the ground and the athlete's weight (mg).



Write an expression for:

- the net force acting on the athlete; ______________________________
- the frictional force acting on the athlete. ______________________________

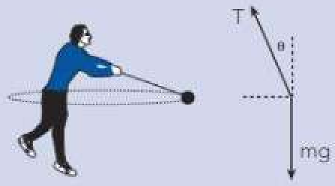
(b) A bike rider leans in to a bend when travelling along a horizontal circular track. As before, the only forces acting on the bicycle are the reaction force from the ground and the weight force.



Write an expression for:

- the centripetal force (F_c) acting on the bike; ____________________
- the force that balances the weight force. ________________________

(c) During the hammer throw the only forces acting on the hammer are the tension force (in the arm or chain) and its weight.



Write an expression for:

- the net force acting on the hammer;

  ____

- the frictional force that must exist between the hammer thrower's feet and the ground.

  ____

1.4 SATELLITE MOTION

We saw in projectile motion that if a body is given horizontal velocity it will fall with a curved path to the ground.

If sufficient velocity is given to the object then the curve of its fall will match the curvature of the Earth. We would then have the situation of the object falling around the Earth rather than onto the Earth. The velocity to achieve this is about 8 kms^{-1} or nearly 29000 km h^{-1}.

Satellites then may be considered as bodies that are simply in free fall around the Earth.

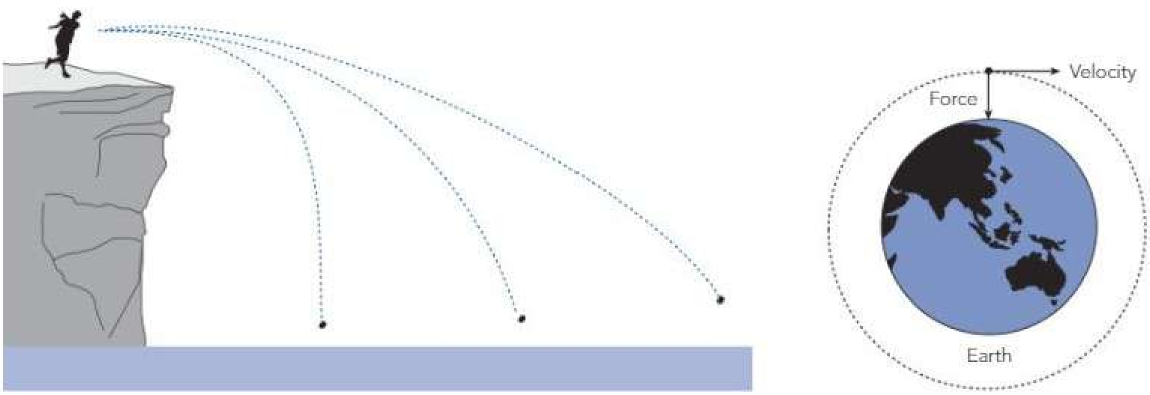


Figure 1.13 Satellites falling around the Earth. A force continually acts on a satellite. Due to its tangential velocity it moves in a circular path.

Question 1.15

If a cannon ball could be fired from the top of a very high mountain with a velocity of 29000 km h^{-1} it would not actually achieve orbit. Explain.

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Achieving stable orbit

A satellite is continually moving in a circular path. If it is to stay in orbit then the centripetal force (Fc) required for this circular motion must equal the force of attraction between itself and the body it is orbiting (Fg).

Hence the important relationship:

$$Fc = Fg$$

$$\frac{mv^2}{r} = \frac{GMm}{r^2}$$

Which gives:

$$\boxed{v^2 = \frac{GM}{r}}$$

v = velocity of satellite
m = mass of satellite
M = mass of central mass (e.g. Earth)
r = orbital radius

From this relationship and using $v = \frac{2\pi r}{T}$ it is possible to calculate the velocity and period for any satellite at some given altitude. Note that for these calculations the mass of the satellite is irrelevant.

$$T^2 = \frac{4\pi^2}{GM} \times r^3 \quad \text{or} \quad \frac{T^2}{r^3} = \frac{4\pi^2}{GM} \qquad \text{(one of Kepler's Laws)}$$

Worked Example 1.10

A Landsat satellite is placed in an orbit 700 km above the Earth. Calculate the velocity of this satellite and determine its period of rotation.

$m_E = 5.97 \times 10^{24}$ kg
$r_E = 6.38 \times 10^6$ m
$h = 7.00 \times 10^5$ m
$v = ?$
$T = ?$
$G = 6.67 \times 10^{-11}$ N m^2 kg^{-2}

$$\frac{mv^2}{r} = \frac{Gm_Em}{r^2}$$

$$v^2 = \frac{Gm_E}{r}$$

$$= \frac{(6.67 \times 10^{-11})(5.97 \times 10^{24})}{7.08 \times 10^6}$$

$$v = 7.50 \times 10^3 \text{ m s}^{-1}$$

Hence the satellite's velocity is 7.50×10^3 m s^{-1}.

To find the period

Use $v = \frac{2\pi r}{T}$ $\therefore T = \frac{2\pi r}{v}$

$$= \frac{(2)(\pi)(7.08 \times 10^6)}{7.50 \times 10^3}$$

$$= 5.93 \times 10^3 \text{ s}$$

The period of rotation is 98.9 minutes.

Question 1.16

Derive the T^2/r^3 relationship for satellites orbiting a central mass M by combining $v = 2\pi r / T$ with $v^2 = GM/r$.

Question 1.17

A satellite in orbit is continually under the gravitational attraction of the body it is circling. Why then does its speed not increase?

Question 1.18

A communications satellite is placed in a geosynchronous orbit around the Earth. It appears to be stationary above some point on Earth.

(a) What must be the period of such a satellite? Why?

(b) Must it have an equatorial or polar orbit? Why?

(c) Determine the orbital radius of such a satellite.

Question 1.19

The period of Earth's orbit around the sun is 3.156×10^7 s (~365.25 days). The mean distance of the Earth from the sun is 1.50×10^{11} m while that of Jupiter is 7.78×10^{11} m. Using only this information determine the period of Jupiter's orbit around the sun.

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Weightlessness

The weight of a body is the force with which it is attracted to the Earth, or some other body. Our own sensation of weight is given to us by the reaction force that the ground exerts upon us.

Apparent weightlessness can occur:

- **in free fall:** if you are falling freely then there is no reaction force exerted on you and you would have a feeling of weightlessness
- **in orbit:** within an orbiting satellite you would feel weightless since you are essentially in free fall. A weight force is still acting upon you and it is the force that is keeping you moving in a circular path.
- **"looping the loop":** if you are moving in a vertical circle with sufficient velocity then you will experience weightlessness at the top (i.e. when $\frac{mv^2}{r} = mg$)

In all of the cases above you experience apparent weightlessness. True weightlessness however can only occur if you are an infinite distance from the earth or other bodies, an unlikely event. You would be weightless, however, at any point in space where the influence of different gravitational fields cancel each other.

Question 1.20

Assuming no effect from other heavenly bodies, there will exist a point between the Earth and the Moon where you could be truly weightless. Estimate how far along the path from the Earth to the Moon this would occur. Assume for simplicity that the Earth's mass is 81 times that of the moon (it is actually 81.36).

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1.5 TORQUE AND EQUILIBRIUM

Centre of mass

As we saw in the section on gravitation the concept of a centre of mass of a body is a convenient one for mathematical calculations. It is the single point about which the body's mass is evenly distributed. The centre of mass of a body is also often referred to as its centre of gravity. For simplicity we can consider these to be the same point, although it is not exactly true in a non-uniform gravitational field.

Finding centre of mass

The simplest way to find the centre of mass of an object is to find the point about which it balances. This is usually the geometrical centre of the object if it is regular in shape and uniform in density. A convenient method where practicable, is to suspend the object. The centre of mass will lie directly below it. By repeating the process from a different suspension point the exact location of the centre of mass is found.

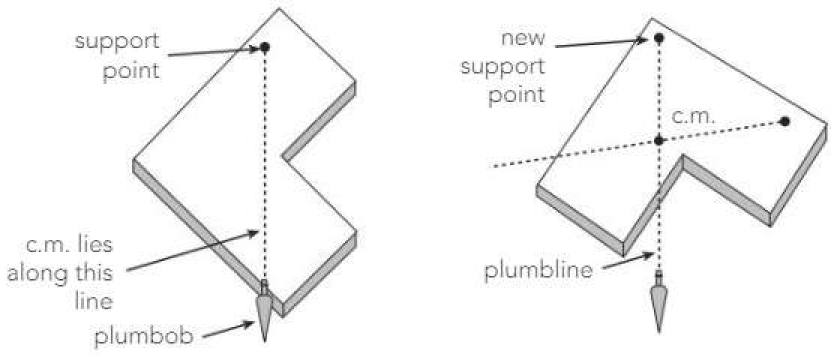


Figure 1.14 Finding centre of mass of a lamina.

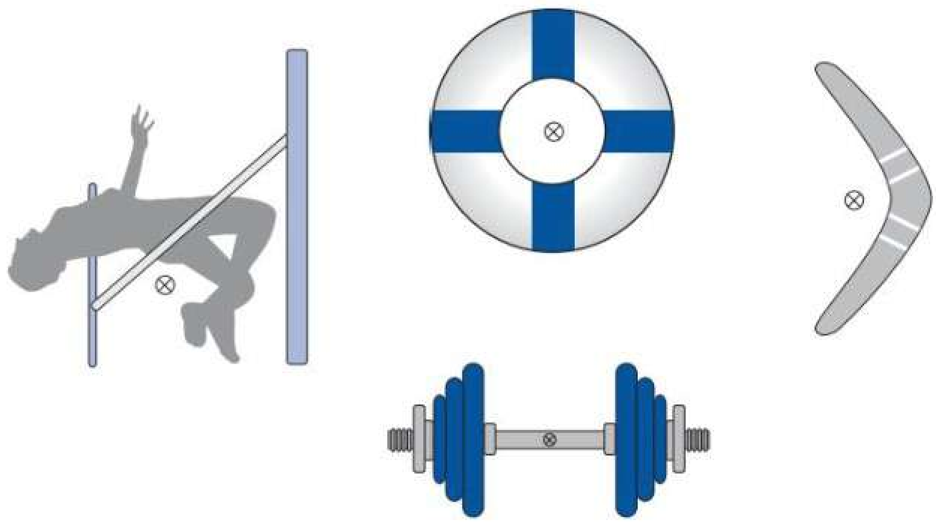


Figure 1.15 The centre of mass of some familiar objects.

Stability (Static Equilibrium)

The stability of an object or structure depends very much on the position of its centre of mass in relation to its support.

A body may be in either stable, neutral or unstable equilibrium.

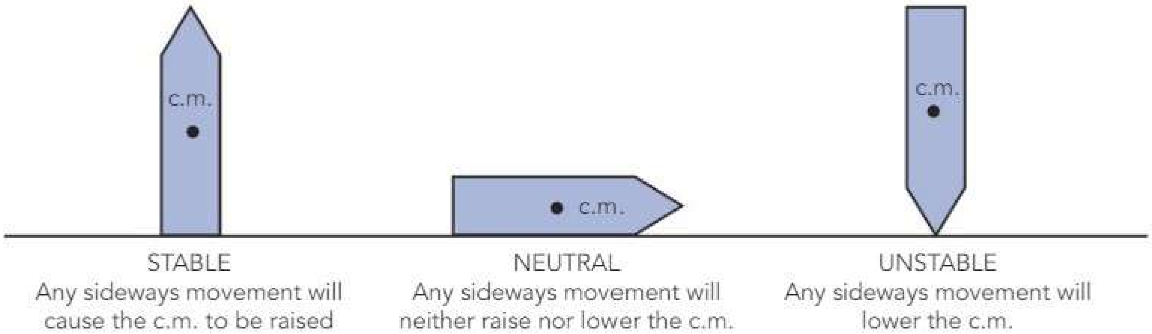


Figure 1.16 *The three types of equilibrium.*

Good stability is generally achieved by keeping the centre of mass as low as possible. Motor cars have a wide base for stability. Tall buildings use large amounts of heavy concrete in the foundations below ground in order to lower the centre of mass. A structure will become unstable and topple if the line of its centre of mass falls outside the objects base.

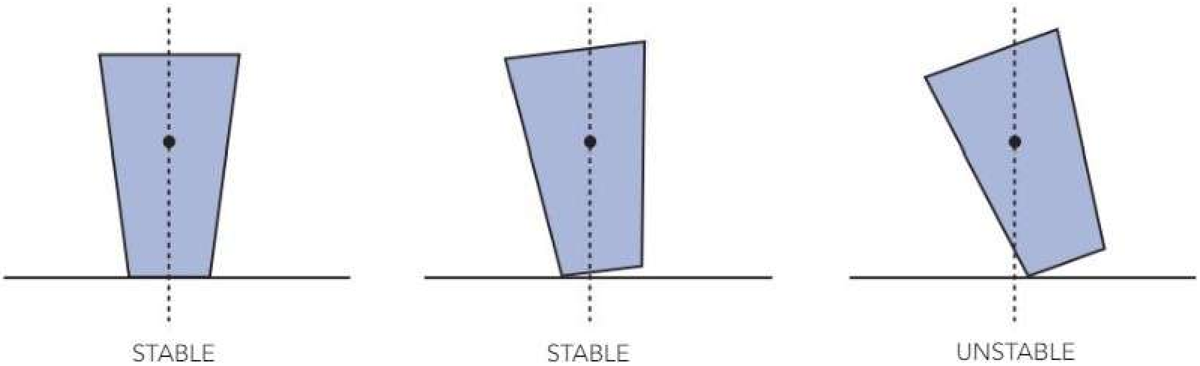


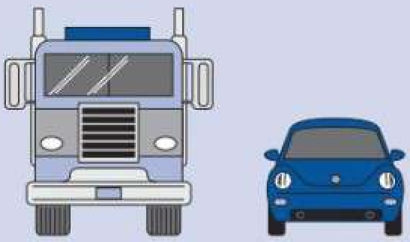
Figure 1.17 *Toppling occurs if the c.m. is outside the base of support.*

Question 1.21

Rob is carrying a can of heavy paint in his left hand and has a noticeable lean to the right as he is doing so. Why is this?

Question 1.22

(a) Estimate the approximate centre of mass for each of the vehicles shown below and mark it on the diagram.



(b) Which vehicle is more stable? Explain why.

____

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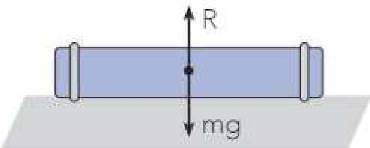
Forces in Equilibrium

One of the conditions for a body to be in static equilibrium is for all forces acting on it to be in balance such that the net force is equal to zero.

$\Sigma F = 0$ That is, the vector sum of all forces acting on the body is zero.

The simplest and most common example of this is a body, such as a book, at rest on a study table. The book has two forces acting on it; the weight force due to gravity and the reaction force from the table pushing back. The two forces are equal and opposite in direction and hence the net force acting on the book is zero. Several examples are illustrated below.

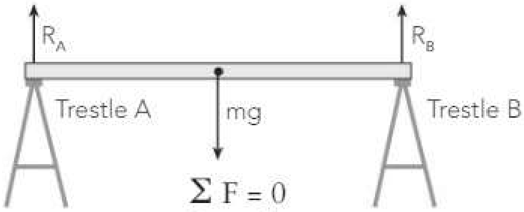
(i) A book at rest on a table



$\Sigma F = 0$

$\therefore$ $R = m\,g$

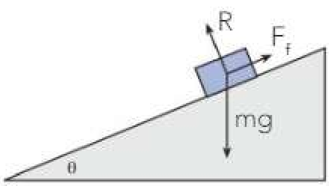
(ii) A plank supported by 2 trestles



$\Sigma F = 0$

$\therefore$ $R_A + R_B = mg$

(iii) A box at rest on an inclined plane



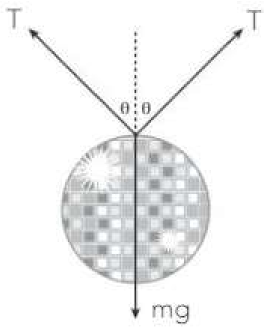
The force of friction counteracts the component of the weight force acting down the plane

$\Sigma F = 0$

parallel to the plane $F_f = mg \sin \theta$

perpendicular to the plane $R = mg \cos \theta$

(iv) A mass supported by cables



$\Sigma F = 0$ (in all directions)

Vertically: $T \cos \theta + T \cos \theta = mg$

Horizontally: $T \sin \theta = T \sin \theta$

* *See also Worked Example 1.15*

Figure 1.18 *Forces in equilibrium*

Forces causing rotation – Torque

A force can be applied in such a way that it causes the rotation of a body about a point. When we open a door for example or turn on a tap or use a spanner the force we apply creates a turning effect. This turning effect, or moment of a force, is called torque.

Another common example is the torque created by the force we apply on a bike pedal.

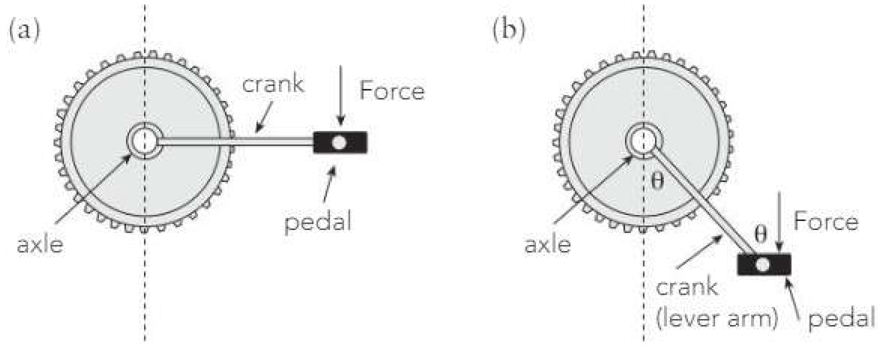


Figure 1.19 Turning effect of a force (torque). Maximum torque will occur where the force is at right angles to the lever arm.

The moment of a force is calculated by multiplying the force by the effective perpendicular distance from the fulcrum.

$$\tau = r\,F\,\sin\theta$$

τ	=	moment or torque (N m)
F	=	force (N)
r	=	perpendicular distance to the pivot point (m)
θ	=	angle between force and lever arm

In Figure 1.19 above, the force will cause a clockwise moment in both cases. In case (b), however, the moment will be much less as the effective perpendicular distance from the fulcrum is less.

Worked Example 1.11

A force of 125 N is applied by Paula using a spanner to loosen a bolt as shown.

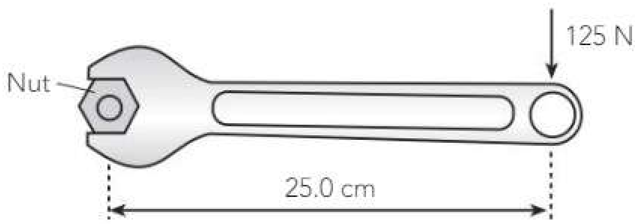
(a) Assuming the force is applied at right angles calculate the torque created.

(b) Calculate the force the spanner exerts on the nut. Assume the force applied to the nut is at a perpendicular distance of 8.00 mm from the centre.

(c) The nut proves too tight to loosen with this force. Suggest a possible solution to increasing the force on the nut if 125 N is the maximum force Paula can use.

(a) $\tau = r\,F$

$= (0.250)(125) = 31.25$ N m

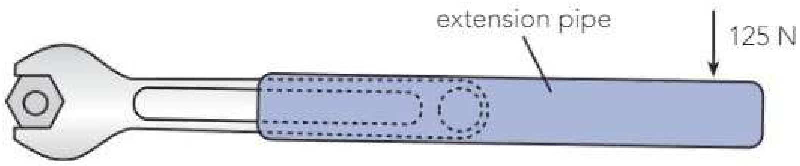


(b) $\tau = r\,F$

$31.25 = (8.00 \times 10^{-3})(F)$

$F = 3.91 \times 10^{3}$ N

(c) Will need to increase the 'lever arm' length in order to increase the torque using the same applied force. Hence either use a longer spanner (if available) or increase the effective length of the spanner by attaching an extension pipe.

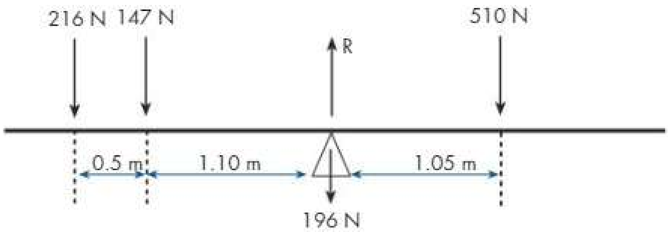


Worked Example 1.12

Julie is working out the best position from which to balance Chelsea and Hannah on a seesaw. Her mass is 52.0 kg and she is 1.05 m from the pivot point of a seesaw of mass 20.0 kg. Hannah (15.0 kg) and Chelsea (22.0 kg) are respectively 1.10 m and 1.60 m from the pivot point on the other side as shown.

(a) Draw a vector diagram showing all forces.
(b) Calculate the clockwise and anticlockwise moments (torque).
(c) Does equilibrium exist? If not, where should Julie sit to achieve balance?
(d) Calculate the magnitude of the reaction force.

(a)



(b) $\Sigma\tau_{cw} = (510)(1.05)$
$= 536$ N m cw

$\Sigma\tau_{acw} = (147)(1.10) + (216)(1.60)$
$= 507$ N m acw

(c) Not in equilibrium. Seesaw will turn clockwise. For equilibrium $\Sigma\tau_{cw} = \Sigma\tau_{acw}$
$\therefore$ $(510)\,x = 507 \;\;\therefore\;\; x = 0.99$
$\therefore$ Julie needs to move 0.06 m closer to the centre.

(d) $\Sigma F = 0$ $\quad\quad \therefore R = 216 + 147 + 510 + 196 = 1069$ N

Principle of moments and equilibrium

The conditions for the equilibrium of a body are:

(i) $\Sigma F = 0$ That is, the vector sum of all forces acting on the body is zero.
and
(ii) $\Sigma \tau = 0$ That is, the sum of the moments about any point also be zero.

The second condition is often referred to as the Principle of Moments and can be expressed as:

$$\Sigma \text{ clockwise moments} = \Sigma \text{ anti-clockwise moments}$$

or

$$\Sigma\tau_{cw} = \Sigma\tau_{acw}$$

Note: the point about which moments are taken should always be specified.

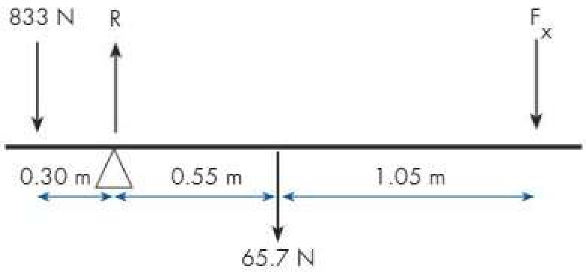
There are a variety of situations where the rules above can be used to solve problems. Some typical examples are illustrated on the following pages.

Worked Example 1.13

Simple Lever: John is using a lever of mass 6.70 kg to raise a heavy rock of mass 85.0 kg. The lever is 2.10 m in length and arranged as shown. The rock is 20.0 cm from one end and 30.0 cm from the pivot point.

(a) Draw a vector diagram to show all forces.
(b) Determine the force that John has to apply downwards in order to just lift the rock.
(c) What is the reaction force at the pivot?

(a) Simplified vector diagram.



(b) Weight of lever

$$w = mg$$
$$= (6.70)(9.80)$$
$$= 65.7 \text{ N}$$

Weight of rock

$$= (85.0)(9.80)$$
$$= 833 \text{ N}$$

For equilibrium - take moments about the pivot point.

$$\Sigma\tau_{cw} = \Sigma\tau_{acw}$$
$$(65.7)(0.55) + (F_x)(1.60) = (833)(0.30)$$
$$F_x = 133.6 \text{ N}$$

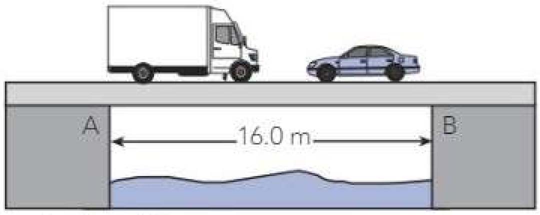
∴ John must apply a downward vertical force of 134 N.

(c) For equilibrium the sum of all forces must be zero,

i.e.
$$\Sigma F_y = 0$$
$$R = 833 + 65.7 + 134$$
$$R = 1033 \text{ N} = 1.03 \times 10^3 \text{ N}$$

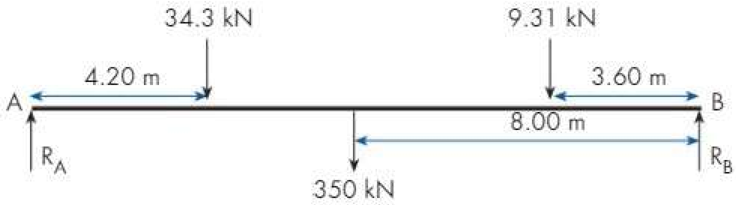
Hence the support must be able to supply a reaction force of 1.03×10^3 N.

Worked Example 1.14



Simple Bridge: A small truck of mass 3.50 tonne and a car of mass 950 kg are situated on a bridge as shown. The truck is 4.20 m from A and the car 3.60 m from B. The bridge has a weight of 350 kN and is 16.0 m long. Determine the reaction forces at ends A and B.

A simplified vector diagram is essential .



Taking moments about point A

$$\Sigma\tau_{cw} = \Sigma\tau_{acw}$$

$$(34.3 \times 10^3)(4.2) + (350 \times 10^3)(8) + (9.31 \times 10^3)(12.4) = (R_B)(16)$$

$$R_B = 191.2 \text{ kN}$$

$$\therefore R_B = 191 \text{ kN}$$

To find R_B we can simply sum the vertical forces for equilibrium.

$$\Sigma F_y = 0$$

$$R_A + R_B = 34.3 \text{ kN} + 350 \text{ kN} + 9.31 \text{ kN}$$

$$\therefore \quad R_A = 393.6 \text{ kN} - 191.2 \text{ kN}$$

$$R_A = 202.4 \text{ kN}$$

Hence the reaction forces at A and B are 202 kN and 191 kN.

Question 1.23

Referring to the problem above:

(i) We found R_A by using $\Sigma F = 0$. Verify the calculation by taking moments about B to find R_A.

(ii) If the truck and car were to pass each other exactly in the middle of the bridge, what would be the values for R_A and R_B? (A simple calculation will give you this).

There are many everyday situations which are similar to the "simple bridge problem" solved above.

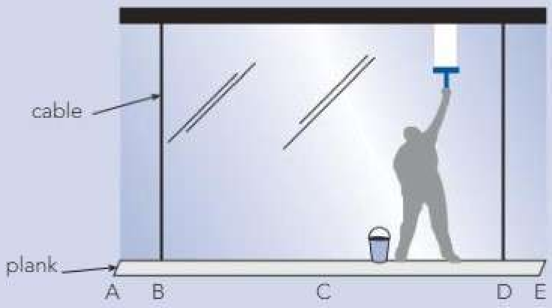
These include such situations as:

- a plank supported on two trestles;
- two workmen carrying a long object on their shoulders;
- a painter's plank supported at its ends by overhead cables;
- a motor vehicle's weight being supported by tyres at the front and back.

In each of the cases above, moments about a pivot point will give one unknown, while using $\Sigma F = 0$ will give the other.

Question 1.24

A window cleaner of mass 76 kg is standing 2.0 m from one end of a 5.0 m plank (12.0 kg) which is supported by cables attached 1.0 m from each end.

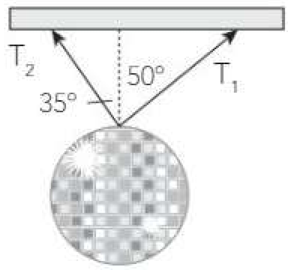


(a) Sketch a vector diagram showing all forces acting on the plank.

(b) Where must the window cleaner stand so that the tensions in the cables are equal? What would the tensions be?

(c) Where must the window cleaner stand so that the tension in the cable attached to B is a maximum (careful). Why?

Worked Example 1.15



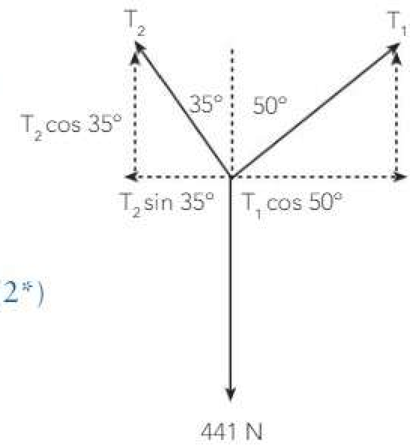
Cables supporting a load: A large decoration weighing 441 N is being supported by two cables as shown. Determine the tension in each cable.

A vector diagram, approximately to scale is essential. Note that T_2 is likely to be greater than T_1 (Why?).

There are two methods of solving this problem.

- **Method A:** Equate vertical forces and horizontal forces then solve the two simultaneous equations.
- **Method B:** Use the triangle addition of forces to give a null (zero) vector.

Using method A



$$\Sigma F_y = 0 \qquad \therefore T_2 \cos 35° + T_1 \cos 50° = 441 \text{ N}$$

$$0.819T_2 + 0.643T_1 = 441 \quad (1^*)$$

Also

$$\Sigma F_x = 0 \qquad T_2 \sin 35° = T_1 \sin 50°$$

$$0.574T_2 = 0.766\, T_1 \quad (2^*)$$

Solve 1* and 2* by eliminating one of the unknowns.

From (2*) we get $T_2 = \frac{0.766}{0.574} = 1.334\, T_1$

substituting into (1*) we get

$$(0.819)(1.334\, T_1) + 0.643\, T_1 = 441$$

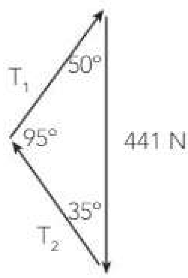
Hence $T_1 = 254$ N

substitute the value of T_1 into (1*) and we get

$$0.819\, T_2 + (0.643)(254) = 441$$

$$T_2 = 339 \text{ N}$$

Using method B



Since $\Sigma F_y = 0$ simply add the three forces as a triangle of forces giving a null vector. To avoid confusion, always begin by drawing the weight force vector as it is directly downwards.

Then systematically add the two tension vectors to complete a triangle where the tail of each vector is on the head of the previous one. Be careful not to change the actual orientation of each vector (i.e. the direction it points). In determining the angles of the triangle it's best to work out the angles that the tension forces make with the vertical first.

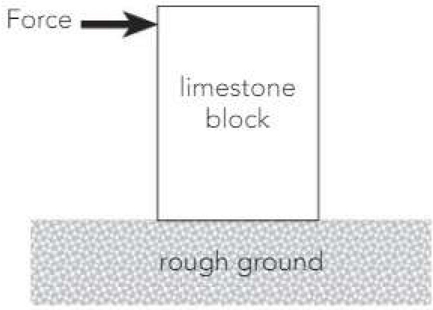
To solve use the sine rule. $\frac{T_1}{\sin 35°} = \frac{T_2}{\sin 50°} = \frac{441}{\sin 95°}$

$$\therefore \quad T_1 = 441 \frac{\sin 35°}{\sin 95°}, \quad T_2 = 441 \frac{\sin 50°}{\sin 95°}$$

$$= 254 \text{ N} \qquad\qquad = 339 \text{ N}$$

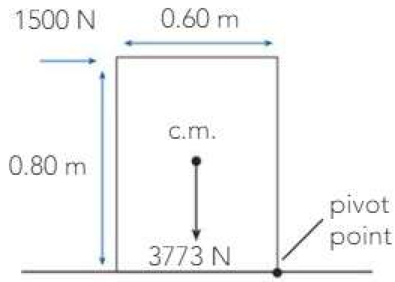
Method B is far superior!

Worked Example 1.16



Will it tip? A large limestone block 80 cm high and 60 cm wide is to be tipped over by applying a force at the top as shown. The mass of the block is 385 kg and the force being applied is 1500 N. Will it tip over? (Assume no sliding occurs).

Taking moments about the pivot point – and considering only perpendicular distances



$$\Sigma\tau_{cw} = (1500)(0.80) = 1200 \text{ N m}$$

$$\Sigma\tau_{acw} = (3773)(0.30) = 1132$$

$$\Sigma\tau_{cw} > \Sigma\tau_{acw}$$

$\therefore$ Limestone block will tip over.

Question 1.25

In the example on the previous page the cables are at different angles. Suppose the cable on the right is adjusted so that it too makes an angle of 35° to the vertical.

(a) How would you expect the value of T_1 to change? Why?

____

(b) How would you expect the value of T_2 to change? Why?

____

(c) Which arrangements would give the least tension for both cables? What would this tension be?

____

____

Question 1.26

In Example 1.16 the block will just tip over onto its large side. If a force is now applied in a similar manner in order to tip it back up again what would be the value of this force?

____

____

____

____

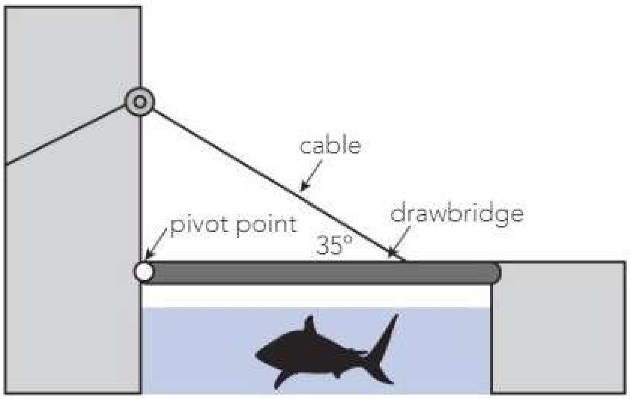
____

Worked Example 1.17

The drawbridge problem – a supported cantilever. A bridge that can be raised to allow boats to pass under it is 9.60 m long and attached to a cable inclined 35° to the horizontal.

The mass of the bridge is 12.0 tonne and the cable is attached 7.20 m from the pivot point. The bridge is horizontal and just being raised from its ground support.

Determine:
(a) the tension force in the cable;
(b) the reaction force at the pivot.



(a) We begin with a simplified vector diagram showing only the forces *acting on the bridge*. There are only three. The direction of the reaction force is only an estimate at this stage.

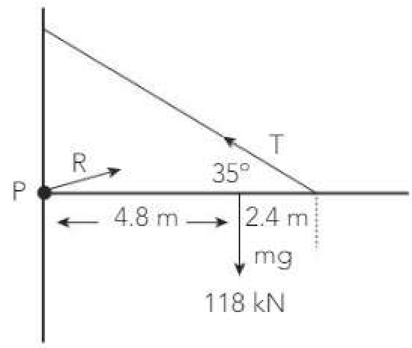
We find T by taking moments about the pivot point P.

$$\sum \tau = 0$$

$$\sum \tau_{CW} = \sum \tau_{ACW}$$

$$(118 \times 10^3)(4.8) = (T \text{ Sin } 35°)(7.2)$$

$$T = 1.37 \times 10^5 \text{ N}$$



We could have also found the a.c.w. moments by multiplying T by the perpendicular distance of the cable from the pivot point. Not an advantage in this case as it would require extra calculations.

(b) To find the reaction force R we simply do a triangle of forces and use the cosine rule.

$\sum F = 0$

$\therefore$ vector triangle will add to null vector

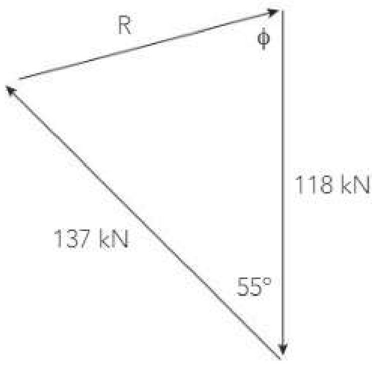
$R^2 = (1.18 \times 10^5)^2 + (1.37 \times 10^5)^2 - 2(1.18 \times 10^5)(1.37 \times 10^5)(\cos 55)$

$R = 1.19 \times 10^5$ N

Also to find ϕ

$$\frac{1.37 \times 10^5}{\sin \phi} = \frac{1.19 \times 10^5}{\sin 55} \quad \therefore \phi = 70.5°$$

$\therefore$ Reaction force at the pivot is 1.19×10^5 N at 70.5° to the wall (to the vertical).



Question 1.27

(a) As the drawbridge in the above problem is raised what will happen to the tension in the cable? Why?

____

____

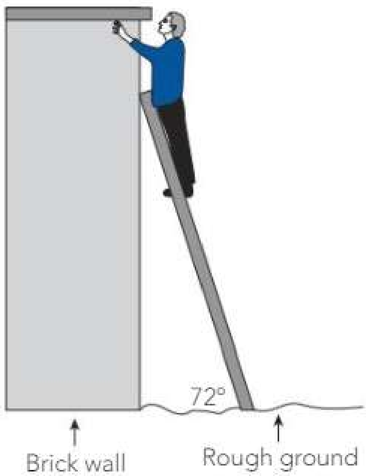
(b) How will the direction of the reaction force at the pivot change? Why?

____

____

Worked Example 1.18

The ladder problem. Rob is investigating some storm damage and is using an 18.5 kg ladder of total length 4.80 m as shown. The ladder is inclined at 72° to the horizontal and is resting on rough ground. Rob's weight is 735 N and he is situated 3.60 m from the bottom of the ladder.



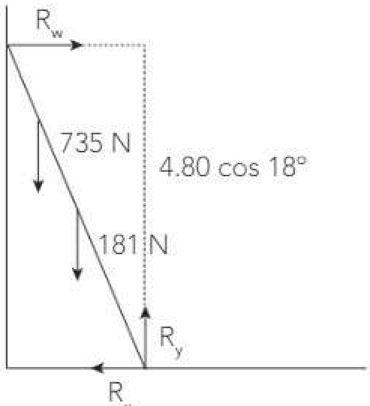
Determine:

(a) The force exerted by the wall on the top of the ladder. Assume wall is smooth.

(b) The minimum force of friction required for the ladder not to slip.

(c) The total reaction force exerted by the ground.

We begin with a simplified vector diagram showing only the forces acting *on the ladder*.



Note that R_x and R_y are components of the reaction force of the ground on the ladder

The reaction force from the wall is perpendicular since the wall is smooth and hence there is no vertical component.

The reaction force on the ground is broken up into its two components to simplify the problem. (Note that the reaction force will not necessarily be directed along the ladder.)

For equilibrium:

$\sum F_y = 0 \qquad \therefore R_y = 735 + 181$

$= 916$ N

Also $\sum F_x = 0 \qquad \therefore R_w = R_x$

Also $\sum \tau = 0$, hence taking moments about the pivot on the ground.

$$\sum \tau_{CW} = \sum \tau_{ACW}$$

$$(R_w)(4.80 \cos 18^\circ) = (735)(3.60 \cos 72^\circ) + (181)(2.40 \cos 72^\circ)$$

$$R_w = 209 \text{ N}$$

Note: in calculating the moments, we used the component forces perpendicular to the ladder. Hence answers are:

(a) The force exerted by the wall $R_W = 208.5$ N

(b) The minimum force of friction is $R_X = 208.5$ N.

(c) Total reaction force exerted by the ground can be found by adding RX and RY vectorially (using Pythagoras). This will give $R_{TOTAL} = 939$ N, 12.8° to the vertical.

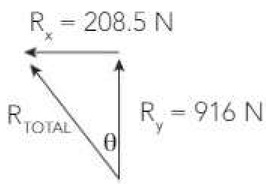
Using Pythagoras for part (c)

$R_T^2 = R_x^2 + R_y^2$

$R_{TOTAL} = 939$ N

$\tan\theta = \frac{208.5}{916} \therefore \quad \theta = 12.8°$

$R_{TOTAL} = 939$ N, 12.8° to the vertical



Question 1.28

(a) In the example 1.18, if Rob moves a little further up the ladder how will the following be affected? Explain each answer.

(i) R_W ______________________________

(ii) R_X ______________________________

(iii) R_Y ______________________________

(b) How will the direction of the reaction force at the pivot change? Why?

(c) How can it be ensured that R_X will be large?

REVIEW QUESTIONS

Chapter 1: Gravity and Motion

Gravitation

1. (a) Calculate the force of gravitational attraction that the Earth exerts on the Moon.
   (b) What gravitational force does the Moon exert on the Earth?
   (c) What evidence do we have of the Moon's attractive force?

2. Two small jars of peanut paste, each of mass 300 g are resting on a kitchen bench some 15.0 cm apart (centre to centre).
   (a) Determine the gravitational force of attraction between these two jars?
   (b) Why do they not accelerate towards each other?

3. An astronaut's tool box has a mass of 3.50 kg. What will be:
   (a) Its mass while in orbit 1000 km above the Earth?
   (b) Its weight on the surface of the Moon?

4. The acceleration due to gravity (g) at the Earth's surface is usually taken as 9.80 m s^{-2} although its value is slightly different in different locations. How would you expect the value of g to vary (more or less than 9.80 m s^{-2}) for the following situations? Give the reason for your answer.
   (a) At the equator of the Earth.
   (b) At the poles of the Earth.
   (c) On the top of a high mountain.
   (d) At the bottom of a deep mine or deep ocean.

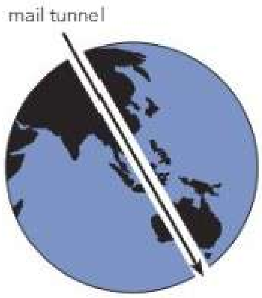
   Note: For (c) and (d) assume g = 9.80 m s^{-2} at the surface.

5. Calculate the height above the Earth that a rocket must reach for the acceleration due to gravity to be:
   (a) ¼ of (g) on Earth.
   (b) 1% of (g) on Earth.

6. A new planet Jumbo is discovered which has a diameter three times that of the Earth and 21 times its mass. Determine:
   (a) the value of (g) on Jumbo (use g = 9.80 on Earth).
   (b) the ratio of the density of the planet Jumbo to that of the Earth.

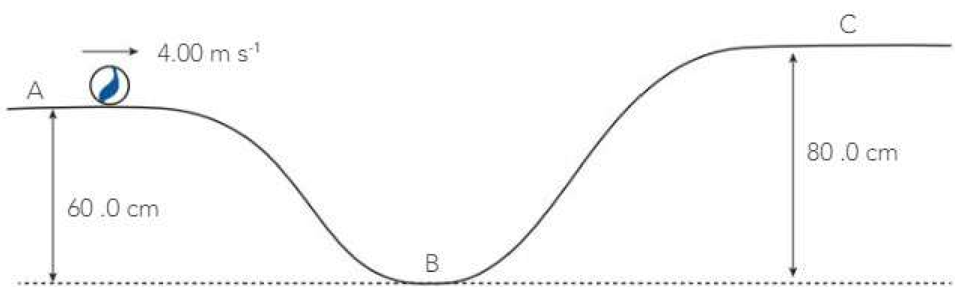
7. An astronaut is stranded exactly ¾ of the way to the Moon.
   (a) In which direction will he begin to fall?
   (b) What will be his acceleration?
   (c) If he maintained this acceleration how long would it be before he landed?
   (d) In actual fact it would take a lot less time than this. Clearly explain why.

8. Frank, an imaginative businessman, suggests the construction of a mail tunnel right through the centre of the Earth. The mail would travel in a tube from one end of the Earth to the other, quickly and without the use of any fuel for energy.
   (a) What are some likely difficulties that the businessman would encounter?
   (b) Assuming that the tunnel could be constructed, at which point(s) in the tunnel would you expect:
      (i) the velocity to be a maximum?
      (ii) the acceleration to be a maximum?
      (iii) the force on the mail tube to be zero?
   (c) If feasible to build, would such tunnels be effective if they connected points such as Perth and Melbourne directly? Explain.



9. Livia is skiing down a slope of 15.0° to the horizontal towards a jumping point and reaches a maximum velocity of 75.0 kmh^{-1}. Livia has a mass of 67.0 kg.
   (a) What is the weight force acting on Livia parallel to the slope?
   (b) Why is her velocity no longer increasing? Explain.
   (c) If the jumping point is a further 45.0 m vertically below her, how long will it be before she reaches it?

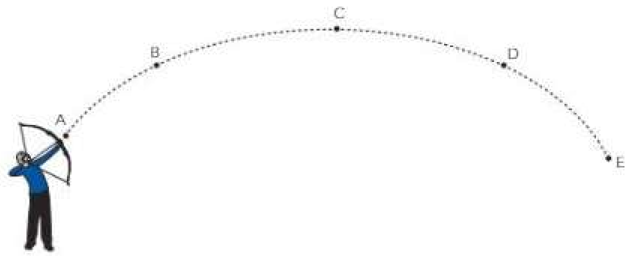
10. A marble of mass 50.0 g and an initial velocity of 4.00 m s^{-1} rolls down a smooth track from point A as shown. It rolls freely down the track to point B and continues upwards towards point C. Assuming no friction or air resistance determine the following:
   (a) Potential and kinetic energy of the marble at point A.
   (b) Velocity of the marble as it reaches point B.
   (c) If the marble is likely to reach point C.



Projectile motion

11. A long jumper is able to take off with a velocity of 8.25 m s^{-1} at 12.5° to the horizontal. Calculate:
   (a) the initial horizontal velocity,
   (b) the vertical take off velocity.

12. Rob fires an arrow from point A and hits a target E as shown. Points B and D are at the same height. C is the point of maximum height.



Assuming no effects from air resistance:

(a) At which point has the arrow got the greatest vertical speed?

(b) What is the acceleration at point C?

(c) At which point/s, if any, is the velocity zero?

(d) At points B and D, which of the following, if any, would have equal values:

  (i) velocity?

  (ii) speed?

  (iii) acceleration?

  (iv) kinetic energy?

13. Aaron throws a ball to John with a velocity of 16.0 m s^{-1} at an angle of 35.0° above the horizontal. Assuming no air resistance find:

(a) The maximum height that the ball will reach.

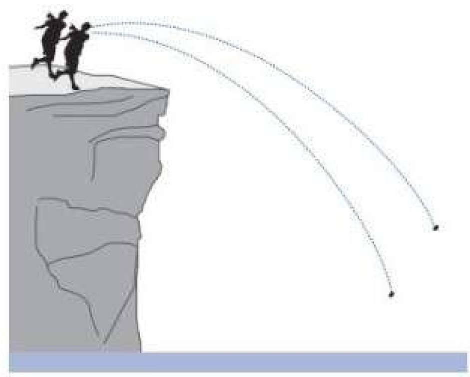
(b) How far John is from Aaron if he is able to catch the ball at the same height as it was thrown.

14. A rifle is fired horizontally at a target 450 m away. The bullet is found to hit 15.0 cm below the target.

(a) What was the velocity of the bullet?

(b) What adjustment is usually made to a rifle in order to ensure the bullet hits the target?

15. Aaron and John are seeing who can throw the furthest from a high cliff face into the ocean.



(a) They find that they get the best results when they throw at an angle of less than 45.0°. Explain why this is the case.

(b) Aaron throws a small rock with a velocity of 24.0 m s^{-1} at an angle of 30.0° above the vertical. The rock hits the water 3.60 s later.

  (i) how high above the water was the rock released?

  (ii) how far horizontally did the rock travel?

16. Natasha releases a ball from the free-throw line with a velocity of 7.00 m s^{-1} at an angle of 51.0° from the horizontal. Assume that the ball was released at a height of 2.30 m above the ground and that the basket is 3.05 m high.

(a) If the ball passes exactly through the hoop as it is falling calculate

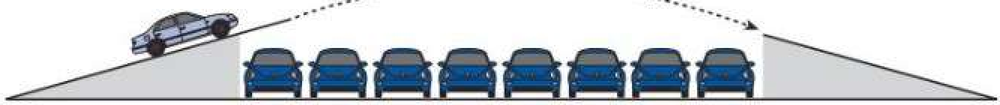
  (i) time of flight,

  (ii) the distance of the free-throw line from the centre of the hoop.

(b) Suggest why higher angles than 45° are generally favoured by basketballers when taking their shots.

17. A cricket ball is thrown at an angle of 20.0° to the horizontal and reaches a maximum height of 15.0 m above its release point. How fast was it thrown?

18. In a stunt car record attempt, a car is driven off a ramp at 90.0 kmh^{-1}. The ramp is inclined at 15.0° and is similar to a ramp placed on the other side of several cars.



(a) What will be the stunt car's vertical take off velocity?
(b) For how long will the car be airborne?
(c) How close should the ramps be for the car to just make it to the second ramp?

Circular motion

19. A student whirls a small mass of 325 g tied to the end of a string in a horizontal circle of 1.90 m radius. The mass moves at a constant speed and completes 10 revolutions in 12.5 seconds. Determine:
(a) the speed of the mass.
(b) the net force acting on the string

20. Robbie wants to show Paula how he can make water defy gravity. He partly fills a bucket of water and then proceeds to swing it in a vertical circle of 95.0 cm effective radius once every second.
(a) Determine if Robbie will be successful in his demonstration.
(b) Has Robbie defied gravity? Explain.

21. Whenever a bicycle rider travels around a bend it is noticeable that she leans inwards into the bend rather than remaining vertical.
(a) Explain clearly why this is necessary.
(b) Which factors would influence the angle of lean?

22. The spin dryer of an automatic washing machine is 48.0 cm in diameter. While spin drying a load of washing it rotates at 150 rpm.
(a) Determine the maximum acceleration of an article of clothing spinning inside the dryer.
(b) How does this compare with the acceleration due to gravity?
(c) Explain how the dryer is able to remove water from the clothes by this process.

23. A tumble dryer is designed so that it will "air" clothing by allowing it to fall directly to the bottom of the tumbler rather than continually sticking to its sides. If the dryer has a 50.0 cm diameter, below what speed (in rpm) should it operate to achieve a tumbling action?

24. A car of total mass 1240 kg is moving with a constant speed of 60.0 kmh^{-1} as it travels along a bend whose radius of curvature is 450 m. Assuming that the road is horizontal:
(a) Determine the centripetal force necessary for the car to be able to go around this bend.

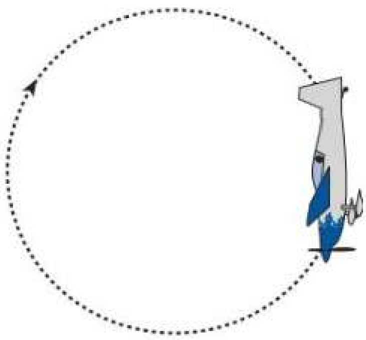
(b) How is this force applied to the car?

25. A car of total mass 850 kg is travelling around a bend of 120 m in radius. The maximum force of friction available between the road surface and the four car tyres is 1600 N.
   (a) What is the maximum velocity with which the car can negotiate this bend?
   (b) What is the car's acceleration at this maximum velocity? In which direction is this acceleration acting?
   (c) While travelling at this maximum velocity the car applies its brakes to slow down. What will be the initial effect on the cars acceleration? What is likely to happen?
   (d) Determine the angle of banking which would allow this car to safely negotiate this bend without any friction.

26. Aaron is pushing John on his favourite swing which has a seat supported by two ropes, each 1.85 m in length. John has a mass of 52.5 kg and as he swings to and fro he achieves a maximum velocity of 5.00 m s^{-1}.
   (a) Calculate the maximum tension in the supporting ropes. Assume that the seat has a mass of 500 g.
   (b) When does this occur?

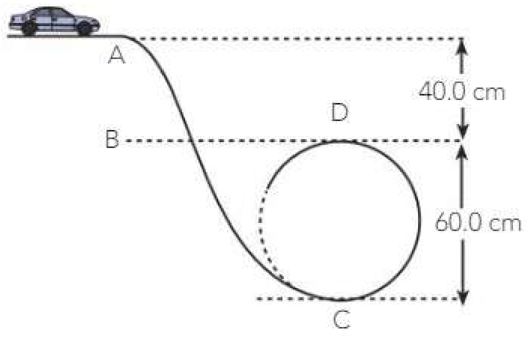
27. An aircraft is circling Perth airport while it is waiting to land. It is flying at 350 kmh^{-1} in a horizontal circle of 8.50 km radius.
   (a) What is the acceleration of the aircraft?
   (b) What angle will it need to bank at to achieve this?

28. A pilot is doing a "loop the loop" by flying his plane in a vertical circle of 3.50 km radius. He is able to keep the speed of the plane constant during the flight and completes each loop in 85.0 s.
   (a) What is the speed of the plane?
   (b) When will he feel heaviest?
   How heavy will he feel?
   Assume the pilot's mass is 84.5 kg.
   (c) If the pilot is able to withstand "4.00 g" of acceleration will he complete this particular exercise safely? ("1 g" = 9.80 m s^{-2})



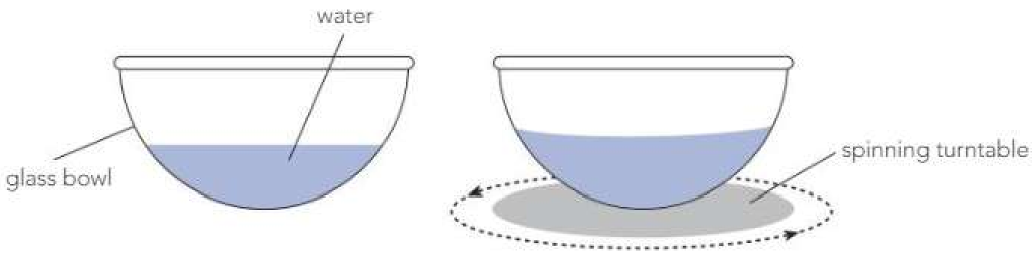
29. A mass of 1.00 kg is attached to a strong light cable and whirled in a vertical circle of 65.0 cm radius with a constant speed of 7.50 m s^{-1}. Determine:
   (a) the ratio of the net force acting on the mass at the bottom of the circle to that at the top.
   (b) the ratio of its kinetic energy at the bottom of the circle compared to that at the top.
   (c) the ratio of the tension in the cable at the bottom of the circle compared to that at the top.

30. A toy metal car is allowed to roll down a frictionless track from A as shown. It is initially at rest.



(a) What will be its velocity at:
   (i) B
   (ii) C
(b) Will it always remain in contact with the track as it does a vertical loop?

31. A circular glass bowl was partly filled with water and then placed on a spinning turntable. It was noticed that the level of the water curved towards the side of the container as shown.



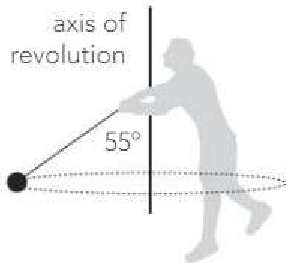
(a) What has caused this effect? Why?
(b) Why is the slope of the water highest near the edge of the bowl?
(c) If the experiment was repeated on the moon would the result be different? Explain. (Assume same rate of spinning and that the experiment is conducted in a room with normal atmospheric pressure).

32. (a) When motor bikes or cars go over curved humps on the road with too great a speed they can become airborne. Explain why this occurs.
(b) At a rally car meeting a curved hump is made so that its curvature is 8.50 m radius at its apex.

(i) What minimum speed will the rally car need to achieve to become airborne?
(ii) How far horizontally along the track would the cars land? Assume it reaches the horizontal portion of the road which is 8.50 m below the apex.

33. Two skaters have joined hands and are skating rapidly around each other about a common point between them. Describe their movement at the instant they let go of each other.

34. A hammer thrower has gradually increased the speed of his hammer so that it completes one revolution in 2.20 s. The hammer may be considered to be moving in a horizontal circle of 1.70 m radius and that the angle of the connecting chain to the vertical axis is 55.0°. The mass of the hammer is 7.26 kg.



(a) What is the velocity of the hammer?
(b) What is the magnitude and direction of the nett force acting on the hammer?
(c) What force is exerted on the hammer thrower's arms?

Satellite motion

35. John has a mass of 55.0 kg. What will be:
(a) His weight at the Earth's surface?
(b) His weight at an altitude of 700 km above the Earth?
(c) His apparent weight while orbiting in a satellite 700 km above the Earth. Explain.

36. Due to the Earth's rotation (once every 24.0 hrs) a person's apparent or measurable weight is less than expected.
(a) Where would this effect be most noticeable, at the equator or the poles of the Earth?
(b) Calculate the maximum percentage (%) difference that this effect will have on your measurable weight.
(c) If you wanted to lose your weight completely what should the period of the Earth's rotation be?

37. A spaceship is to be placed in orbit around the Moon so that it remains directly over a lunar module which has landed on the near side of the Moon. This will allow the spaceship to remain in direct contact with both the lunar module and the Earth.
(a) Calculate the distance from the moon that the spaceship must orbit. The Moon's period of rotation is 2.36×10^6 s.
(b) This orbit is often impractical because it is too far removed from the lunar module. If the spaceship wishes to orbit at 100 km above the Moon's surface, what orbital speed must it achieve?

38. One of Kepler's laws states that the ratio r^3/T^2 is a constant for all satellites orbiting the same central mass such as the planets orbiting the sun. Use this law to determine the period of the Hubble space telescope which orbits the Earth at a height of 593 km given that the orbital radius of a geostationary satellite is 4.22×10^7 m.

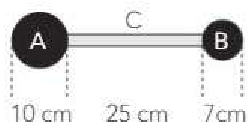
39. A spaceship is investigating a strange new planet by orbiting at a distance of 30,000 km. It is estimated that the unknown planet has a diameter of 20,000 km. The spaceship then completes two closer orbits one at a distance of 20,000 km and the other at only 10,000 km from the planet.
(a) In which of the three orbits does the spaceship:
(i) have the greatest velocity?
(ii) have the greatest acceleration?

(b) Draw graphs using arbitrary units to show how the velocity and acceleration of the spaceship varies for the three different orbits.
(c) The orbital velocity of the spaceship at its lowest orbit was measured to be 8.66×10^3 m s^{-1}. What is the mass of the unknown planet?

40. An orbiting space station needs to jettison a capsule so that it will fall to Earth. If the capsule is fired directly at the Earth it will not reach it.
(a) Explain clearly why it will not fall to Earth (Hint: vector diagrams may also help).
(b) In which direction should it be fired and with what velocity?

Torque

41. A weight lifter has a barbell composed of a large mass A of 6.00 kg connected to a smaller mass B, of 2.00 kg by way of a metal bar C also of mass 2.00 kg. The diameters of A and B are respectively 10.0 cm and 7.0 cm. The bar is 25.0 cm long.



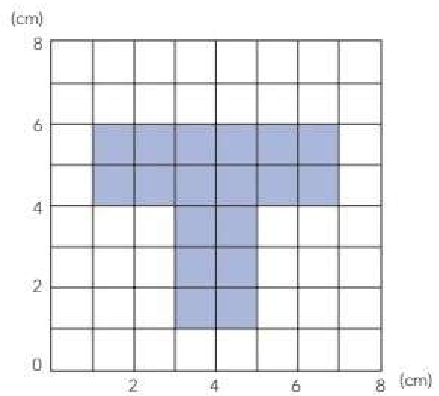
Determine the point along AB that the weight lifter can comfortably lift the barbell with one hand.

42. John is standing with his heels and back to a wall while in the school gymnasium. To his surprise he finds that it is impossible for him to bend over and touch his toes while this close to the wall. Why is this?

43. Infirm or elderly people sometimes use a walking stick as an aid to walking. Explain why the stick increases their stability.

44. It is noticeable that whenever a painter carries a large can of paint in one hand, he tends to hold up his other hand away from his body. Why is this?

45. A uniform lamina is "T" shaped and of dimensions as shown.
(a) Estimate its centre of mass and indicate it on the diagram.
(b) Use the Moments Principle to determine its exact position.



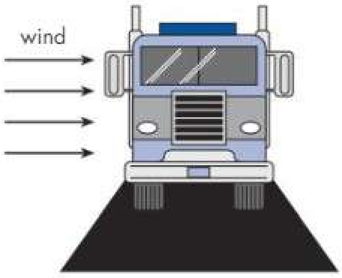
46. Rita devised an ingenious method of determining the position of her centre of mass using only a set of bathroom scales and a wooden plank. Rita firstly weighed herself by standing freely on the scales and got a reading of 54.0 kg. She also weighed the plank which gave a reading of 12.0 kg. Finally she lay on the plank with her feet directly over the brick support and her friend Lyn recorded a reading of 41.5 kg. The supports for the plank are 1.60 m apart.
   (a) Determine the height above the ground for Rita's centre of mass.
   (b) What are some precautions (or improvements) that Rita must consider to ensure an accurate result?

Equilibrium

47. Explain why it is not possible for you to get up from your seat without first leaning forward.

48. (a) What are two factors which influence the stability of a vehicle such as a furniture van?

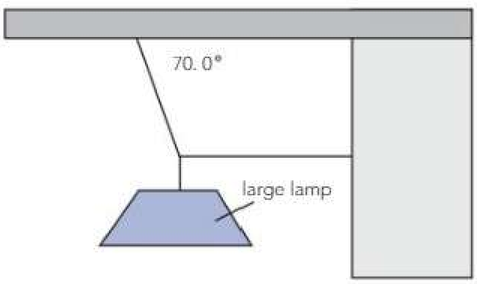
   (b) A strong wind is acting sideways on a van which is 2.60 m high and whose effective wheel base is 1.65 m. The van's total mass is 3250 kg. Its centre of mass is 1.25 m above the ground and centrally located.



   What force of wind would cause this van to just lose balance? Assume the wind force is acting perpendicularly and 2/3 of the way from the ground.

49. A tightrope walker recently undertook the stunt of walking on a high wire stretched between the spires of two tall buildings. To assist him, he carried a fairly long weighted pole.
   (a) How does the pole assist him with his walk?
   (b) If the combined weight is 950 N and the wire makes an angle of 5.00° to the horizontal at both ends, determine the tension in the wire.

50. A large lamp of mass 32.5 kg is supported by three strong cables as shown. The longer cable makes an angle of 70.0° to the ceiling while the other is perpendicular to the wall. Assuming their masses are negligible, find the tension in each of the three sections of cable.

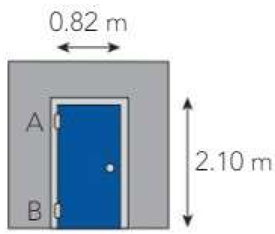


51. Vanessa took her two younger brothers to play on a seesaw. John (mass 32.0 kg), sat 80.0 cm from one end with Robert (mass 25.0 kg) 1.20 m from the same end. If the seesaw is 3.80 m in length, where must Vanessa (mass 56.0 kg) sit in order to balance her two brothers?

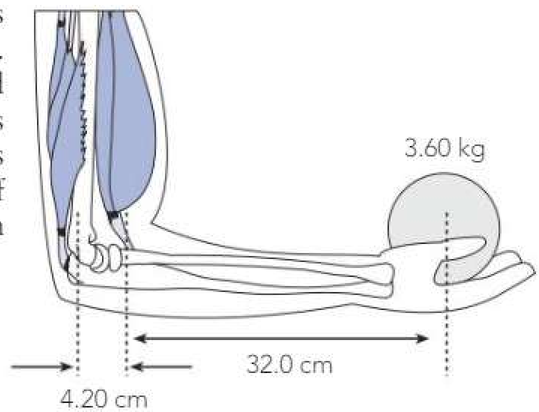
52. A temporary workbench is set up using a 3.20 m plank of 15.0 kg mass supported by two trestles located 80.0 cm from either end. A heavy box of mass 24.0 kg is located 1.00 m from one end.
 (a) Determine the reaction forces supplied by each trestle.
 (b) Determine the closest distance that the 24.0 kg mass can be placed from the end of the workbench without the workbench tipping over.

53. A sign is supported from a beam 3.20 m long which is itself supported by a wall and cable. The cable is attached 40 cm from the end of the beam and makes an angle of 35° with it. The mass of the beam is 25 kg and that of the sign 7.5 kg. Assume that the sign is uniform and attached symmetrically along the beam. Determine:
 (a) the tension in the cable;
 (b) the reaction force of the wall on the beam.

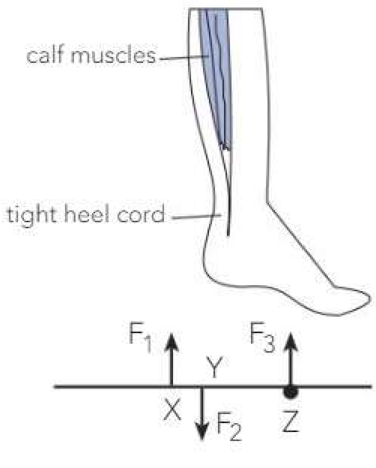
54. A door of mass 12.5 kg is hinged at A and B, 25 cm from either end. The door is hinged so that all the weight is supported by hinge B while hinge A prevents sideways movement. Assuming that the door is of uniform density determine:
 (a) the sideways reaction force at A;
 (b) the total reaction force supplied by hinge B.



55. Calculate the force exerted by a biceps muscle when lifting a 3.60 kg mass. Assume the biceps muscle is located 4.20 cm from the pivot point and acts at right angles to the arm whose mass is 1.65 kg. Consider the centre of mass of the arm to be 15.0 cm from the pivot point.

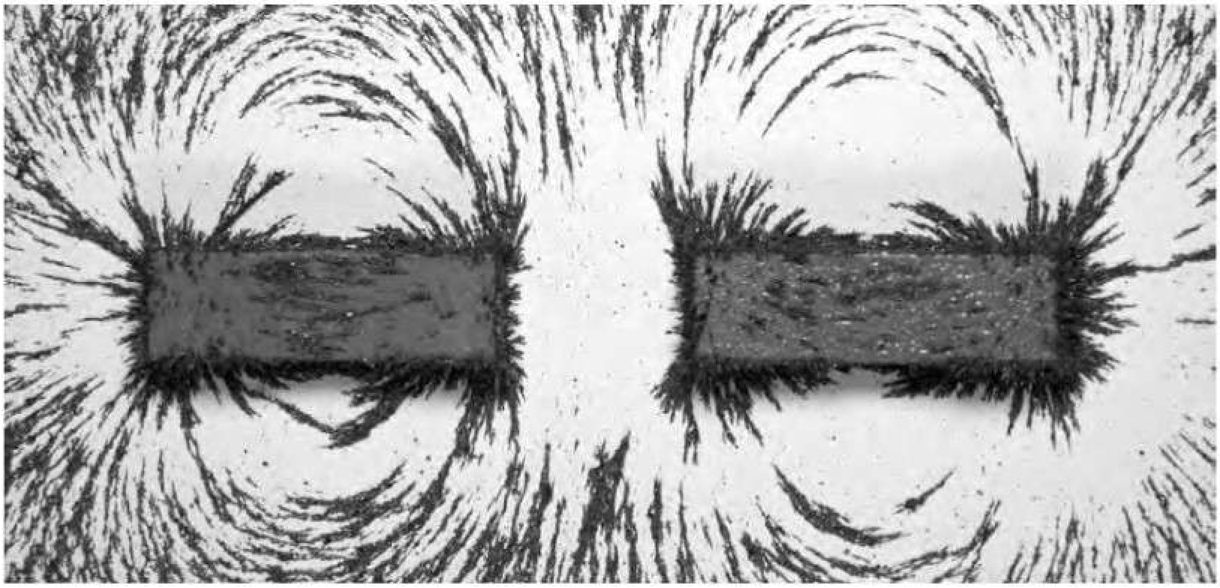


56. Matthew is balancing all his weight (620 N) on the toes of one foot. A simplified diagram shows the position of his calf muscle, body weight and pivot point. Assume XY = 3.80 cm, YZ = 12.0 cm.
 (a) Determine the tension in the calf muscle (F_1).
 (b) What must be the reaction force acting at Z? (F_3)
 (c) $\Sigma(F_1 + F_2 + F_3) = 0$. How is this possible?



ELECTROMAGNETISM

2



SYLLABUS CHECKLIST

SCIENCE UNDERSTANDING – ELECTROMAGNETISM

- ☐ electrostatically charged objects exert a force upon one another; the magnitude of this force can be calculated using Coulomb's Law.

  This includes applying the relationship:

  $$F = \frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r^2}$$

- ☐ point charges and charged objects produce an electric field in the space that surrounds them; field theory attributes the electrostatic force on a point charge or charged body to the presence of an electric field.

- ☐ a positively charged body placed in an electric field will experience a force in the direction of the field; the strength of the electric field is defined as the force per unit charge

  This includes applying the relationship:

  $$E = \frac{F}{q}$$

- ☐ when a charged body moves or is moved from one point to another in an electric field and its potential energy changes, work is done on the charge by the field.

  This includes applying the relationship:

  $$V = \frac{W}{q}$$

- ☐ the direction of conventional current is that in which the flow of positive charges takes place, while the electron flow is in the opposite direction.

- ☐ current-carrying wires are surrounded by magnetic fields; these fields are utilised in solenoids and electromagnets.

- ☐ the strength of the magnetic field produced by a current is a measure of the magnetic flux density.

  This includes applying the relationship:

  $B = \frac{\mu_0}{2\pi} \frac{I}{r}$

- ☐ the strength of the magnetic field produced by a current is a measure of the magnetic flux density.

- ☐ magnets, magnetic materials, moving charges and current-carrying wires experience a force in a magnetic field when they cut flux lines; this force is utilised in DC electric motors and particle accelerators.

  This includes applying the relationship:

  $F = q\,v\,B \text{ where } v \perp B, \;\; F = I\,l\,B \text{ where } l \perp B$

- ☐ the force due to a current in a magnetic field in a DC electric motor produces a torque on the coil in the motor.

  This includes applying the relationship:

  $\tau = r_{\perp} F$

- ☐ an induced emf is produced by the relative motion of a straight conductor in a magnetic field when the conductor "cuts" flux lines.

  This includes applying the relationship:

  $\text{induced emf} = l\,v\,B \text{ where } v \perp B$

- ☐ magnetic flux is defined in terms of magnetic flux density and area.

  This includes applying the relationship:

  $\Phi = B\,A_{\perp}$

- ☐ a changing magnetic flux induces a potential difference; this process of electromagnetic induction is used in step-up and step-down transformers, DC and AC generators.

  This includes applying the relationships:

  $\text{induced emf} = -N \frac{(\Phi_2 - \Phi_1)}{t} = -N \frac{\Delta\Phi}{t} = -N \frac{\Delta(B\,A_{\perp})}{t}$

  $\text{AC generator } emf_{max} = -2NlvB = -2\pi NBA_{\perp}f, \; emf_{rms} = \frac{emf_{max}}{\sqrt{2}}$

  $\frac{V_p}{V_s} = \frac{N_p}{N_s}$

  $P = V\,I = I^2\,R = \frac{V^2}{R}$

- ☐ conservation of energy, expressed as Lenz's Law of electromagnetic induction, is used to determine the direction of induced current.

2.1 ELECTROSTATICS

If two objects of different materials are rubbed together, such as a plastic ruler and a woollen jumper, static electricity results. The friction between the objects causes a transfer of electrons from one of the materials to the other. This results in the bodies acquiring equal and opposite static charges.

Electrostatics is the study of the causes and effects of these static charges. Some common occurrences that can be explained by electrostatics are listed.

- You can sometimes get a small electrical shock after walking across new carpet.
- A plastic comb run through your hair will attract small pieces of paper.
- A balloon that is rubbed against some clothing will tend to stick to walls.
- You can sometimes feel a small electrical shock from a car after travelling for some time.

Electric Charge

Electrostatic experiments with many different materials have established the following:

- Only two types of charges exist, positive and negative. Positively charged objects have a deficiency of electrons. Negatively charged objects have an excess of electrons.
- Like charges repel, unlike charges attract.
- Both positively and negatively charged objects attract neutral conductors.

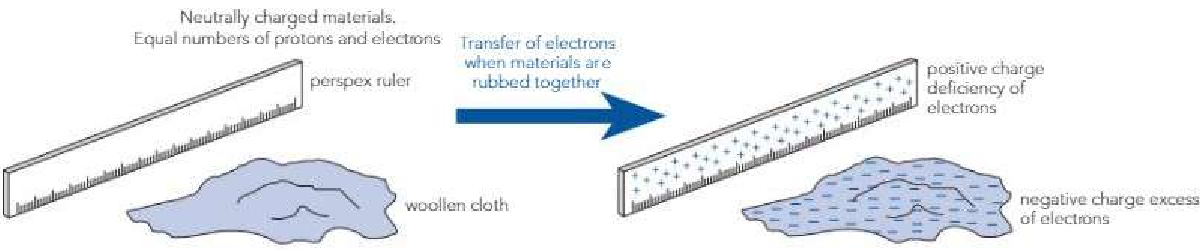


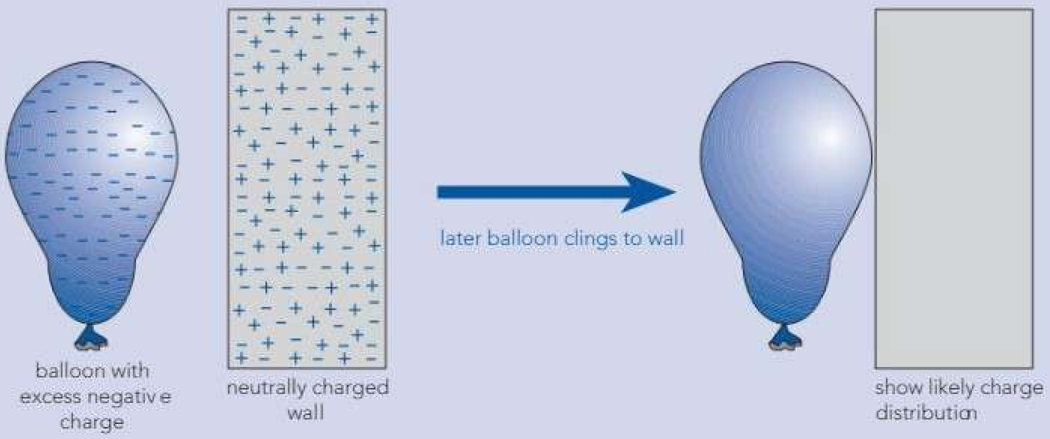
***Figure 2.1** Acquiring static charge through friction. When the ruler is rubbed with the cloth the cloth pulls some electrons from atoms on the surface of the ruler. This leaves the ruler with less electrons than protons (positive) and the cloth with excess electrons (negative).*

Question 2.1

Electrostatic charge due to friction is always the result of electrons transferring from one material, or surface, to another. In terms of the structure of atoms explain why a transfer of protons does not occur.

Question 2.2

A party balloon is charged by rubbing it on some clothing and then placed near (but not touching) a neutrally charged wall. It is found that the balloon drifts towards and clings to the wall. Explain how this is possible. (Hint: firstly complete the sketch below to show change in charge distribution.)



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Force between charges

It has been shown by experiment that charged objects exert forces on each other. These forces, called **electrostatic forces**, can act at a distance. Their nature and magnitude depends on the individual charges and their distance apart. In summary we can show that like charges repel and unlike charges attract and that the force between them increases greatly if they are closer together.

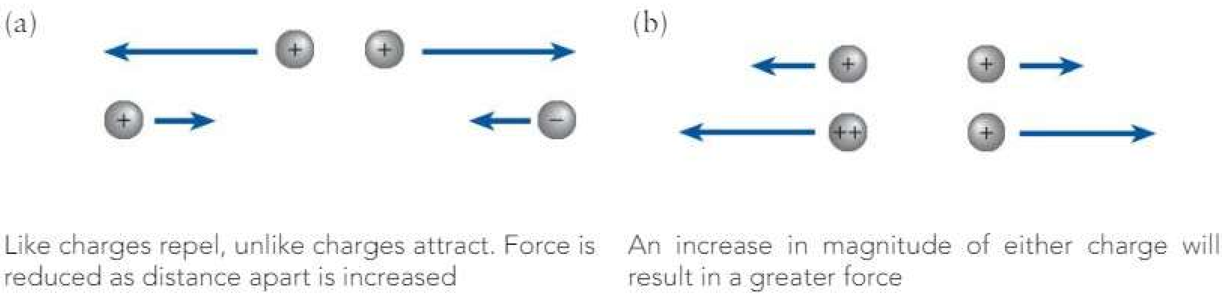


***Figure 2.2** The nature of forces between charges. Like charges repel, unlike charges attract. Forces are proportional to the product of the charges and inversely to the square of their distance apart.*

Force between charges – Coulomb's Law

In his experiments with charged objects Charles Coulomb was able to show that the force they exerted on each other depended on both their individual charges and their distance apart.
He found that:

- $F \propto q_1 q_2$ Force was directly proportional to the product of the two point charges.
- $F \propto \frac{1}{d^2}$ Force was inversely proportional to the square of the distance between the two charges.

Coulomb's Law expresses these findings for the force between two point charges as follows:

$$F = \frac{1}{4\pi\varepsilon_0} \frac{q_1 q_2}{r^2}$$

or

$$F = k \frac{q_1 q_2}{r^2}$$

F = force between point charges (N)

q_1 = charge on body 1 (C)

q_2 = charge on body 2 (C)

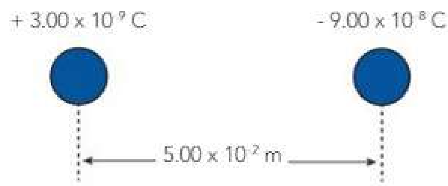
r = distance between two charges (m)

k = $\frac{1}{4\pi\varepsilon_0}$ = 9.00×10^9 N m^2 C^{-2} for a vacuum

ε_0 = 8.85×10^{-12} F m^{-1} is the electronic constant (permittivity of free space)

Worked Example 2.1

Two small spheres carrying a charge of + 3.00×10^{-9} C and - 9.00×10^{-8} C respectively are placed 5.00×10^{-2} m apart in a vacuum. Calculate the force that exists between the charges.



$$F = \frac{1}{4\pi\varepsilon_0} \frac{q_1 q_2}{r^2}$$

$= 9.00 \times 10^9 \times 3.00 \times 10^{-9} \times 9.00 \times 10^{-8} / (5.00 \times 10^{-2})^2$

$= 9.72 \times 10^{-4}$ N. The force is attractive

Question 2.3

An electron is placed exactly midway between the two point charges shown in the worked example above. The charge on an electron is – 1.60×10^{-19} C.

(a) Determine the forces acting on the electron from each of the two point charges and hence the net force.

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(b) In which direction will the electron move and what will be its initial acceleration?

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2.2 ELECTRIC FIELDS

Electrostatic forces can be detected in the space around a charged object. The region in which such forces can be found is called an electric field. This is similar in some ways to gravitational fields. Just as a force is exerted on a mass placed in a gravitational field, a force is exerted on a charge placed in an electrical field. However gravitational fields can only attract while electrical fields can attract or repel.

- An electric field exists at a point if a charge placed at that point experiences a force.
- An electric field is a vector quantity.
- The direction of an electric field is taken as the direction that a positively (+) charged body would move if placed at that point.
- An electric field is represented by lines of force or flux lines.

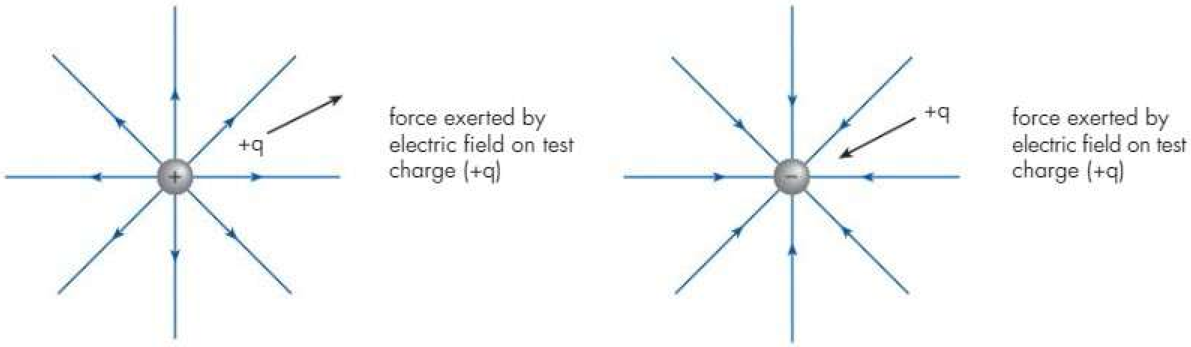


Figure 2.3 Electric field patterns near positive and negative point charges. The arrows indicate the direction that a positive test charge would move if placed at that point. Hence arrows are always away from positive. The magnitude of an electric field is defined as the force per unit charge and is strongest where lines of force are closer together.

Electric fields between charges and plates

Where there is more than a single point charge the resulting electric field distribution will be the vector sum of the individual fields at any particular point.

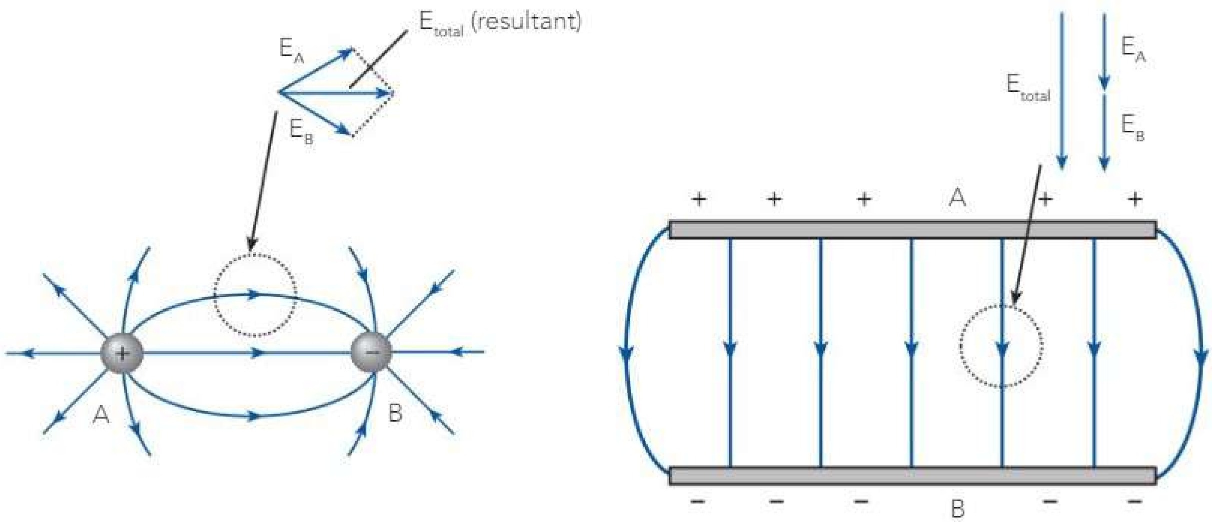


Figure 2.4 Electric fields are vector quantities. Where more than one point charge exists the resulting field is the vector sum of the individual fields at any point. Between parallel plates the resulting field is uniform.

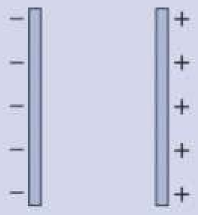
Question 2.4

For each of the following draw the electric field distribution associated with it.

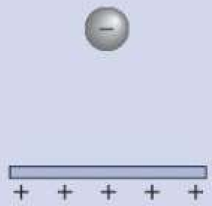
(a)

(b)

(c)



(d)



Electric fields in a metal conductor

An electric field will cause charges to move if they are free to do so. For example, if a battery is connected to the ends of a conductor, the resulting electrical field will cause a net flow of electrons. The electrons will move in the opposite direction to the field.

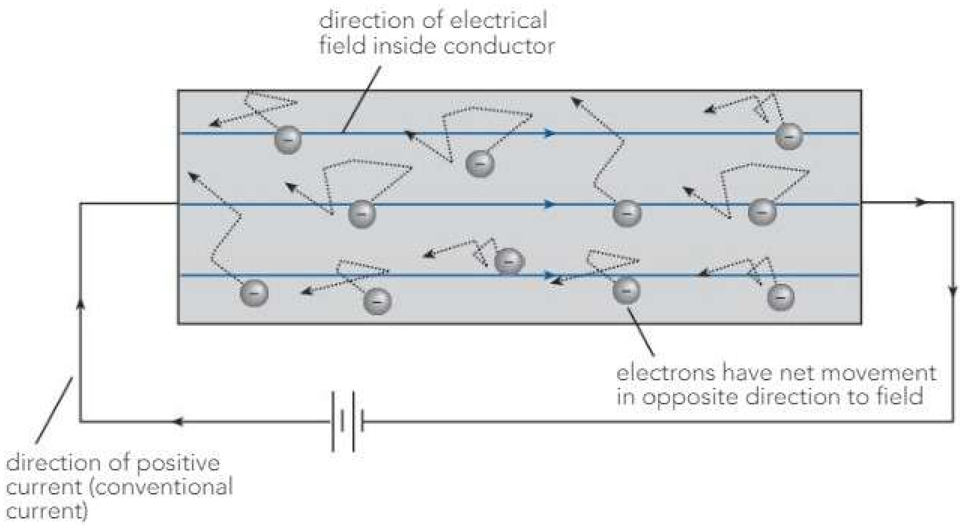


Figure 2.5 Electric fields cause a net flow of charge in a conductor.

Electric potential

Charged bodies can gain electrical potential energy when they are moved in an electrical field in a similar manner to which masses gain gravitational potential energy when they are lifted in a gravitational field. Consider a positively charged body that cannot move, such as the charged metal sphere in Figure 2.6. If a positive charge is to be brought near the sphere, say to point B, then work has to be done on the charge in order to overcome the force of repulsion.

- The work done in bringing a distant positive charge to point B is stored as electrical potential.
- If the charge is moved to A it will acquire a higher electrical potential energy.

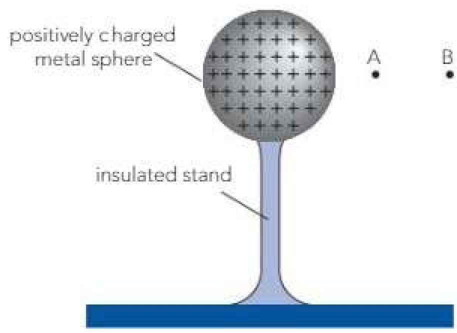


Figure 2.6 Points in an electrical field. Point A has a higher potential than B.

- Points A and B are points at different electrical potential. Point A has a higher potential than point B.

Electrical potential difference (Voltage)

Moving a charge in an electric field involves work (energy) and hence a change in electrical potential energy. A potential difference of 1 volt exists between two points if a charge of 1 coulomb moving between those points has its electrical potential energy changed by 1 joule.

The voltage, correctly termed EMF (electromotive force) of an electrical source such as a battery, is a measure of the energy supplied to each coulomb of charge passing through it. Hence a source such as a battery supplies electrical potential energy.

$$V = \frac{W}{q}$$

V = electrical potential difference voltage (volts, V)
W = work done or energy acquired (joules, J)
q = charge being moved (coulombs, C)

Electric field strength

Electric field strength or electric field intensity is defined as the force exerted on a unit charge.

$$E = \frac{F}{q}$$

E = electrical field strength (N C^{-1})
F = force (N)
q = charge being moved (coulombs C)

Worked Example 2.2

Electrons in an old style TV tube are accelerated through a potential difference of 2.00 kV. Given that the mass of electrons is 9.11×10^{-31} kg and that their charge is 1.60×10^{-19} C determine

(a) The work done on the electrons.
(b) The kinetic energy of the electrons.
(c) The final velocity of the electrons, assuming they were initially at rest.

$V = 2.00 \times 10^3$ V
$q = 1.60 \times 10^{-19}$ C
$m = 9.11 \times 10^{-31}$ kg
$W = ?$
$E_K = ?$
$u = 0$
$v = ?$

(a) $W = qV$

$= (1.6 \times 10^{-19})(2000)$

$= 3.20 \times 10^{-16}$ J

(b) E_K = work done on electrons

$= 3.20 \times 10^{-16}$ J

(c) $E_K = \frac{1}{2}mv^2$

$= 3.20 \times 10^{-16}$ J

$\therefore v^2 = \dfrac{(2)(3.2 \times 10^{-16})}{9.11 \times 10^{-31}}$

$v = 2.65 \times 10^7 \text{m s}^{-1}$

Electric current

Any material which contains electric charges that are free to move is called a **conductor.** If such a material is connected between points of different electrical potential, then a flow of charge will occur. The rate of flow of electric charges, whether positive (+) or negative (–) is called an electric current. In a conducting solution both positive and negative ions are charge carriers while in a metallic conductor only electrons are charge carriers.

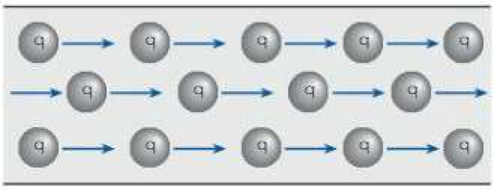


Figure 2.7 Current flow in a conductor. Current is defined as the net amount of charge passing a given point per second. See also Figure 2.5.

Conventional current is defined as being in the direction of positive charge flow. It may be considered as a current opposite in direction to a flow of electrons. When we refer to the direction of current in a circuit we are referring to conventional current.

Direct current (DC) refers to a current supply where the flow of charge is always in one direction (e.g. current from a battery).

Alternating current (AC) refers to a current supply where the flow of charge alternates back and forth (e.g. household supply).

An **electric current** (I) is defined as the net amount of charge passing a given point per second. In an electric circuit current is measured with an ammeter placed in series at that point in the circuit. The unit of current is the ampere (A).

$$I = \frac{q}{t}$$

I = current in amperes (A)

q = charge in coulombs (C)

t = time in seconds (s)

Worked Example 2.3

A point charge of 4.55 μC experiences a force of 1.62×10^{-3} N when placed in an electrical field. Determine the electrical field strength at that point.

$$E = \frac{F}{q} = \frac{1.62 \times 10^{-3}}{4.55 \times 10^{-6}} = 3.56 \times 10^{2}\ \mathrm{N\ C^{-1}}$$

The direction of the electric field would be in the direction of the force.

Electric field strength between parallel plates

The electric field between two parallel plates is uniform as shown previously in Fig 2.4. As a charged particle moves through such a field the force from one plate increases while that from the other plate decreases so that the total force remains constant.

If a free charge is placed in the electric field between two plates work will be done on the charge. The work done in moving the charge can be calculated as shown below.

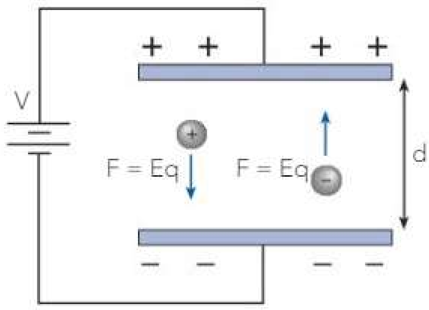


Figure 2.8 The movement of free charged particles between parallel plates. Positive charges experience a force towards the negative plate while for negative charges the force is in the opposite direction. The force on each charge (Eq) remains constant throughout. The work done on each charge is given by $W = F.s = V.q$

Consider a charged particle being accelerated between two parallel plates a distance d apart as shown in Fig 2.8 above. The voltage between the plates is V.

$$\begin{aligned} \text{Work done} &= \text{Force} \times \text{distance} \\ W &= Fs \\ &= Eqd \end{aligned}$$

As we saw earlier, potential difference, or voltage, can be defined as work per unit charge.

i.e. $V = \dfrac{W}{q}$ or $W = Vq$

hence $Vq = Eqd$

and $E = \dfrac{V}{d}$ which is an alternate formula for calculating electric field strength.

$$E = \frac{V}{d}$$

E = electrical field strength ($\mathrm{V\ m^{-1}}$)

V = voltage between plates (V)

d = distance between plates (m)

Note that the units $\mathrm{N\ C^{-1}}$ and $\mathrm{V\ m^{-1}}$ are equivalent

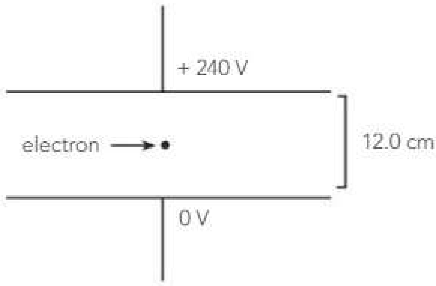
Worked Example 2.4

Two charged parallel plates are 12.0 cm apart with a potential difference of 240 V between them.
(a) Calculate the electric field strength between them.
(b) What force would be exerted on an electron located midway between the plates?
(c) What force would be exerted on a proton located at the same point?

(a) $E = \dfrac{V}{d} = \dfrac{240}{0.120} = 2.00 \times 10^{3}\ \text{Vm}^{-1}$

(b) $F = Eq = (2.00 \times 10^{3})\ (1.60 \times 10^{-19})$
$= 3.20 \times 10^{-16}\ \text{N}$

(c) The force on the proton would be the same magnitude as for the electron, 3.20×10^{-16} N, but in the opposite direction.



Worked Example 2.5

Two charged parallel plates are 5.00 mm apart and have an electric field intensity of $4.30 \times 10^{4}\ \text{Vm}^{-1}$ between them.
(a) Determine the potential difference across the plates.
(b) If an electron moves from the negative plate to the positive plate determine the gain in its kinetic energy.
(c) If the electron was originally at rest determine its final velocity.

(a) $E = \dfrac{V}{d}$ Hence $V = Ed = (4.30 \times 10^{4})\ (5.00 \times 10^{-3})$

$= 2.15 \times 10^{2}\ \text{V}$

(b) $W = qV = (1.60 \times 10^{-19})\ (2.15 \times 10^{2})$
$= 3.44 \times 10^{-17}\ \text{J}$

(c) $W = E_K = \frac{1}{2} mv^2$

$v^2 = 2\dfrac{E_K}{m} = (2)\ (3.44 \times 10^{-17})/9.11 \times 10^{-31}$

$v = 8.69 \times 10^{6}\ \text{m s}^{-1}$

Question 2.5

A proton in an electric field experiences a force of 2.65×10^{-20} N to the East. Determine the electric field strength at this point.

Question 2.6

Two parallel plates 20.0 mm apart are connected to a 9.00 V battery.

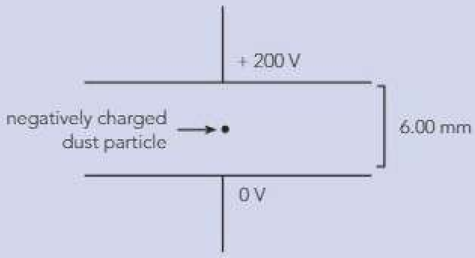
(a) Determine the electric field intensity between the plates.

(b) Determine the force that would be exerted on an electron 15.0 mm from the positive plate.

(c) What would be the change, if any, to the force acting on the electron if it:
(i) was located midway between the plates?
(ii) was located midway between the plates but the plates were moved closer together so that the distance between them was only 10.0 mm?

Question 2.7

A dust particle of mass 3.45×10^{-6} kg carrying a charge of -8.00×10^{-18} C is located midway between two parallel plates as shown. The dust particle is at rest when a voltage of 200 V is applied across the plates.



(a) Determine the electric field strength between the plates.

(b) What will be the force acting on the dust particle at the position shown?

(c) If the dust particle moves 2.00 mm closer to the positive plate due to this force what will be its velocity?

2.3 MAGNETIC FIELDS

Properties of magnets

- Magnets all attract objects made of iron. Small pins or iron filings are easily attracted and tend to cluster around the two poles of the magnet.
- All magnets, regardless of shape, have two ends (or faces) called poles, where the magnetic effect is strongest.
- Magnets which are suspended so that they are free to rotate, align themselves with the Earth's magnetic field. The end of the magnet which points towards the north magnetic pole (near the Earth's geographic north pole) is called the north seeking pole or simply north pole.
- Magnets interact with each other. The forces which exist between two magnets near each other are such that *"Like poles repel, unlike poles attract."*

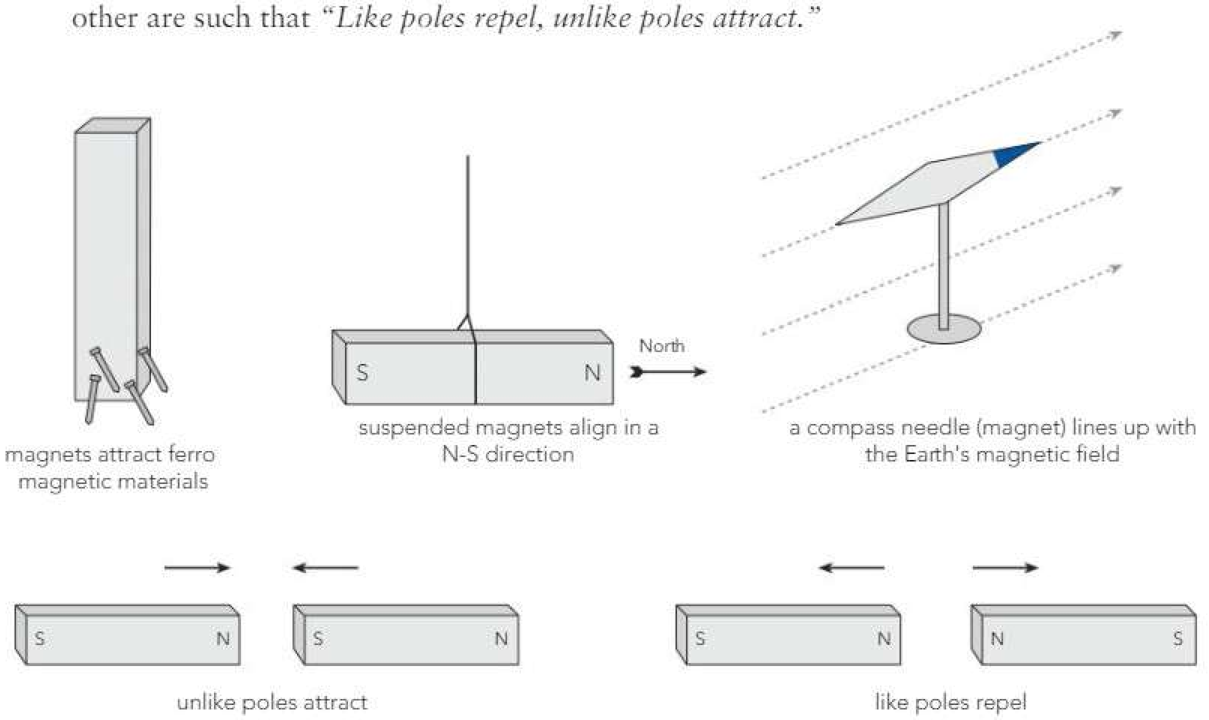
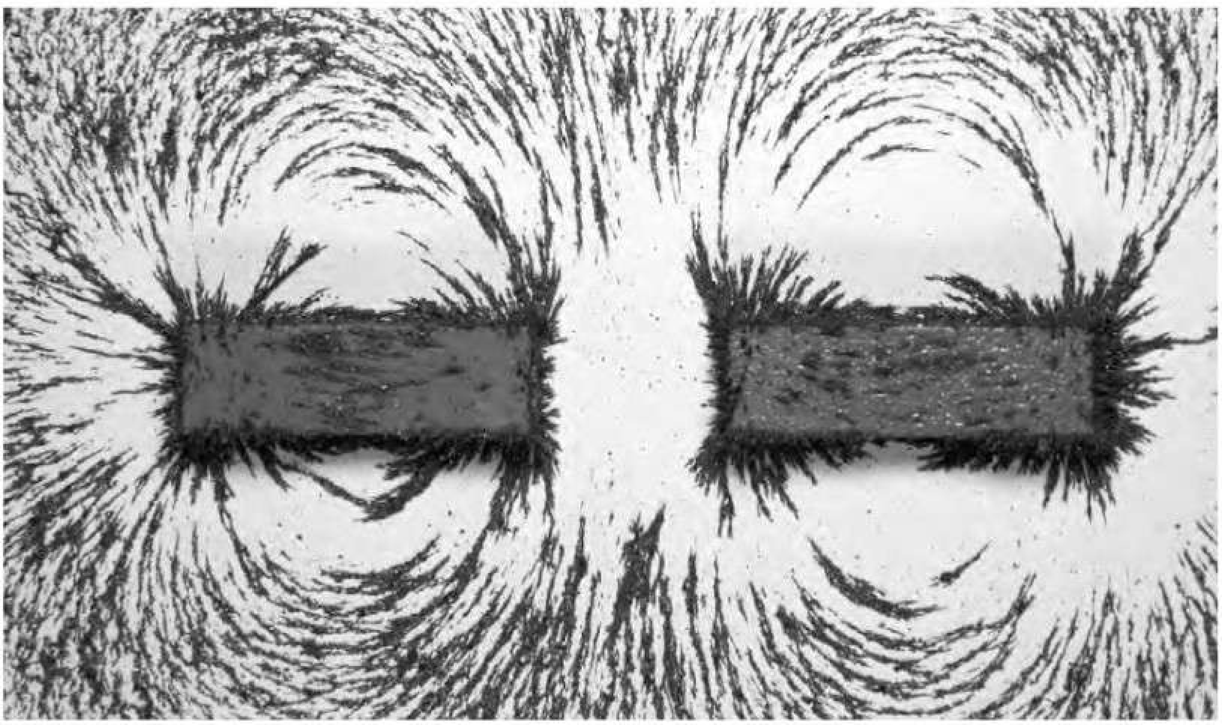


Figure 2.9 *Properties of magnets. Unlike poles attract, like poles repel. Magnets align themselves in the direction of a magnetic field.*



Magnetic domains

If a magnet is broken into smaller pieces it is found that each piece, no matter how small, will act as an individual magnet. North and south poles are always present. This observation supports the idea that magnetic materials are made up of areas or domains of tiny particles which themselves act as tiny magnets. When these domains are aligned then it is said that the material is magnetised.

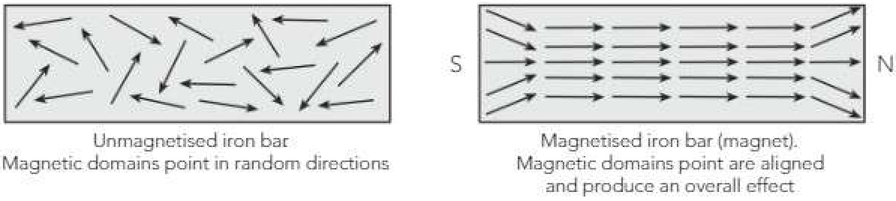


***Figure 2.10** Magnetic domains (dipoles) in a magnet. In a magnet the magnetic domains are more aligned.*

Magnetic fields of magnets

If a compass needle is brought near a magnet it is deflected by the magnetic field surrounding it. A magnetic field is a region in which magnetic forces are observable. Its direction and magnitude can be represented by lines of magnetic flux.

- The direction of the flux lines at any point is the direction that the north of a compass would point. (Note direction of plotting compasses below.)
- The density of the field lines indicates the magnitude of the magnetic field.
- Flux lines never cross each other.

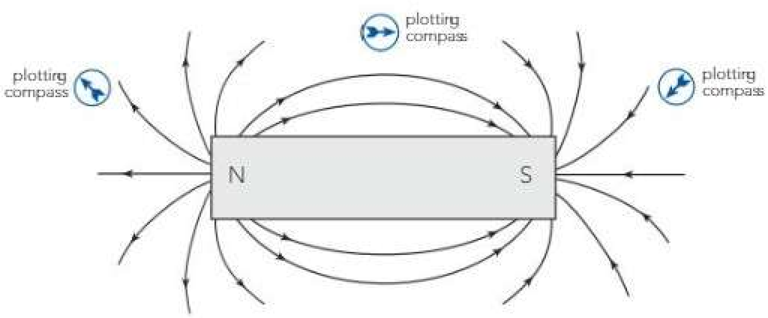


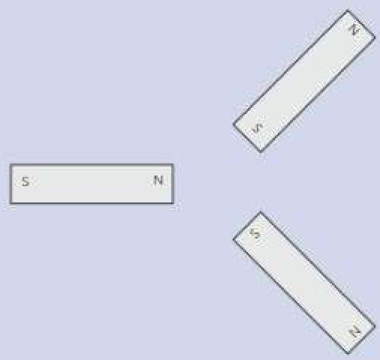
***Figure 2.11** Magnetic field around a magnet. A plotting compass will align itself with the direction of the field. Note that the plotting compass points to the S pole of a magnet.*

Question 2.8

Sketch the magnetic fields in each of the following cases.

(a)

(b)



Earth's magnetic field

The Earth is surrounded by a magnetic field known as the magnetosphere. It is believed that electric currents within the core of the Earth cause these magnetic fields much as if a giant magnet existed there.

Points to note

- The magnetic north and south poles are situated near but not at the same point as the geographic poles. The angle of declination is that between the axis of the magnetic poles and geographic poles.
- The Earth's field is as if the North of a magnet existed at the South magnetic pole.
- At most points of the Earth's surface its magnetic field is not parallel to the ground. The angle between the Earth's field and the Earth's surface is known as the angle of dip. In Perth it is approximately 66°.

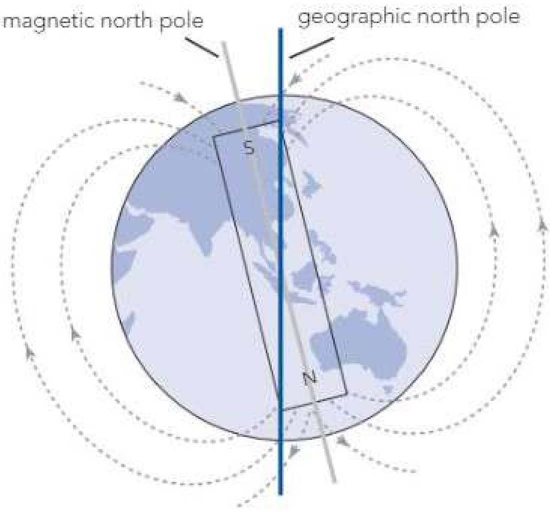


Figure 2.12 The Earth's magnetic field

Question 2.9

A compass needle is mounted so that it can move freely in a vertical plane. What angle (approximately) would you expect the needle to make with the horizontal at the following points on Earth?

(a) Equator ____________ (b) Magnetic North Pole ____________

(c) Perth ____________ (d) Geographic North Pole ____________

Question 2.10

A student checking the Earth's magnetic field with a compass needle noticed that the needle dipped slightly at one end rather than being horizontal.

(a) Explain why this may be occurring.

____

____

____

(b) If the student is located in Perth which end of the compass is dipping down?

____

(c) Whereabouts on Earth would this effect not be noticeable? Why?

____

____

Magnetic fields due to electric currents

- **Current in a single straight wire**

Wires carrying electric currents are surrounded by magnetic fields. The pattern of these fields is concentric around the wire and can be determined using small plotting compasses.

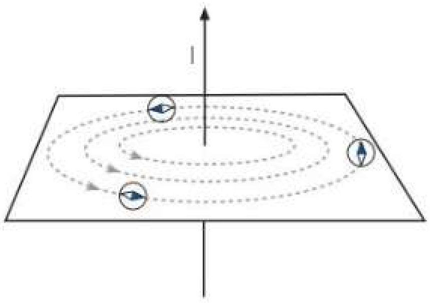
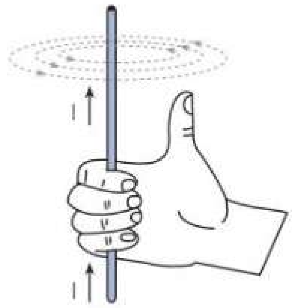


Figure 2.13 *Magnetic field surrounding a current carrying conductor. The field strength depends on the size of the current and the distance from the conductor.*



The Right Hand Grip Rule: *Finding the direction of the magnetic field around a current carrying conductor. The thumb points in the direction of the conventional current (i.e. positive to negative), while the curled fingers indicate the direction of the flux lines.*

- **Current in wire loops**

If a current carrying conductor is wound in the shape of a loop, the pattern of the magnetic field created resembles that of a magnet (see figure below). The strength of such a field can be greatly increased by using a long coil wound into many closely spaced loops. These many coils are in effect an electromagnet (solenoid).

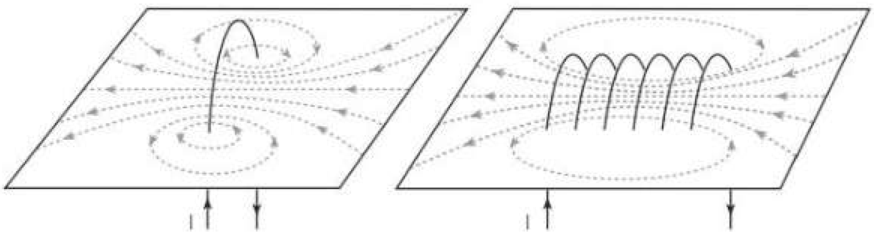


Figure 2.14 *Magnetic fields created by currents moving in wire loops*

- **The magnetic field strength produced by a current**

The magnetic field strength (B) at any given point near a current carrying straight wire will depend on the magnitude of the current and its distance from the wire as follows.

- $B \propto I$ — B is directly proportional to the magnitude of the current
- $B \propto 1/r$ — B is inversely proportional to the distance from the wire

$$B = \frac{\mu_0}{2\pi}\frac{I}{r}$$

B = magnetic field strength or flux density (Wb m^{-1} or T)

I = current (Amps, A)

r = distance from conductor wire (m)

μ_0 = magnetic constant (permeability of free space)

$= 4\pi \times 10^{-7}$ N A^{-2} $= 1.26 \times 10^{-7}$ N A^{-2}

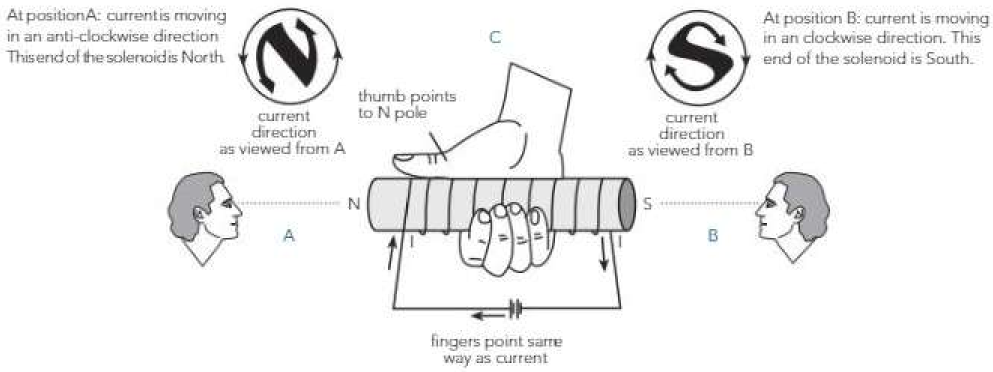
Worked Example 2.6

What will be the magnitude and direction of the magnetic field created by a current of 3.50 A flowing vertically upwards at a distance of 20.0 cm from the conductor? *Hint: Use the right hand grip rule to determine direction.*

$$B = \frac{\mu_0}{2\pi}\,\frac{I}{r} = 4\pi \times 10^{-7} \times 3.50 / 2\pi \times 0.020 = 3.5 \times 10^{-5}\ \text{Wb m}^{-2}\ \text{North}$$

Determining the polarity of a solenoid

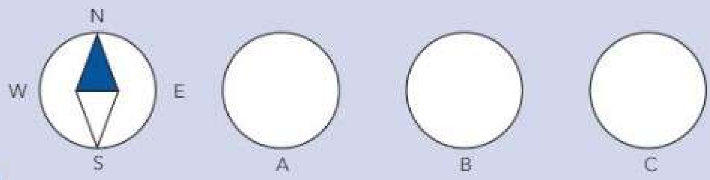
Method 1 – Viewing direction of current from one end
Imagine that you are at positions A or B and determine the direction (C.W. or A.C.W.) of the current in the coil as it would appear to you.



Method 2 – Use the right hand curl rule
Curl your right hand around the solenoid, as shown above, so that your fingers are in the same direction as the current around the coil. Your thumb will point North.

Question 2.11

Indicate the approximate direction that a compass needle (shown) would point if it were placed at each of the points A,B,C in the solenoid shown on the bottom of previous page.



Question 2.12

(a) The strength of an electromagnet may be increased in various ways. Describe three methods.

(i) ______________________________

(ii) ______________________________

(iii) ______________________________

(b) Compare the magnetic field of a solenoid to that of a permanent magnet in terms of:

(i) similarities ______________________________

(ii) differences ______________________________

Question 2.13

A horizontal wire is carrying a current of 10.0 A in a northerly direction.

(a) Determine the magnetic field strength for a point P, located 1.50 m directly above the wire.

____

____

____

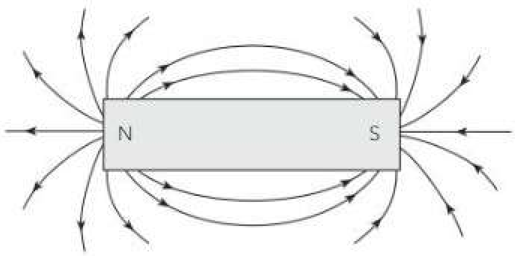
(b) In which direction would a compass point if placed at point P?

____

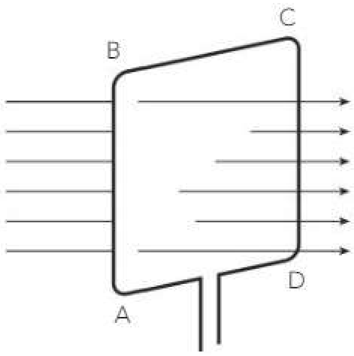
Magnetic field strength

Magnetic field strength (sometimes called magnetic flux density) is a vector quantity and is represented by the symbol B. It is measured in tesla (T). The direction of a magnetic field is indicated by the direction of the magnetic flux lines and its magnitude by the number of these lines per unit area.

$\phi = B\ A$	ϕ = magnetic flux (Wb) B = magnetic flux density (Wb m^{-2} or T) A = area (m^2)



(a) Magnetic flux density is much greater through near the poles of a magnet.



(b) Uniform magnetic field passing a coil (see worked example next page).

Figure 2.15 The vector nature of magnetic fields

Worked Example 2.7

The magnetic field illustrated in Fig 2.15 (b) has a magnitude of 4.20×10^{-4} T and its direction is horizontal and to the East. The coil illustrated is 30.0 cm wide and 45.0 cm high. Calculate the total flux passing through the coil if:

(a) the plane of the coil is at right angles to the field;
(b) the plane of the coil is parallel to the field;
(c) the plane of the coil is at 45° to the field.

$$A = L \times B = (0.450)(0.300)$$
$$= 0.135 \text{ m}^2$$
$$= ?$$
$$B = 4.20 \times 10^{-4} \text{ T}$$

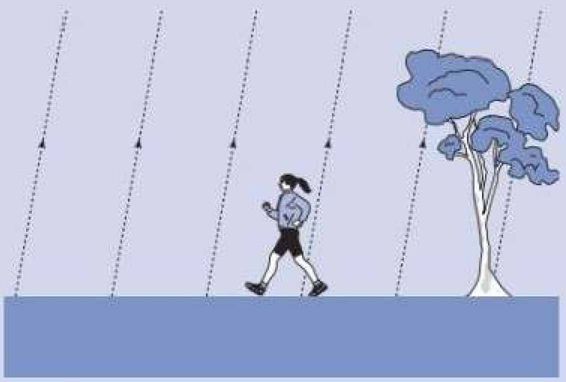
(a) $\phi = BA$
$= (4.20 \times 10^{-4})(0.135)$
$= 5.67 \times 10^{-5}$ Wb

(b) Since field is parallel to plane of coil no flux lines would be enclosed within it (ie. $\phi = 0$).

(c) Using vectors
$\phi = BA \sin 45°$
$= 5.67 \times 10^{-5} \sin 45°$ Wb
$= 4.01 \times 10^{-5}$ Wb

Question 2.14

At a particular point in W.A. the magnetic flux density was found to be 6.20×10^{-6} T at an angle of 70° to the horizontal. A student would like to construct a coil whose area could encompass one weber of flux.



(a) Calculate the **minimum** area of such a coil

___

___

(b) Explain clearly the orientation required for such a coil to achieve this.

___

___

(c) Is this experiment likely to cause any particular difficulties?

___

___

2.4 MAGNETIC FORCES

Force on a conductor in a magnetic field

Where a conductor carrying an electric current is placed in a magnetic field a force will result. This force is due to the interaction of the magnetic field created by the current in the wire with the magnetic field it is placed in. The force of this interaction is given by:

$$F = I\,l\,B$$

F = force (N)
I = current (A)
l = length of conductor (m)
B = magnetic flux density (T)

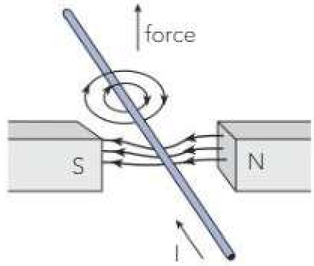
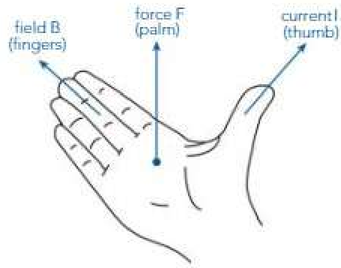


Figure 2.16 Force on a current carrying conductor.

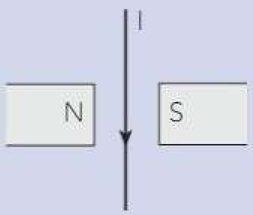
The right hand palm rule:
We can find the direction of the force exerted on a conductor in a magnetic field using the method illustrated above. The field (B), force (F) and current (I) are all at right angles to one another.



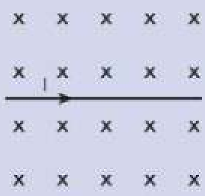
Question 2.15

State or indicate the direction of the force acting on the current carrying conductor in each of the following by applying the right hand palm rule. Where magnetic field lines are not shown it may be helpful to draw them in first.

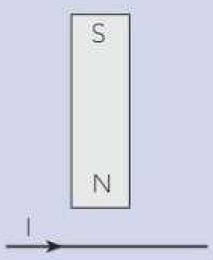
(a)



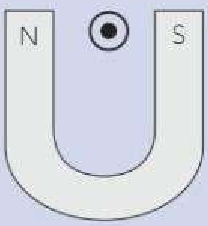
(b)



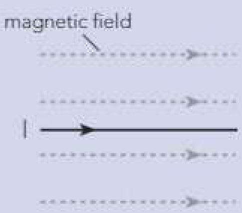
(c)



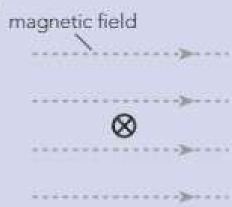
(d)



(e)



(f)



Force on a moving charged particle in a magnetic field

A moving charge creates a magnetic field around itself. If the charge passes through an area which already has a magnetic field then there will be an interaction – that is a force will be exerted on the particle. The force will be at right angles to the motion of the particle (consistent with the right hand palm rule) and causes the particle to move in a circular path.

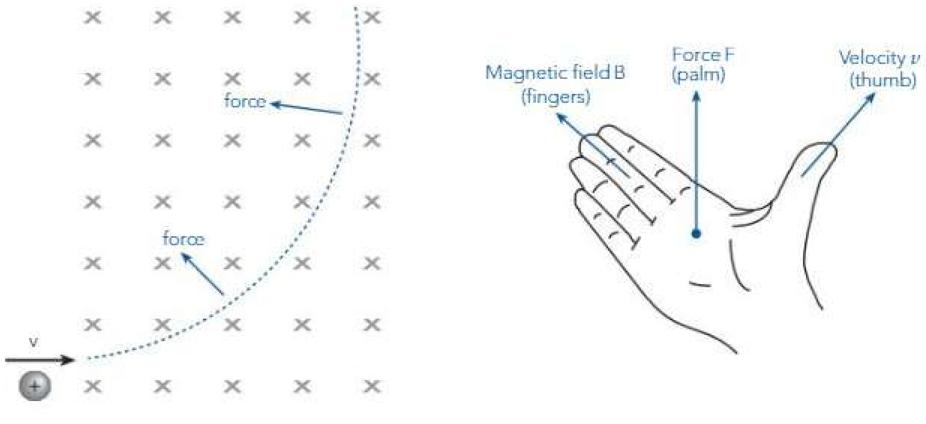


Figure 2.17 *Force on a moving charge in a magnetic field. The force is always at right angles to the motion of the particle.*

The right hand palm rule gives the direction of the force which is always at right angles to the movement. This causes circular motion.

The force on the charged particle is given by:

$$F = q\,v\,B$$

F =	Force on charged particle (N)
q =	charge on particle (C)
v =	velocity of particle ($m\ s^{-1}$)
B =	magnetic field strength (T)

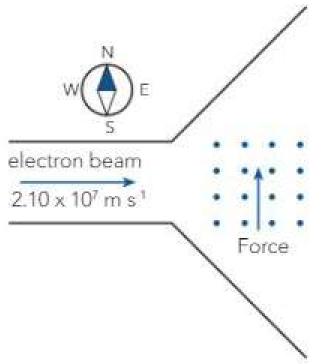
Worked Example 2.8

An electron beam in an old style T.V. tube is moving horizontally eastwards towards the screen at $2.10 \times 10^7\ m\ s^{-1}$ as it passes through a deflecting magnetic field. The magnetic field is 8.25×10^{-3} T vertically upwards.

(a) In which direction is the electron deflected?

(b) Calculate the force exerted on the electron and the consequent acceleration (given $q_e = 1.60 \times 10^{-19}$ C, $m_e = 9.11 \times 10^{-31}$ kg).

(c) What effect will this have on the path of the electron?



(a) Using the right hand palm rule (but remembering that electrons are negative) we can see that the beam of electrons in the T.V. tube will be deflected towards the north.

(b)

$q = 1.6 \times 10^{-19}$ C

$m_e = 9.11 \times 10^{-31}$ kg

$B = 8.25 \times 10^{-3}$ T

$F = ?$

$$F = q\,v\,B = (1.6 \times 10^{-19})(2.10 \times 10^{7})(8.25 \times 10^{-3}) = 2.77 \times 10^{-14}\ \text{N (direction as shown)}$$

$$a = \frac{F}{m} = \frac{2.77 \times 10^{-14}}{9.11 \times 10^{-31}} = 3.04 \times 10^{16}\ m\ s^{-2}$$

(c) Electron will move in a circular path, anticlockwise.

Worked Example 2.9

A proton initially at rest is accelerated horizontally due East through a potential difference of 45.0 kV. It then enters a vertical (upwards) magnetic field of 0.250 T. Determine:

(a) The velocity achieved by the proton.
(b) The force exerted on the proton by the magnetic field.
(c) The radius of curvature of the protons path in the magnetic field and its direction of motion.

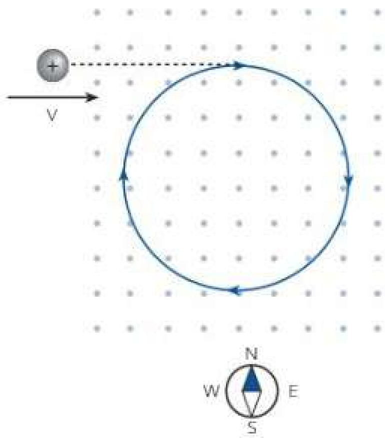
(a) The proton will gain kinetic energy from the electrical work done on it.

ie. $$E_K = \frac{1}{2}mv^2 = Vq$$

$$\therefore v^2 = \frac{2Vq}{m}$$

$$= \frac{(2)(4.50 \times 10^4)(1.60 \times 10^{-19})}{1.67 \times 10^{-27}}$$

$$\therefore v = 2.94 \times 10^6 \text{ m s}^{-1}$$



(b) $$F = qvB$$
$$= (1.6 \times 10^{-19})(2.94 \times 10^6)(0.25)$$
$$= 1.17 \times 10^{-13} \text{ N}$$

(c) $$F_C = \frac{mv^2}{r} = 1.17 \times 10^{-13}$$

$$\therefore r = \frac{mv^2}{1.17 \times 10^{-13}} = \frac{(1.67 \times 10^{-27})(2.94 \times 10^6)^2}{1.17 \times 10^{-13}}$$

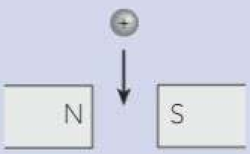
$$= 0.123 \text{ m}$$

Hence the proton would follow a circular path of 12.3 cm radius in a clockwise direction if viewed from above.

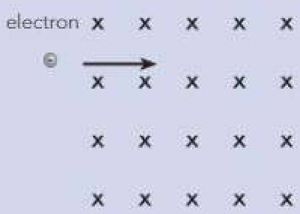
Question 2.16

State or indicate the direction of the force acting on the charged particle in each case.

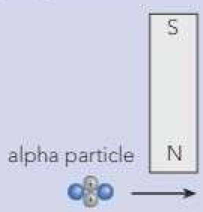
(a)



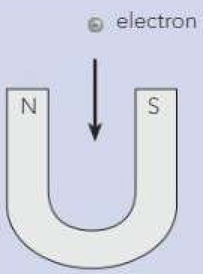
(b)



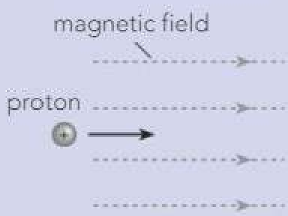
(c)



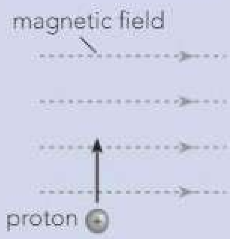
(d)



(e)

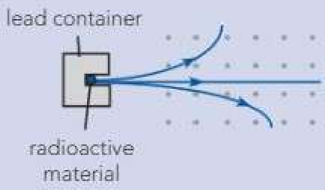


(f)



Question 2.17

(a) The radiation from a radioactive material is allowed to pass through a magnetic field and it is found to break up into three distinct paths. Assuming these to be alpha (α), beta (β), and gamma (γ) radiation, correctly label the diagram shown.



(b) Assuming that the alpha and beta particles (electrons) are emitted from the radioactive source at 10 m s^{-1} and 1.0×10^8 m s^{-1} respectively:

(i) which particle will have the greatest force exerted on it? By what factor?

____

____

____

(ii) which particle will be deflected the most? Note: The mass of an alpha particle is approximately 7300 times that of a beta particle.

____

____

____

Question 2.18

An electron and a proton enter a magnetic field from the same direction and with the same velocity. Compare their consequent paths in the magnetic field in terms of:

(a) direction;
(b) radius of curvature.

____

____

____

The cathode ray oscilloscope (CRO)

The cathode ray oscilloscope (or CRO for short) can be described as a simple type of television set which can measure and display electrical information. It essentially displays voltage in a graphical form. It can be used to:

- trace signals and measure voltages when checking electronic equipment
- analyse electrical inputs from any number of sources (e.g. sounds, pressure, temperature)
- trace faults in motor car engines and electronic systems
- monitor patients' vital signs such as heart beat.

A CRO consists of a large evacuated tube as shown below. Its important parts are:

- a heater and electron gun
- focusing and accelerating anodes
- deflection plates (horizontal and vertical)
- a fluorescent screen.

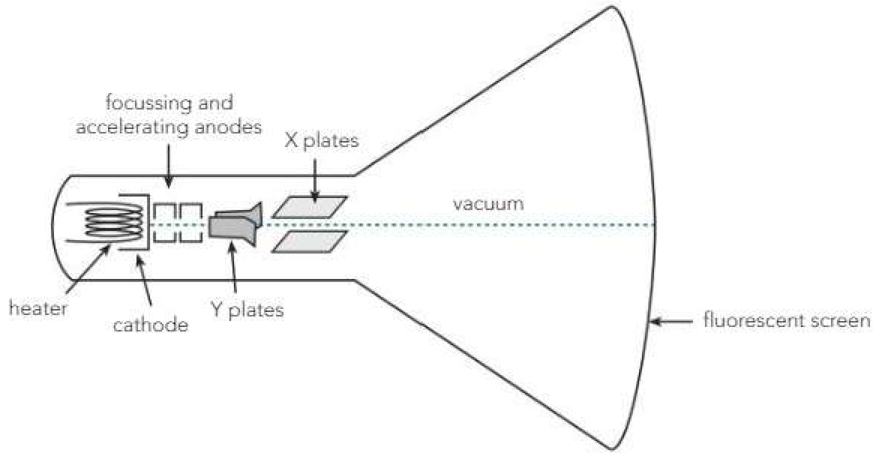


Figure 2.18 Simplified diagram of a CRO. Electrons are emitted from the heater filament and accelerated by the positively charged anodes towards the fluorescent screen. Electrical voltages (signals) applied to the deflection plates result in a measurable graphic display (trace) on the screen.

Worked Example 2.10

An electron beam in a cathode ray oscilloscope is accelerated through 2.00 kV. Determine:

(a) the velocity that the electrons achieve;
(b) the time taken for them to reach the screen which is 25.0 cm from the anode;
(c) the energy each electron gives upon hitting the screen.

(a)

$V = 2.00 \times 10^3$ V

$q = 1.60 \times 10^{-19}$ C

$W = ?$

$v = ?$

$m_e = 9.11 \times 10^{-31}$ kg

$$W = Vq = \frac{1}{2}mv^2$$

$$\therefore v^2 = \frac{2Vq}{m} = \frac{(2)(2000)(1.60 \times 10^{-19})}{9.11 \times 10^{-31}}$$

$$v = 2.65 \times 10^7 \text{ m s}^{-1}$$

(b)

$v = 2.65 \times 10^7$ m s^{-1}

$s = 0.250$ m

$t = ?$

$$v = \frac{s}{t}$$

$$\therefore t = \frac{0.250}{2.65 \times 10^7} = 9.43 \times 10^{-9} \text{ s}$$

(c) On colliding with the screen the electrons would give up all their kinetic energy in the form of light and heat.

$$E_K = \frac{1}{2}mv^2 = \frac{1}{2}(9.11 \times 10^{-31})(2.65 \times 10^7)^2 = 3.20 \times 10^{-16} \text{ J}$$

This of course is the same energy as given to it by the electrical field between the cathode and anode (i.e. W = Vq).

Worked Example 2.11

An electron beam in a CRO tube has a velocity of 8.44×10^6 m s^{-1} as it passes between two deflecting plates where the electric field intensity is 6.50×10^3 Vm^{-1}. The electron beam is at right angles to the electric field and is in its influence for 1.88×10^{-9} s. Determine:

(a) the force exerted on each electron and consequent acceleration
(b) the lateral (sideways) velocity gained by the electrons
(c) the angle of deviation of the electron beam.

(a) $F = Eq = (6.50 \times 10^3)(1.60 \times 10^{-19}) = 1.04 \times 10^{-15}$ N

$a = \dfrac{F}{m} = \dfrac{1.04 \times 10^{-15}}{9.11 \times 10^{-31}} = 1.14 \times 10^{15}$ m s^{-2}

(b) $v^2 = u + at$

$= 0 + (1.14 \times 10^{15})(1.88 \times 10^{-9}) = 2.15 \times 10^6$ ms^{-1}

(c) Using vectors

$\tan \theta = \dfrac{2.15 \times 10^6}{8.44 \times 10^6}$

$\theta = 14.3°$

2.5 THE DC ELECTRIC MOTOR

A simple electric motor consists of a coil of wire carrying a current in a magnetic field as shown below. Current passes through brushes and split rings (commutator) into the coil (armature). A turning effect (torque) is created by equal and opposite forces acting on two sides of the coil. For dc current a split ring commutator is necessary in order to reverse the current flow each 180°.

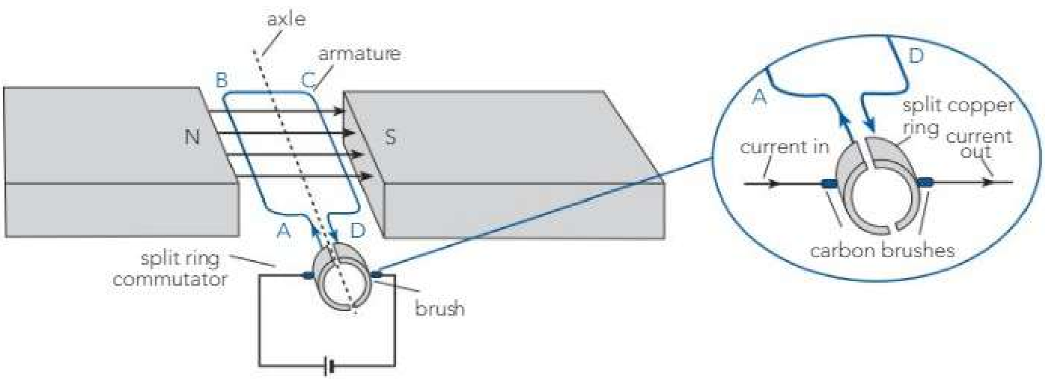


Figure 2.19
(a) A simple DC electric motor. The flow of current in the coil creates forces; downward in AB and upward in CD. These two forces combine to create a turning effect (torque) on the coil.
(b) The commutator consists of carbon brushes which tranfer current to the split ring. The split ring allows for the reversal of current direction in the coil every 180° so that the coil continues to turn in one direction.

Torque on a DC motor coil

The flow of current in a coil creates forces on the parts of the coil which are at right angles to the magnetic field. In the DC motor shown above, a downward force acts on side AB, and an equal but upward force acts on side CD. These equal and opposite forces create a turning effect. No forces act on sides BC and AD as the current in this part of the coil is travelling parallel to the magnetic field.

The torque (τ) created by the forces acting on each side of the coil depend on their perpendicular distance from the axis of rotation. This is a maximum when the plane of the coil is parallel to the magnetic field. The forces themselves depend on the current (I), the length of conductor at right angles to the field (l) and the strength of the magnetic field (B). We can determine torque as follows:

$\tau = r_{\perp}F$ (one side)	τ	=	torque (Nm)
$\tau = r\,(IlB)$ (one side)	r	=	distance, perpendicular, of the force from the axis of rotation (m)
Total torque given by	F	=	force acting on one side of the coil (N)
$\tau_{total} = 2\,r\,IlB$	I	=	current through the coil (A)
	l	=	length of side of coil perpendicular to the magnetic field
	B	=	magnetic field strength (T)

Worked Example 2.12

In the DC motor shown above, Figure 2.19, a current of 2.50 A is flowing in the direction ABCD for the instant shown. The coil dimensions are AB = CD = 45.0 cm, AD = BC = 25.0 cm. The magnetic flux density is 8.20×10^{-2} T. For simplicity we assume that the magnetic flux density is the same for all positions of the coil.

(a) Determine the magnitude and direction of the force acting on side AB of the coil.
(b) Determine the torque created by this force.
(c) What is the total torque acting on this single coil?

(a)

I = 2.50 A
l = 0.450 m
B = 8.20×10^{-2} T

$F = IlB$
$= (2.50)(0.450)(8.20 \times 10^{-2})$
$= 9.23 \times 10^{-2}$ N downwards.
(Right hand palm rule)

(b)

F = 9.23×10^{-2} N
R = 0.125 m

$\tau = r_{\perp}F$
$= (0.125\text{ m})(9.23 \times 10^{-2}) = 1.15 \times 10^{-2}$ N m

(c)

$\tau_{total} = 2\,(r_{\perp}F)$
$= 2.31 \times 10^{-2}$ N m

Question 2.19

Consider the DC motor shown in Figure 2.19 and the data given in the Worked Example above to answer the following.

(a) The coil is supported by an axle as shown. In which direction (CW or ACW) will the loop begin to rotate? (As viewed from the front.)

____

(b) Assume the coil has rotated 45° from the position shown in Figure 2.19. What change will occur (if any) to the following:

(i) the force on AB ____________________________

(ii) the force on CD ____________________________

(iii) the torque on the coil. ____________________________

(c) When the coil has rotated to a vertical position, explain what happens.

____

(d) Relative to the magnetic field, which way must the plane of the coil face for maximum torque to occur?

____

____

(e) If you wished to improve the strength and efficiency of this simple motor describe some changes you could make.

(i) ____________________________________

(ii) ____________________________________

(iii) ____________________________________

(iv) ____________________________________

2.6 ELECTRIC POWER GENERATION

Electromagnetic induction

We have already seen that when a current carrying coil is placed in a magnetic field a force on the coil results. This is the basis of the motor principle.

It is also true that when a coil is placed in a changing (or moving) magnetic field a current results in the coil. This means of production of an electric current is referred to as electromagnetic induction and is the basis of the generator principle.

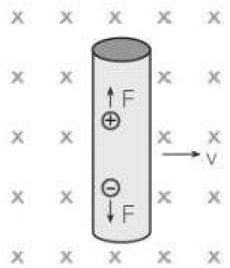


Figure 2.20 *Conductor moving through a magnetic field. Forces act on all charged particles within the metal (F = qvB). An induced emf (potential difference) results.*

Induced current and PD in a moving conductor

When a conductor moves through a magnetic field as shown in Figure 2.20 a force results on both the positive and negative charges within the metal. The direction of this force can be verified by using the right hand palm rule. Although the positive charges usually cannot move, the free negative charges move to one end of the conductor, thereby creating a potential difference (voltage) between the two ends of the conductor. If these ends are joined to an external circuit then a current would flow.

The potential difference or emf created by a conductor moving in a magnetic field can be calculated as shown below.

$\text{emf} = l\,v\,B$	emf	=	induced voltage (V)
	l	=	length of conductor in magnetic field (m)
	v	=	velocity (m s^{-1}), at right angles to B
	B	=	magnetic flux density (T)

Worked Example 2.13

A wire (AB) is falling between two magnets with a velocity of 6.25 m s^{-1} at the instant shown. The wire is 12.0 cm in length and the magnetic flux density is 0.250 T.

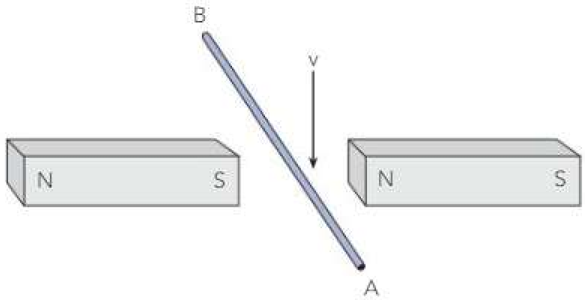
(a) Find potential difference between A and B.

(b) Which end is positive?

(a)

B	= 0.250 T	emf	= l v B
l	= 0.120 m		= (0.120)(6.25)(0.250)
v	= 6.25 m s^{-1}		= 0.188 V
emf	= ?		

(b) Using the R.H. palm rule we can see that the force on positive charges is towards B and negative towards A. (Remember – the magnetic field direction is from north to south.) Hence the negatively charged electrons, which are free to move, bunch up near end A thus leaving end B positively charged.



Question 2.20

In the worked example above, the conductor (AB) had been dropped between the magnets from a small height and allowed to fall freely.

(a) At what instant would you expect the greatest emf to be created? Why?

____

____

(b) Describe the likely movement of the **electrons** within the wire:

(i) just before the wire is dropped

____

(ii) as the wire moves between the magnets

____

(iii) as the wire moves beyond the magnets (assume free fall).

____

Induced current in a coil

If a magnet is moved either towards or away from a coil, a small emf (voltage) is created. This emf will cause a current to flow if there is a complete circuit. It is important to note however, that only when relative motion between the magnet and coil occurs will an induced current exist. More importantly it is the fact that the magnetic field linked with the coil is **changing** which causes the induced current. Faraday's and Lenz's Laws apply to this situation.

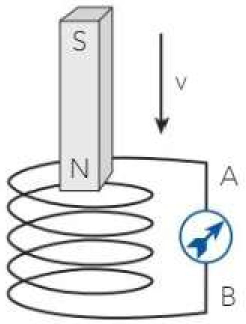


Figure 2.21 *Induced current in a coil. The relative motion between the magnetic field and the coil creates an emf. By completing the circuit a current results.*

Faradays Law of Induction

Essentially, Faraday's Law states that:

"The magnitude of the induced EMF in a coil is directly proportional to the rate of change of magnetic flux associated with that coil."

Mathematically this is expressed as shown below. The inclusion of the negative sign is from Lenz's Law and indicates that the direction of the induced emf is such as to oppose the change in flux causing it. This expression gives the *average emf* as the change in the magnetic flux is occuring over a finite interval of time.

$$\text{emf}_{\text{average}} = -N\frac{\Delta\phi}{\Delta t}$$

emf = induced voltage (V)
N = number of turns of coil
$\Delta\phi$ = change in flux (Wb)
Δt = time taken for flux change (s)

This expression can also be expanded as follows:

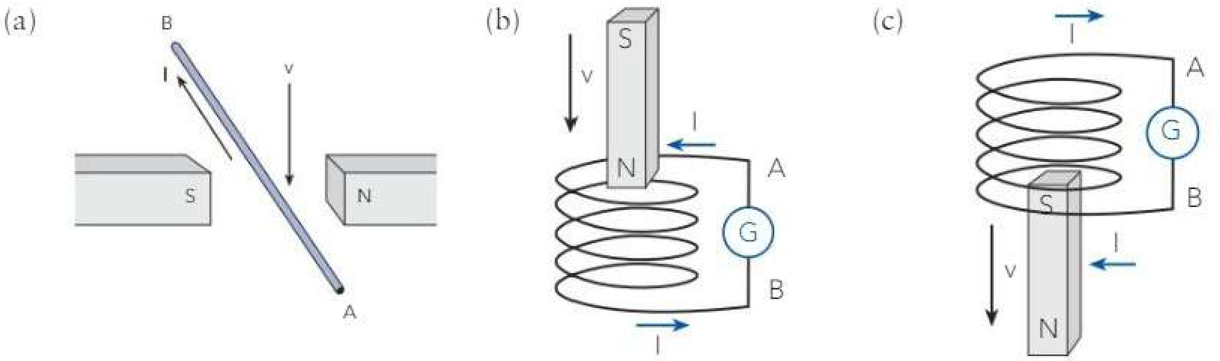
$$emf_{\text{average}} = -N\,\frac{(\Phi_2 - \Phi_1)}{t} \quad or \quad emf_{\text{average}} = -N\,\frac{\Delta(B\,A_\perp)}{t}$$

Lenz's Law

This law will allow us to predict the direction of the current produced by electromagnetic induction:

"The direction of an induced current is such as to always oppose the change that is producing it."

The law is essentially a Conservation of Energy law. It means that in order to keep a coil moving through a magnetic field a resistive force must be overcome. In effect the mechanical work done on the coil to keep it moving is converted to electrical energy in the form of the induced current.



Wire falling between magnets. Current will flow through the conductor from A → B

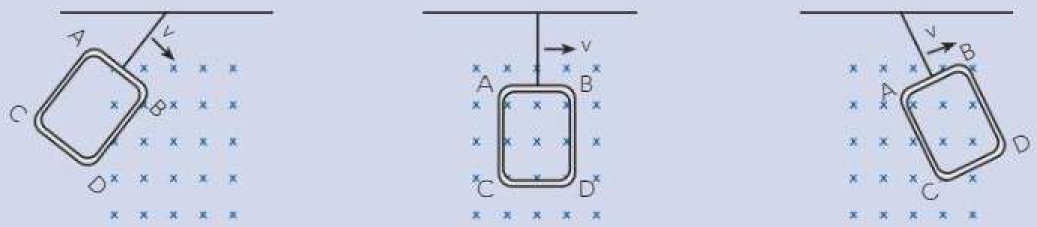
Magnet falling and entering coil. Current will flow through the coil from A → B

Magnet falling and leaving coil. Current will flow through the coil from B → A

Figure 2.22 *Using Lenz's Law to predict direction of induced current. The motion of the induced current in Figure 2.22 (a) will initially be from A to B. This induced current will create an upward force on the wire (check this with the R.H. palm rule). Similarly in Figure 2.22 (b) the initial current will be from A to B in the coil, thereby creating an opposing north pole to the falling magnet. In Figure 2.22 (c) however the current direction reverses as this will create a north pole at the bottom of the coil and hence oppose the magnet leaving.*

Question 2.21

A rectangular copper coil ABCD is attached by a string to a support so that it can swing like a pendulum through a magnetic field as shown. The coil is initially released as shown in (a) and allowed to swing through the field.



(a) (b) (c)

(a) In each of the positions shown above determine the direction of the current flowing (if any) as the copper coil moves through the magnetic field. Give the direction as clockwise or anticlockwise.

(i) At position (a) ______________________________

(ii) At position (b) ______________________________

(iii) At position (c) ______________________________

(b) It is noticed that the system comes to a stop after only two or three oscillations even though the pendulum is freely suspended.

(i) Why is this?

____

____

(ii) Where has the apparent loss of energy gone?

____

____

(c) Can you suggest a practical use of this effect?

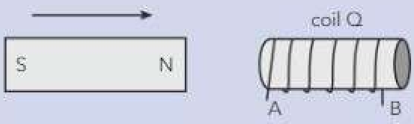
____

____

Question 2.22

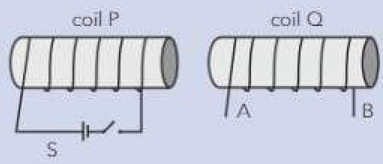
Use Lenz's Law in each case below to determine which end of coil Q (A or B) becomes positive.

(a) Magnet moves towards coil Q.



____

(b) Switch S is closed and current flows in coil P.



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Induced emf in a rotating coil

If a coil is rotated in a magnetic field an induced emf is produced since the magnetic flux enclosed within the coil is continually changing.

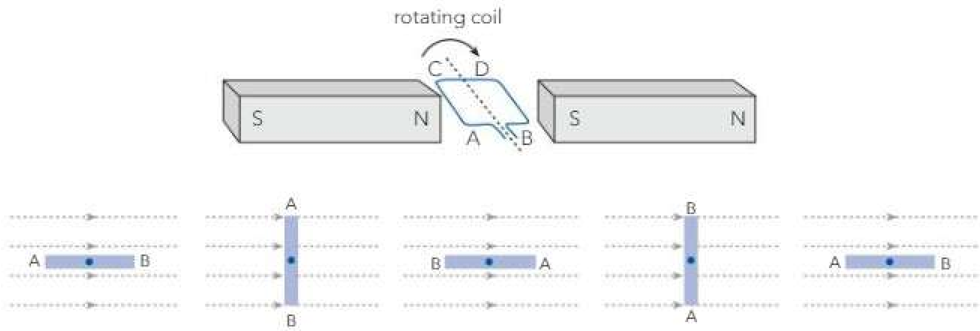


Figure 2.23 *Rotating coil in a magnetic field. The flux enclosed within the coil changes from zero as in position shown at left to a maximum each 90°. The change of flux is most rapid when the plane of the rotating coil is parallel to the magnetic field.*

As the coil is rotated from the position shown in Figure 2.23 the amount of flux (ϕ) enclosed within the coil will change from zero to maximum, back to zero, then a maximum and so on. This change in flux causes an emf to be induced, which in turn causes a current to flow.

Worked Example 2.14

A coil similar to that in Figure 2.23 is rotated 10 times every second in a magnetic field of 0.250 T. The coil is rectangular with sides 50.0 cm by 40.0 cm.

(a) Determine the average emf generated.

(b) Draw a simple emf versus time graph for a single rotation from a position as shown in Figure 2.23.

It is important in a problem like this that we determine the time taken for the coil to turn through 90° (i.e. Δt to go from maximum to minimum or the reverse).

N	=	1	B	=	0.225 T
ϕ_1	=	0	Δt	=	?
ϕ_2	=	?	emf	=	?
A	=	?			

(a)

$$\phi = BA$$

$$\phi_1 = 0 \text{ (field is parallel to plane of coil)}$$

$$\phi_2 = (0.250)(0.500)(0.400) = 0.0500 \text{ Wb}$$

Also

$$f = 10 \text{ Hz}$$

$$\therefore T = \frac{1}{f} = \frac{1}{10} = 0.10 \text{ s}$$

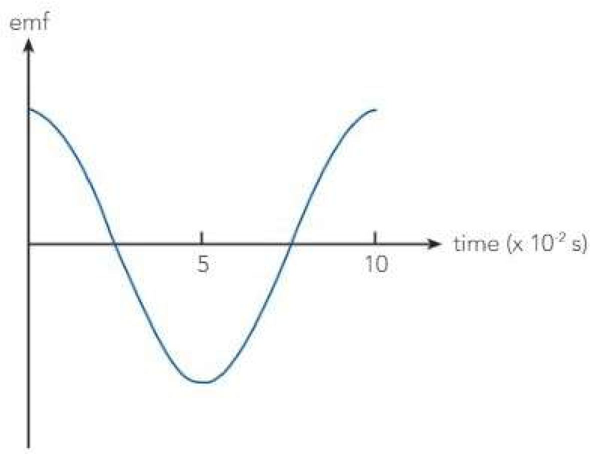
$$\therefore \frac{T}{4} = 0.025 \text{ s}$$

$$emf_{av} = -N\frac{(\phi_2 - \phi_1)}{\Delta t} = \frac{-1(0.0500 - 0.00)}{0.0250} = -2.00 \text{ V}$$

Average emf_{av} = 2.00 V

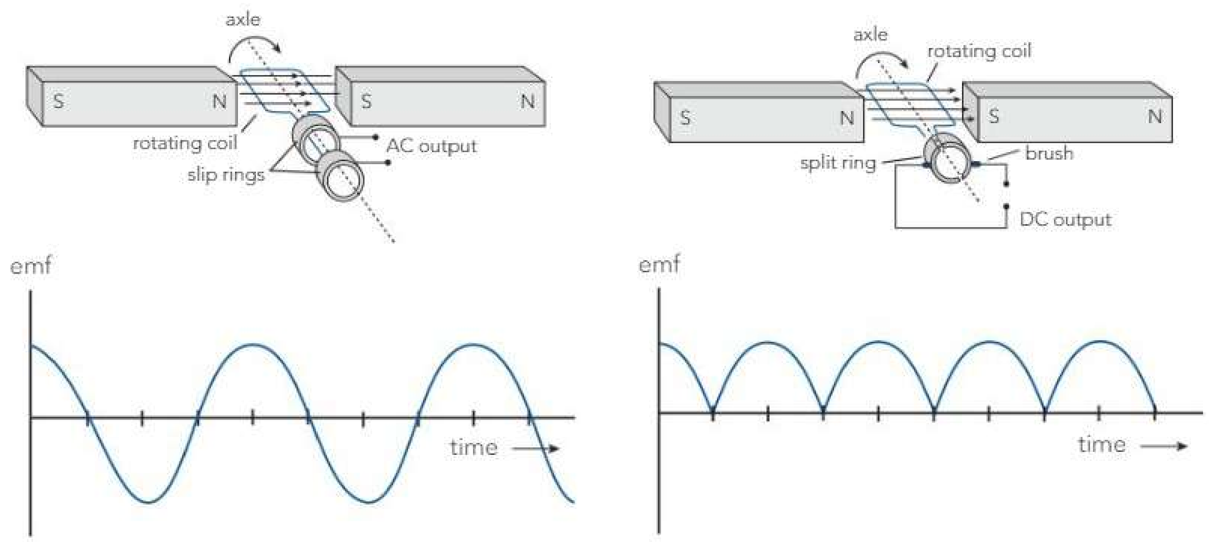
(b) The maximum emf occurs when $\phi = 0$ since the greatest rate of change of flux occurs at this time. The sides of the coil AC and BD are moving at right angles to the magnetic field at this point and hence cutting across flux lines at a maximum rate.

Maximum emf always occurs when the plane of the coil is parallel to the magnetic field.



Electric power generators

The generator is very similar in construction to the electric motor. It is designed however, to convert mechanical energy into electrical energy, the opposite to what occurs with an electrical motor. The AC generator has two slip rings for the transfer of current whereas the DC generator has a split ring instead. Commercial generators usually have field coils instead of permanent magnets and the rotating coil, which usually consists of a large number of turns, is wound onto a soft iron core called an armature.



(a) Simple AC generator. The use of two separate slip rings to transfer the current from the coil creates an alternating current output.

(b) Simple DC generator. The use of a split ring results in a current that reverses every half a cycle so that a DC output is produced.

Figure 2.24 *Simple AC and DC generators and their outputs. In commercial generators several coils are used so as to produce a smooth output and larger currents.*

Calculating AC generator emf

As we have seen above the output from an AC generator varies sinusoidally with time. The induced emf (voltage) is a maximum when the plane of the coil is parallel with the magnetic field as shown in Figure 2.24. It is at this point that flux change is greatest or we can consider that the coil is 'cutting across' the magnetic field most rapidly.

To calculate this maximum emf we can adapt the expression which gives the induced emf for a straight conductor moving in a magnetic field, that is emf = lvB. If we consider the sides of the coil cutting across the magnetic field to be of length l and moving with a velocity v at the instant shown then each side will produce an emf given by lvB. Hence, considering the emf induced in both sides of the coil and a generator with N turns we have the following.

$$emf_{max} = -2\,N\,l\,v\,B$$

emf	=	induced voltage (V)
B	=	magnetic field strength or flux density (T)
v	=	velocity (m s^{-1}) perpendicular to B
N	=	number of turns of coil
l	=	length of side of coil perpendicular to B

A more convenient expression can be derived mathematically from Faradays Law where we have emf = - N $\Delta\phi / \Delta t$. It can be shown that for that for a coil of area A, rotating with a frequency f, the maximum emf is given by the following.

$$emf_{max} = -2\pi NBA_{\perp}f$$

emf	=	induced voltage (V)
B	=	magnetic field strength or flux density (T)
A	=	area of coil (m^2)
N	=	number of turns of coil
f	=	rotation frequency of coil (Hz)

AC power supply

The nature of AC power means that both the voltage and current continually rise and fall and vary sinusoidally with time. Power generated for homes and industry has a frequency of 50 Hz. The peak voltage, that is, the maximum variation of the voltage output from zero, is 340 V.

The effective emf (voltage) is a mathematical average called the root mean square voltage (V_{rms}) which in this case is 240 V. This RMS voltage is equivalent to the DC voltage that would produce the same electrical power as shown on the graphs below.

$$emf_{rms} = \frac{emf_{max}}{\sqrt{2}} \quad \text{or} \quad V_{rms} = \frac{V_{peak}}{\sqrt{2}}$$

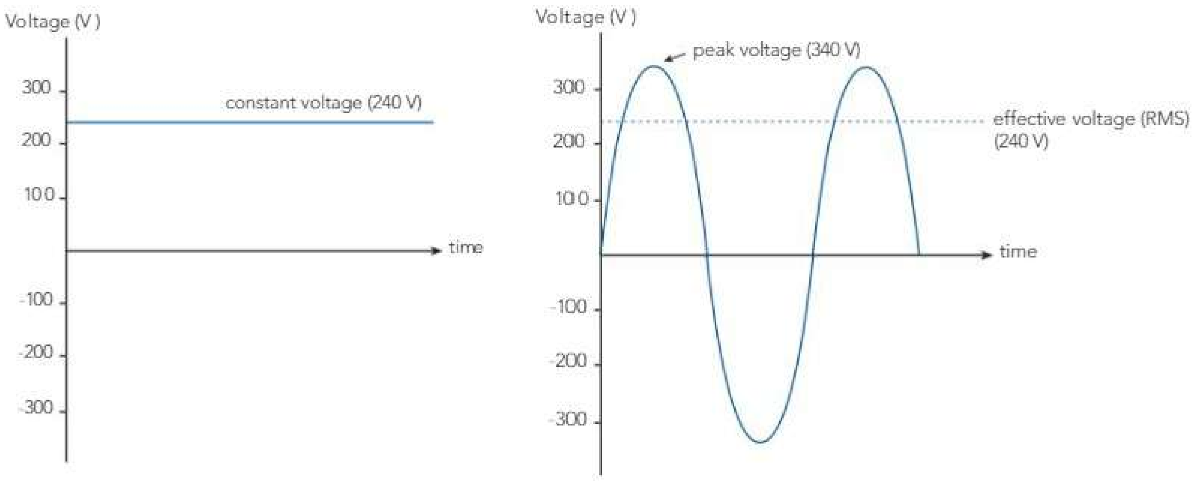


Figure 2.25 Comparing AC and DC voltage. The RMS voltage is the equivalent DC voltage of the same power.

Worked Example 2.15

A flat rectangular coil such as that in Figure 2.24 (a) consists of 40 turns and is 15.0 cm by 25.0 cm. It is rotating in a uniform magnetic field of 0.350 T at 1500 revolutions per minute.

(a) Determine the maximum emf produced by this coil.

(b) What is the RMS voltage produced?

(c) What would be the peak voltage produced if the frequency of rotation is doubled?

(a) N = 40

A = (0.150)(0.250)

= 3.75×10^{-2} m^2

B = 0.350 T

F = 1500/60

= 25.0 Hz

$emf_{max} = -2\pi NBA f$

$= -2\pi (40)(0.350)(3.75 \times 10^{-2})(25.0)$

$= -82.5$ V

The negative sign indicates that the induced emf is in opposition to the change that caused it (Lenz's Law).

The magnitude of the maximum emf = 82.5 V

(b) $emf_{rms} = \dfrac{emf_{max}}{\sqrt{2}}$

$= \dfrac{82.5}{\sqrt{2}}$

$= 58.3\ V$

(c) Since $emf_{max} = -2\pi NBAf$

Doubling the frequency will double the induced emf produced. Hence

Peak voltage $V_{peak} = 165\ V$

Question 2.23

How could the emf produced by a rotating coil be increased? Give at least 3 different ways that this can be achieved and **relate** each method to the equation used above.

(i) ____________________

(ii) ____________________

(iii) ____________________

Question 2.24

Our normal household electrical supply is 240 V, 50 Hz. Assuming this was produced by an ac generator with a single set of coils, how many revolutions per minute (r.p.m.) would these coils need to complete?

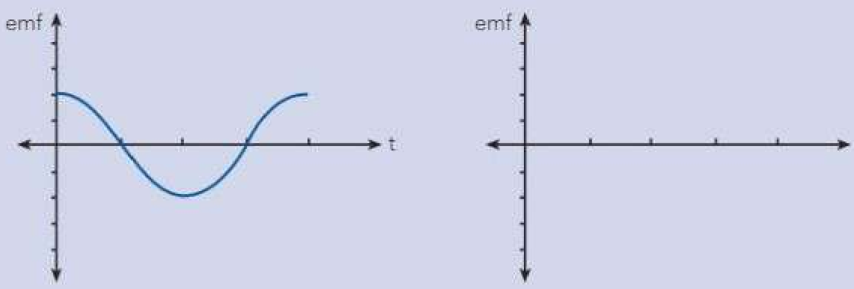
____

____

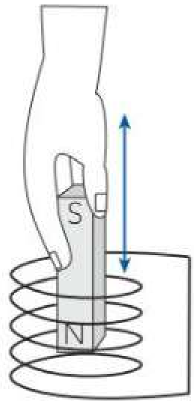
____

Question 2.25

A single rotating coil, similar to figure 2.24(a), was used to produce the voltage versus time graph shown below left. Indicate on the right graph the output you would expect if the frequency of rotation was doubled.



Achieving electromagnetic induction – what matters



Essentially, to achieve an emf, we require a coil and a magnetic field with relative movement or change between them. This can be achieved by a:

- change in the magnetic flux passing through a coil.
  e.g.
  - Magnet is brought closer to or taken away from a coil.
  - The current in an electromagnet near a coil is increased or decreased.
- change in the effective area of the coil
  e.g.
  - Coil rotated so that area facing field changes.
  - Coil shape changes and area increases or decreases.

The rate at which any of the above occur determines the magnitude of the emf. If there is no change, there is no emf.

2.7 TRANSFORMERS AND POWER TRANSMISSION

Transformers

As we have seen, a changing magnetic field will create an emf in a nearby coil. Transformers make use of this principle by creating a continually changing magnetic field in a primary coil which in turn creates a changing emf in a secondary coil.

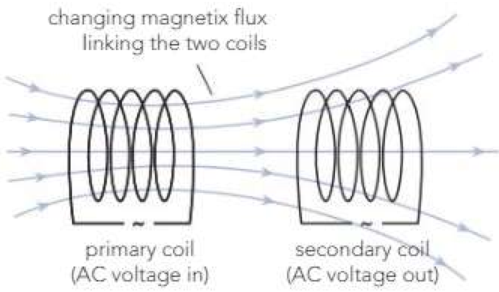


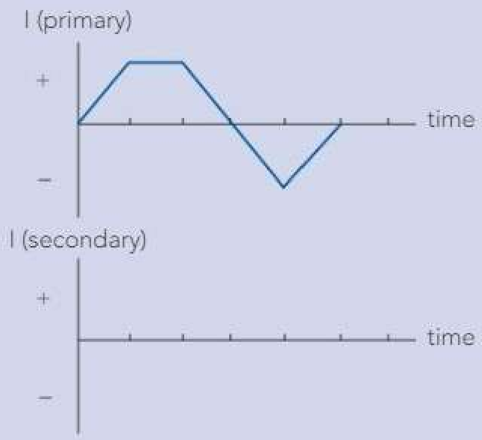
Figure 2.26 *Inducing an emf in a secondary coil. The changing flux created by the alternating voltage in the primary coil creates an alternating emf (voltage) in the second coil.*

If the current in the primary coil shown is increasing steadily, then a constant negative current is induced in the secondary coil. If the current in the primary coil is steady then no current exists in the secondary coil.

Question 2.26

The current in a primary coil such as in Figure 2.26 is varied as shown in the first graph. Indicate how the current in the secondary coil varies with time.

Hints:
(i) Induced emf depends on the rate of change of flux.
(ii) Lenz's Law applies.



A practical transformer

The purpose of transformers is to allow the efficient change of AC voltage, either up or down. The relative number of turns in the primary and secondary coils determines the ratio of input voltage to output voltage.

The use of a laminated soft iron core, onto which both primary and secondary coils are wound, increases the efficiency of a transformer.

- The iron core increases the flux link between the coils.
- The laminations reduce eddy currents and minimise energy lost in the form of heat.

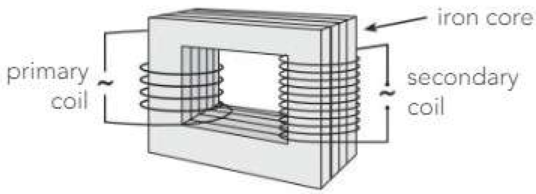


Figure 2.27 *The transformer. An oscillating current in the primary coil creates a continuously changing magnetic field in the iron core. This induces a changing emf in the secondary coil.*

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

V_p = voltage in primary coil
V_s = voltage in secondary coil
N_p = number of turns in primary coil
N_s = number of turns in secondary coil

Question 2.27

A simple transformer is to be used to step down a 240 V AC supply to 12 V AC. If the primary coil has 1000 turns, how many turns should the secondary coil have?

Question 2.28

Transformers cannot change DC voltage. Why is this?

Electrical power

Power is defined as the rate of doing work or releasing energy. From our previous definitions of voltage and current we can see that power can be calculated as follows:

$P = VI$	V = voltage (volts) I = current (amperes) P = power (watts)

Using the Ohm's Law relationship $V = IR$ we can also show that

$$P = \frac{V^2}{R} = I^2R$$

Electrical energy used

The energy consumed by an electrical appliance depends upon the rate of energy use (power rating), and the time for which it is operating.

$E = Pt$ or $E = VIt$	E = energy used (or work done), joules (J) P = power rating, Js^{-1} or watts (W) V = voltage supplied, volts (V) I = current, amperes (A) t = time, seconds (s)

Worked Example 2.16

A motor car's two headlights are each rated at 50.0 W and operate on a 12.0 V power supply. Calculate:

(a) The current flowing in each headlight when they are in use.
(b) The charge passing through each globe every second.
(c) The total energy consumed by the two headlights during a 2.00 hour night journey.

P = 50.0 W each light
V = 12.0 V
I = ?
q = ?
t = 2.00 h

(a) $P = VI$

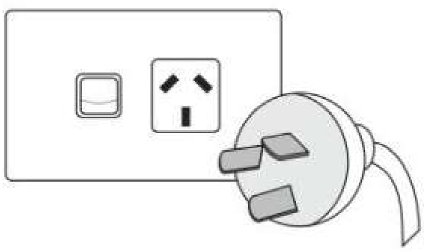
$$I = \frac{P}{V} = \frac{50.0}{12.0} = 4.17 \text{ A (for each light)}$$

(b) $q = It$
$= (4.17)(1)$
$= 4.17$ C

(c) $E = Pt$
$= (50)(2)(2.0 \times 60 \times 60)$
$= 7.20 \times 10^5$ J

Generating electrical power

Electricity for industrial and domestic use is produced by large ac generators which provide high voltages suitable for power transmission, typically 20 kV and 50 Hz. The mechanical input to drive the generators can be provided by a variety of energy sources such as coal, oil, dammed water and nuclear power. A variety of other sources such as wind, tides, geothermal and solar energy are also helping to contribute to the ever increasing demand for electrical power.



Transmission of power

Two main concerns for suppliers of electrical power are the power losses due to resistive heating and being able to meet the variable demand that occurs each day. Transmission losses are minimised by using very high voltages which are later transformed to lower domestic voltages. Typically, power is transmitted at 220 kV. Heating losses are reduced at high voltage because of the lower currents. (See worked example.)

Thick wires, made predominantly of aluminium, help to keep the resistance low and also minimise energy loss. The lightness of aluminium makes it possible to build smaller transmission line towers.

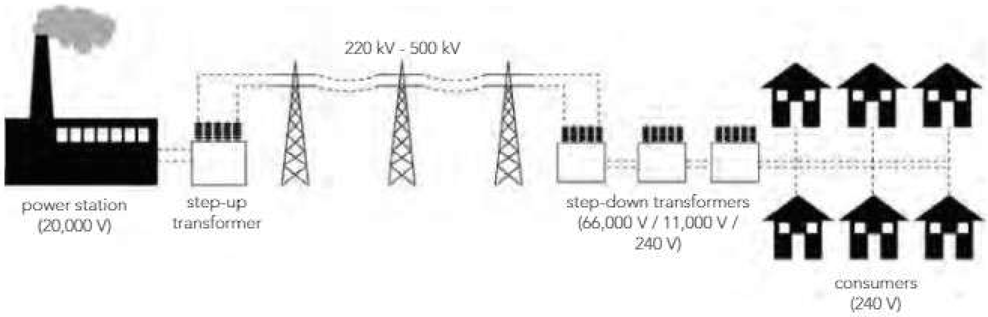


***Figure 2.28** Power is transmitted at high voltages to minimise energy losses. At high voltages the current in the wires is much lower thereby minimising heating losses (I^2R).*

Worked Example 2.17

An AC generator produces 10.0 kW of power which is to be transmitted at 240 V down a line 5.00 km long and whose total resistance is 1.50 Ω. Calculate:

(a) the power loss in the line;

(b) the voltage which reaches the end of the line.

(a) $P = 1.00 \times 10^4$ W

$V = 240$ V

$I_{line} = ?$

$R_{line} = 1.50\ \Omega$

Since $P = VI$

$$I = \frac{P}{V} = \frac{10000}{240} = 41.7 \text{ A}$$

∴ Power loss P (in wires

$$= I^2_{line} R_{line} = (41.7)^2 (1.50) = 2.60 \times 10^3 \text{ W} = 2.60 \text{ kW}$$

This represents over ¼ of the power being lost down the line. This power is lost as heat in the wires (heating effect).

(b) $V = ?$

$I_{line} = 41.7$ A

$R_{line} = 1.50\ \Omega$

Voltage lost along the line

$$V = I_{line} R_{line} = (41.7)(1.50) = 62.5 \text{ V}$$

Voltage which reaches the end of the line will be

$$V_{end} = 240 - 62.5 = 178 \text{ Volts}$$

or

$$\therefore P_{end} = V_{end} \times I$$
$$7.4 \times 10^3 = V_{end} \times 41.7$$
$$V_{end} = 178 \text{ volts}$$

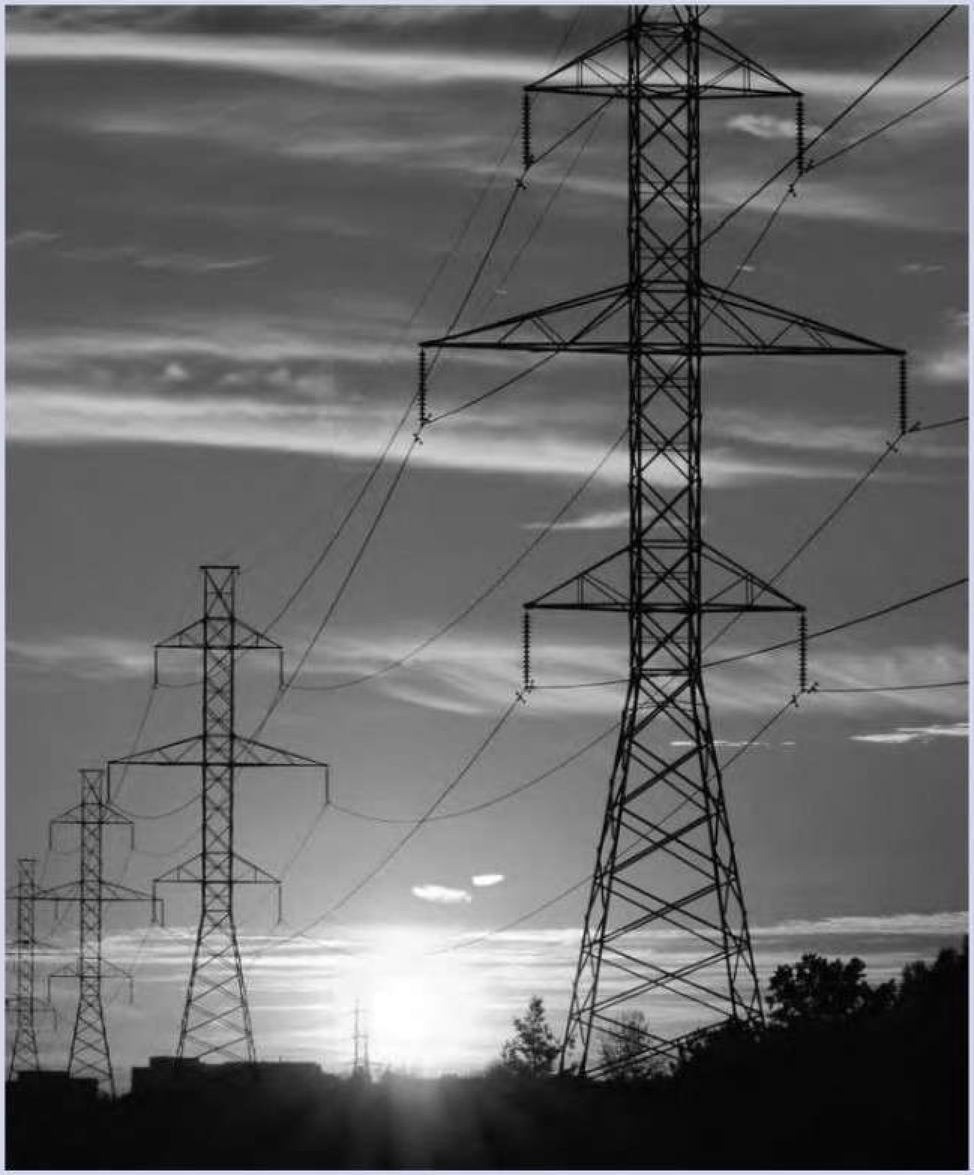
This is not a very satisfactory state of affairs. Imagine the loss over a much longer line. The solution is high voltage transmission.

Question 2.29

Suppose the 10.0 kW of power in the previous problem was transmitted at 66.0 kV instead of 240 V. Determine:

(a) the power loss along the line;

(b) the voltage available at the end of the line.

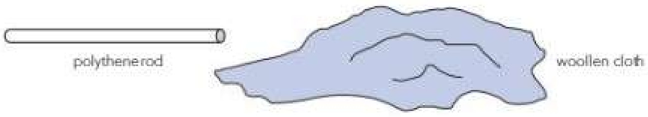


REVIEW QUESTIONS

Chapter 2: Electromagnetism

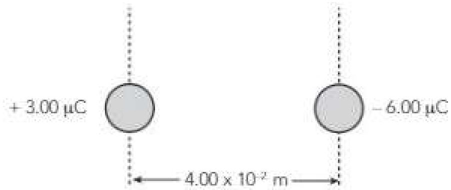
Electrostatics and Electric fields

1. When rubbed with a woollen cloth, polythene acquires a negative charge. Is this negative charge simply created by the rubbing action? Explain your answer.



2. Explain why a hand-held insulator can be charged (e.g. by rubbing) but a hand-held metal rod cannot be charged.

3. Two small metal spheres carrying a charge of +3.00 μC and –6.00 μC respectively are suspended by insulating thread 4.00 cm apart in a vacuum. Calculate the force that exists between the charges.



4. Determine the force between the two charged metal spheres in the previous question if:
   (a) They are now separated by 8.00 cm
   (b) They are firstly allowed to touch and then separated by 8.00 cm.

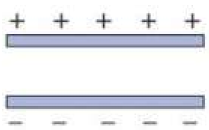
5. For each of the following re-draw the diagram and draw the electric field distribution associated with it.

(a) 

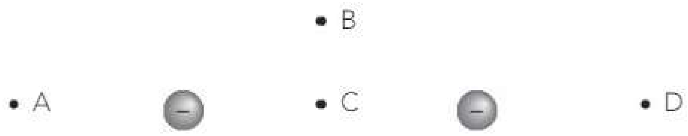
(b) 

(c) 

(d) 

(e) 

6. Two negative charges of equal magnitude are located as shown. Indicate with an arrow the direction of the electric field, if any, at points A, B, C and D.



7. An electron experiences a force of 7.50×10^{-16} N due North when placed in an electrical field. Determine the electric field strength at that point.

8. A 12.0 V battery is connected to 2 parallel plates which are 5.40 mm apart. Determine the:
   (a) electric field intensity between the plates,
   (b) force which would be exerted on a proton placed midway between the plates,
   (c) force which would be exerted on a proton if it was 1.00 mm from the positive plates.

9. An alpha particle of mass 6.65×10^{-27} kg is located midway between two parallel plates where the electric field strength is 1.45×10^{3} V m^{-1}.
   (a) What will be the force acting on the alpha particle?
   (b) What work will be done on the alpha particle if the force moves it 2.65 mm towards the negative plate?
   (c) Calculate the consequent velocity of the alpha particle if it was initially at rest.

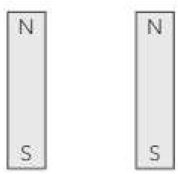
10. Michael set up a small circuit using a battery to supply an electric current to a lamp. If the battery can supply 200 C of electric charge in a 3.00 minute interval, how much electric current can Michael expect to have supplied to the lamp?

11. (a) Define "potential difference".
    (b) An old style TV screen has a potential difference in its picture tube of 3.00×10^{3} V across which electrons (with charge of 1.60×10^{-19} C) are accelerated. Calculate the energy acquired by the electrons as they are accelerated through this potential difference.

Magnetic fields

12. Sketch the magnetic fields surrounding the magnets in the situations shown below. Assume all magnets are of equal strength.

(a)



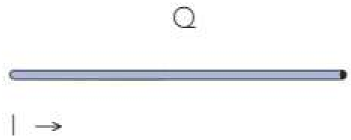
(b)

13. Indicate the direction of the magnetic field (if any) at points P, Q, R, S due to currents shown.

Show field as (X) for into page or (•) for out of page.

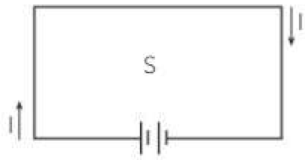
(a)

(b)

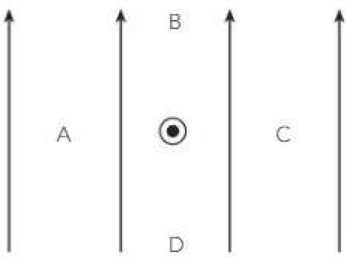


(c)

(d)



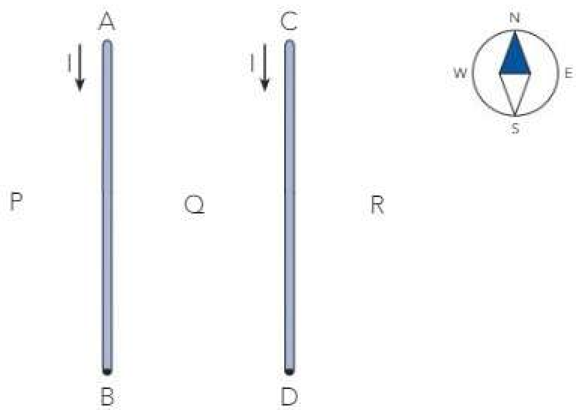
14. A freely suspended vertical wire carries a current vertically upwards as shown (plan view). The Earth's magnetic field is horizontal at this point and in a northerly direction. A small plotting compass is used to check the magnetic field at each of the points shown.



(a) At which of the points shown is it possible that the compass will
   (i) point directly North ?
   (ii) point directly South?
   (iii) be directionless?
(b) In which direction will the freely suspended wire tend to move?

15. A bar magnet and a similarly shaped soft iron bar have been both wrapped with masking tape.
    (a) How could you determine which is the real magnet simply by observing the interaction between the two bars?
    (b) How could you now determine which is the North pole of the bar that is a magnet?

16. Two wires, AB and CD, carry similar currents in the direction shown.

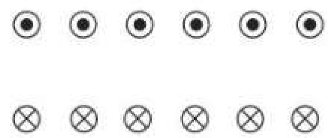


    (a) What are the likely directions of the resulting magnetic fields (if any) at P, Q and R?
    (b) What is the direction of the magnetic field due to the current in AB at the position occupied by wire CD?
    (c) Will a force act on wire CD? If so, in which direction?

17. Sketch the magnetic field lines that would exist in each of the following situations.

    (a) Two parallel wires carrying equal currents in the same direction.

    (b) A current carrying solenoid (cross section).



18. A rectangular loop of wire 25 cm by 35 cm is placed so that its plane is at right angles to a uniform magnetic field of 6.25×10^{-2} T.
    (a) What is the magnetic flux passing through this coil?
    (b) Can this magnetic flux be reduced to zero without altering the magnetic field? Explain.

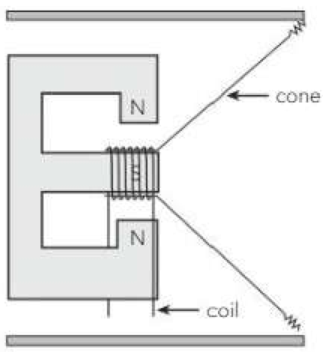
19. A current of 2.75 A is flowing vertically upwards an insulated conductor.
    (a) What will be the magnitude of the magnetic field created by this current at a point located 12.5 cm from the conductor.
    (b) If a plotting compass is located near and immediately west of the conductor in which direction will it point?

Magnetic forces

20. A wire 1.0 m long is supported horizontally in an East-West direction by cotton threads at each end. A current of 12 A is passed through the wire. Assuming that the Earth's magnetic field has a horizontal component of 2.5×10^{-6} T at this point, find the change in tension that will occur in each thread.

21. The coil of a moving coil loudspeaker is situated in a radial field as shown. The coil consists of 200 turns, is circular in shape and 12 mm in radius. The magnetic field strength is 3.5×10^{-1} T.

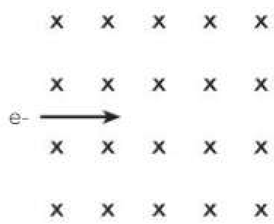
    (a) Calculate the force on the coil when a current of 500 mA is passed through it.
    (b) What effect would each of the following have on the force on the coil:
        (i) doubling the number of turns?
        (ii) doubling the magnetic field strength?
        (iii) doubling the diameter of the coil?



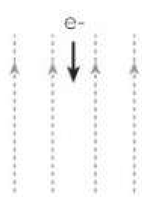
22. Two vertical wires, A and B, each carry an upward current of 2.50 A. The wires are 3.00 cm apart.
    (a) Determine the magnetic field strength created by the current in wire A at the location of wire B.
    (b) Determine the force per metre exerted on wire B due to the magnetic field of wire A.
    (c) Is this force attraction or repulsion?

23. Indicate the direction of the force (if any) that would be exerted on the electrons (e-) and alpha particles which are moving as shown.

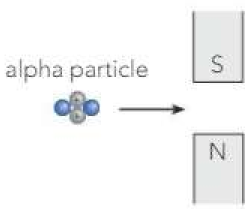
(a)



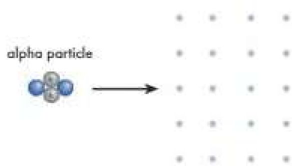
(b)



(c)



(d)



24. Cosmic radiation includes electrons moving at high speeds towards the Earth. How will the electrons' path be affected if they are initially moving directly above either of the Earth's magnetic poles. What are some possible consequences of this phenomenon?

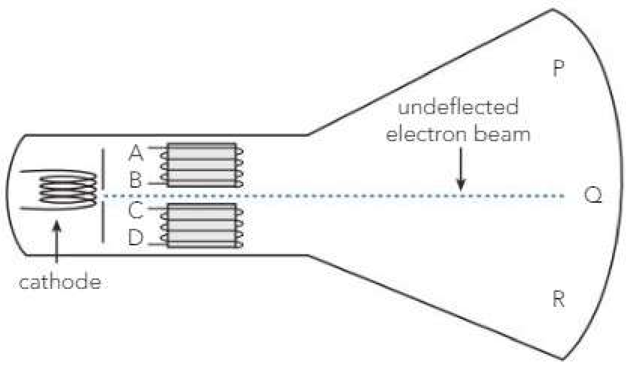
25. A proton (mass 1.67×10^{-27} kg) is fired into a magnetic field of 1.50×10^{-1} T as shown. The proton's velocity is 4.20×10^{5} m s^{-1}.

(a) When the proton enters the field in which direction will the force act?

(b) What is the magnitude of this force?

(c) If an electron (mass 9.11×10^{-31} kg) were fired into the same field with the same velocity, by what factor would the force due to the field change?

Simplified vertical cross section of CRO. Refer Q26 and 27.



26. In a cathode ray oscilloscope (CRO), the path of the electron beam between the anode and screen can be influenced by a pair of electromagnets as shown. The simplified diagram above shows two electromagnets whose polarities depend on the direction of current in the coils. They are designed to deflect the electron beam horizontally from left (out of page in diagram above) to right.

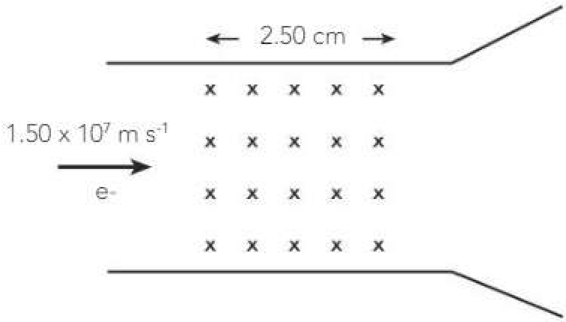
(a) If a common current is made to flow from A to B and C to D determine:
(i) the polarities of the two electromagnets;
(ii) the direction that the electron beam will be deflected to.

(b) If an AC current is applied to the electromagnets, how will this influence the path of the electron beam? Describe what an observer would see on the screen.

27. (a) Describe how the electromagnets in the diagram of the CRO on previous page must be arranged in order that they can deflect the electron beam in a vertical direction, that is, between P and R.

(b) A 1.00 kHz AC signal is applied to the electromagnets which have been moved in order to cause movement of the beam between P and R. Determine the time taken for the electron beam to move between P and R if these points are the maximum points of deflection.

28. An electron beam in a CRO has a velocity of 1.50×10^{7} m s^{-1} and passes through a magnetic field of 2.25×10^{-4} T. The magnetic field's effective width is 2.50 cm.



(a) Determine the force exerted on an electron while in the magnetic field.

(b) How long will it take an electron to traverse the beam?

(c) Determine the lateral (sideways) acceleration of an electron in the beam.

(d) Determine the lateral velocity gained by the electron while in the beam. Assume only a small angle of deflection has occurred.

(e) What will be the angle of deviation of the electron beam?

(Hint: use vectors).

(f) Why are the answers to (d) and (e) only approximate?

29. A parallel beam of fast moving electrons passes through a magnetic field as shown. The field is uniform in intensity and triangular in shape.

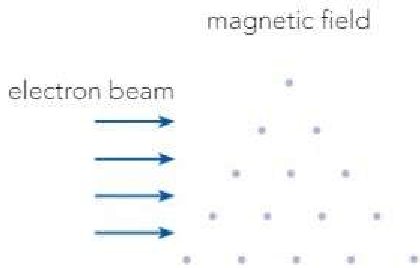
Assumption: *For the purpose of this question we will assume that deflection is small and that electrons pass through the field without being trapped in circular motion.*

(a) In which direction will the electrons be deviated?

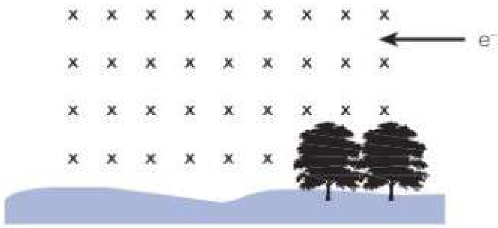
(b) Which part of the electron beam will be deviated the most?

(c) What will be the overall effect of the triangular shaped field on the electron beam?

(d) If the magnetic field direction is reversed, how would this affect the overall direction and intensity of the electron beam? Use a diagram in your explanation.



30. An electron is moving horizontally, due West, through the Earth's magnetic field. The horizontal component of the Earth's field (illustrated) is 2.38×10^{-5} T in the region where the electron is moving:



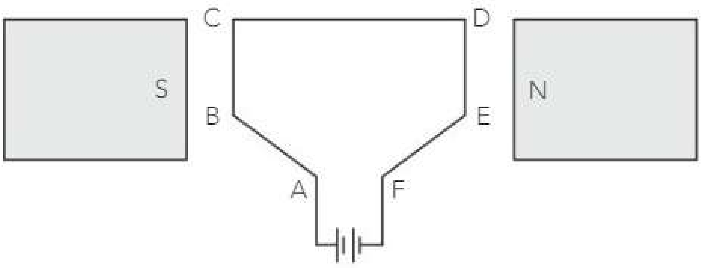
(a) In which direction will the magnetic field act on the electron?

(b) How fast must the electron move in order that it travels in a straight line? (Hint: consider its weight).

(c) In reality which field (gravitational or magnetic) will have the greatest effect on moving charged particles?

DC Electric motors

31. A copper wire loop is connected to a battery and placed between two strong permanent magnets as shown.



(a) What will be the direction of the force that will be exerted on the sections AB, BC and CD of the wire?

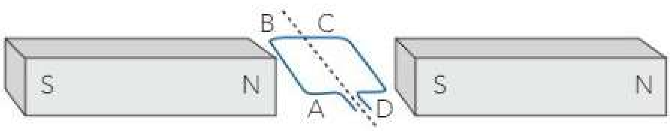
(b) What will be the total effect of all the forces on the wire loop?

32. A coil as shown below is placed between two magnets where magnetic flux density is 4.25×10^{-2} T. The coil dimensions are AB = CD = 25.0 cm, AD = BC = 15.0 cm. The current in the coil, moving in the direction ABCD, is 2.25 A. Assume for simplicity that the magnetic flux density is the same for all positions of the coil.

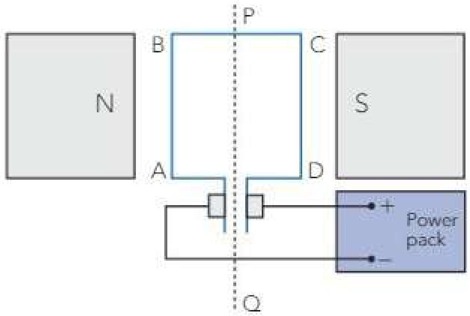
(a) Determine the magnitude and direction of the force acting on side AB of the coil.

(b) Determine the torque created by this force.

(c) What is the total torque acting on this single coil?



33. A square copper coil of sides 16.0 cm is placed in a strong magnetic field of 0.64 T as shown. A current of 4.2 A is passed to the coil using carbon brushes as contacts. The coil is free to rotate about PQ.



(a) Determine the direction and magnitude of the forces acting on
   (i) AB
   (ii) BC
   (iii) CD
(b) What is the total force acting on this coil?
(c) What is the torque about PQ acting on:
   (i) wire AB?
   (ii) wire BC?
   (iii) wire CD?
(d) What is the total torque on the copper coil?
(e) Will the coil move? If so, in which direction as viewed from Q?

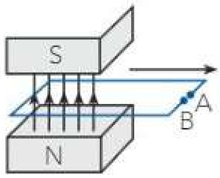
34. A practical or commercial electric motor has many features which allow it to give a smoother and more powerful result. Describe briefly how each of the following contribute to this result.
(a) Multicoil armature.
(b) Segmented commutator.
(c) Field coils.
(d) Laminations.

Electric power generation

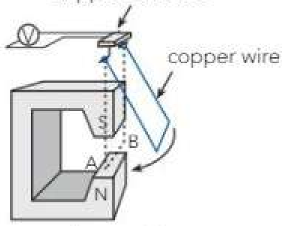
35. A car is travelling due east from Perth in an area where the Earth's magnetic field has a horizontal component of 3.6×10^{-5} T. It is found that a small and constant potential difference exists between the two ends of its 1.6 m vertical aerial at this speed.
(a) Why does a PD exist between the ends of the aerial (assume no effect from radio broadcasts)?
(b) Which end of the aerial will be positive?
(c) How fast is the car travelling if the PD is measured to be 0.125 mV?
(d) What would happen to the PD if the car travelled at the same speed:
   (i) due north?
   (ii) due south?
   (iii) due west?

36. A Boeing 747 is flying horizontally through an area where the Earth's magnetic field is 5.95×10^{-5} T at 67.0° to the horizontal. The plane's speed is 920 km h^{-1} and its wingspan is 41.5 m.
   (a) What is the induced emf between its wingtips?
   (b) Which wingtip is positive? Does the direction of travel of the plane matter?
   (c) Assume the plane was flying due north. If it begins to descend without changing its speed how will the emf between its wings be affected? Explain.

37. An open copper coil is moved at a constant velocity between two magnets as shown.
   (a) Will there be an emf generated? If so, give polarities.
   (b) Will there be any resistive force against the motion of the copper coil? Explain.

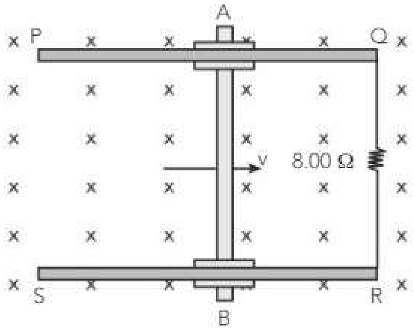


38. A copper wire loop is connected so that it can swing freely between the poles of a horseshoe magnet. Good contact is established at the supports so that any induced emf can be measured. The copper loop is dropped from its raised position and allowed to swing.
   (a) Describe the consequent motion of the pendulum. Explain.
   (b) If the magnet was repositioned so that the poles were reversed and the experiment repeated, would the pendulum move differently? Explain.
   (c) If the magnet was removed and the experiment repeated would the pendulum move differently? Explain.
   (d) How would the current vary with time in the first experiment (a)? Draw the probable shape of a current/time graph for two swings of the wire loop. Assume that current moving from A to B is positive current.



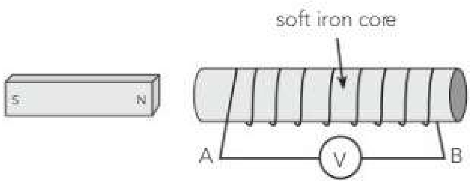
39. A metal rod AB 4.80 cm long is moving along the metal tracks PQ and SR at 12.0 m s^{-1} in a field of 2.56×10^{-2} T. Good electrical contact exists between the metal rod and tracks.
   (a) Determine the P.D. that exists between A and B.
   (b) What is the magnitude of the current through the 8.00 Ω resistor?
   (c) In which direction does this current move through the 8.00 Ω resistor?
   (d) If the rod is to maintain a constant velocity along the tracks, what force must be exerted on it? In which direction?

(e) Suppose the 8.00 Ω resistor was replaced with one of 4.00 Ω.
Would a greater or smaller force be required to maintain constant velocity? Why?



40. The concept of electromagnetic induction was first explained by Michael Faraday.
(a) What is electromagnetic induction?
(b) Describe two important applications.
(c) Is current always associated with electromagnetic induction? Explain.

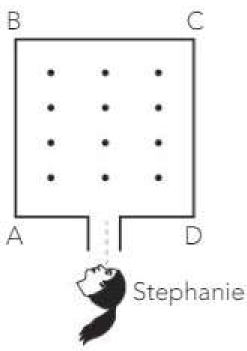
41. A strong magnet is situated near a coil as shown. Indicate in which direction the current (if any) will flow through the voltmeter in the following cases:



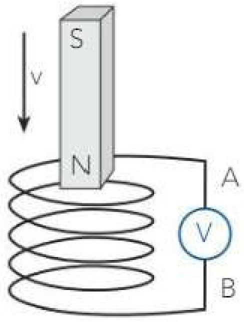
(a) Magnet is moved rapidly away from the coil.
(b) Coil is moved quickly towards the magnet.
(c) Both the coil and magnet are moved quickly to the right at a common speed.
(d) The magnet is rapidly moved in a circle around the coil. Assume the N pole of the magnet always faces the coil and remains at the same distance from it.

42. A small AC generator consists of a rectangular coil of 4.2×10^{-2} m^2 cross-sectional area and with a total of 600 turns. The coil is rotated in a magnetic field of 1.5 T at 3000 rpm and the output voltage is connected to a 100 Ω external load.
(a) Calculate the maximum EMF that this generator will produce.
(b) What current will flow in the 100 Ω resistor?
(c) What power is being generated?

43. A metal loop which measures 25 cm by 25 cm is located in a magnetic field of 0.25 T as shown.
(a) If the magnetic field drops steadily to zero in 0.25 s what emf will be induced?
(b) Which end (A or D) will become positive?
(c) If the magnetic field is maintained at 0.25 T and the loop is rotated clockwise by 90° in 0.25 s (as seen by Stephanie), what emf will be induced? Which end will now be positive?
(d) Draw simple graphs of emf/time for both cases.



44. A magnet is allowed to fall freely through a coil and beyond. The voltage between A and B is measured from the time the magnet is dropped to when it is well beyond the coil.
    (a) Sketch a graph of emf/time for this event.
        Assume a positive emf if A is positive.
    (b) If a small resistor (say 2 Ω), was connected between A and B and the experiment repeated, what difference (if any) would you expect in
        (i) the motion of the magnet;
        (ii) the emf generated?
        Explain any differences.

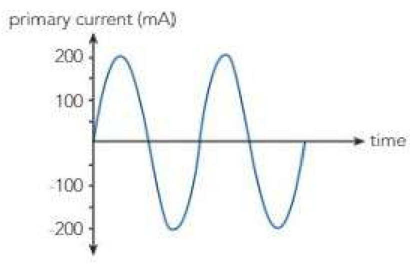


45. A flat rectangular coil consists of 200 turns and is 25.0 cm by 30.0 cm. It is rotating in a uniform magnetic field of 1.25 T at 3000 revolutions per minute.
    (a) Determine the maximum emf produced by this coil.
    (b) What is the RMS voltage produced?
    (c) Describe three different changes that could be made to double the maximum output voltage of this coil.

Transformers and power transmission

46. A transformer in a cassette recorder is designed to step down an AC current of 240 V down to 12 V. There are 1500 turns in the primary coil.
    (a) How many turns must exist in the secondary coil?
    (b) Assuming the transformer is 100% efficient what current will flow in the secondary coil if the primary has 25 mA flowing through it?
    (c) What is the power rating for this transformer?

47. A step up transformer consists of 600 turns in the primary coil and 1200 in the secondary. A 12 V AC, 200 mA current is supplied to the primary coil. A graph of the input current is shown.
    (a) What does the transformer actually step up?
    (b) How does the transformer do this? Explain clearly.



    (c) Calculate the output voltage and current.
    (d) Should the primary or secondary wires be thicker? Explain.

(e) Sketch a graph of output current with time. Label the vertical axis. Hint: Your answer to (b) will help.

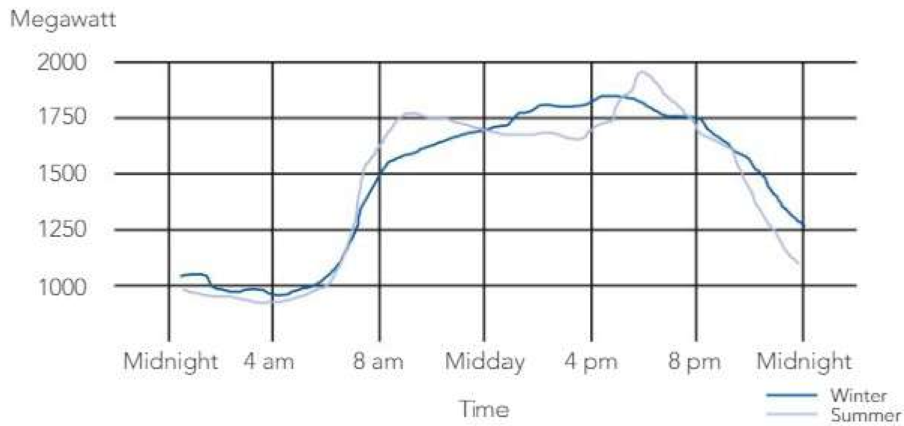
48. A house is supplied with electricity from a power pole by way of a cable whose resistance is 0.45 Ω. In the home the following items are in use:
(i) four 75 W globes;
(ii) a TV set using 195 W;
(iii) a refrigerator which draws 1.85 A;
(iv) a electric bar heater which draws 8.00 A.

(a) Calculate the total power consumption in the home.
(b) What is the magnitude of the current drawn from the power pole? Assume that the voltage at the power pole is 240 V.
(c) Calculate the loss of voltage from the power pole to the house.

49. An AC generator is used to produce 12.0 kW of power for a nearby farm. The electric power is transmitted at 240 V down a line 2.0 km in length and whose total resistance is 0.550 Ω.
(a) Calculate
(i) the power lost in the line;
(ii) the voltage which reaches the end of the line.
(b) Suggest two ways to achieve a near 240 V output at the end of the line.

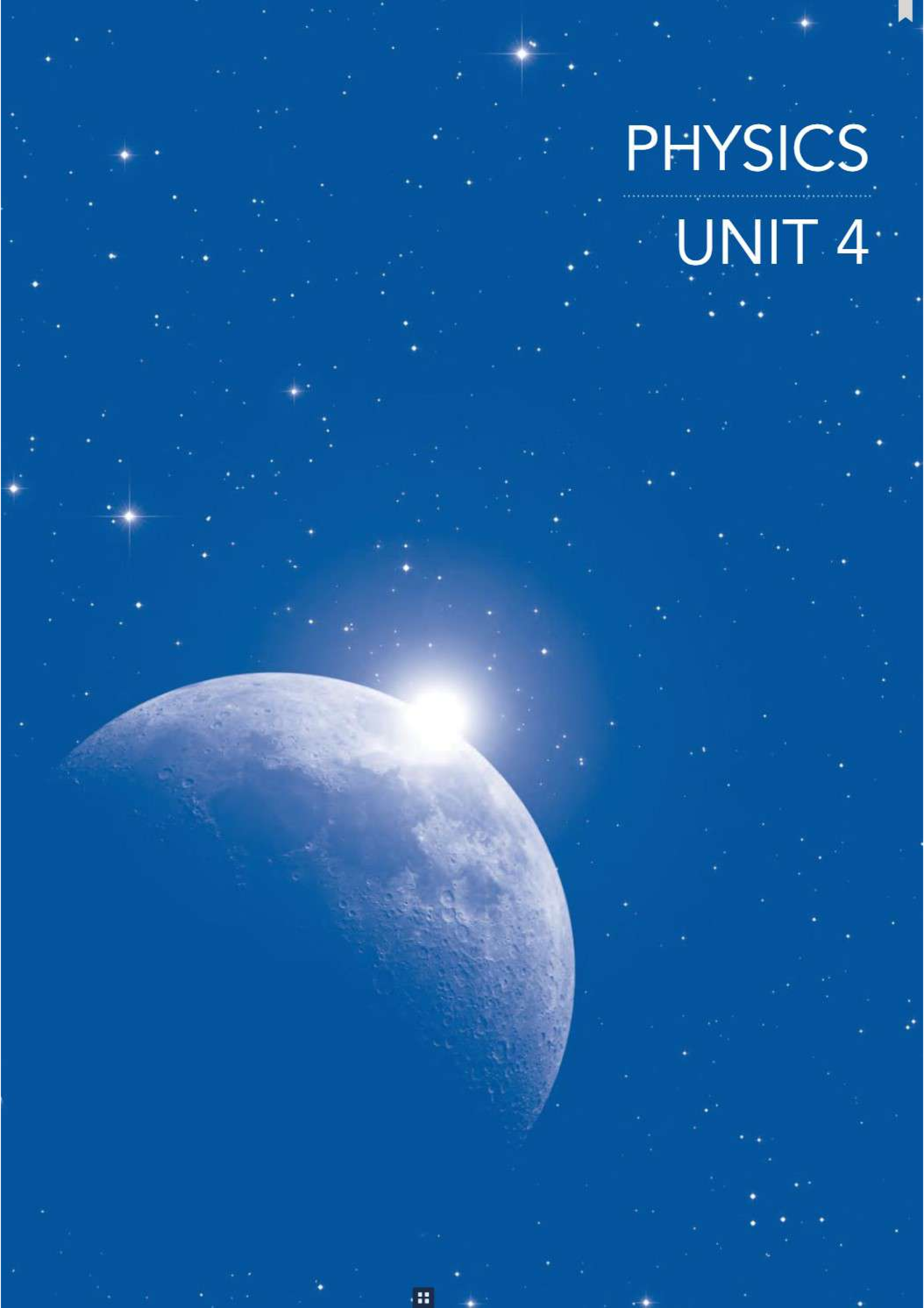
50. The graph below shows the typical load demand for winter and summer in W.A.

Use the graph to answer the following:
(a) In winter, at what time of day is demand for power the highest? Why do you think this is so?
(b) Determine the total energy used between noon and 2.00 pm in winter.
(c) Estimate the average load demand on winter days. What is the total energy consumption for one day?



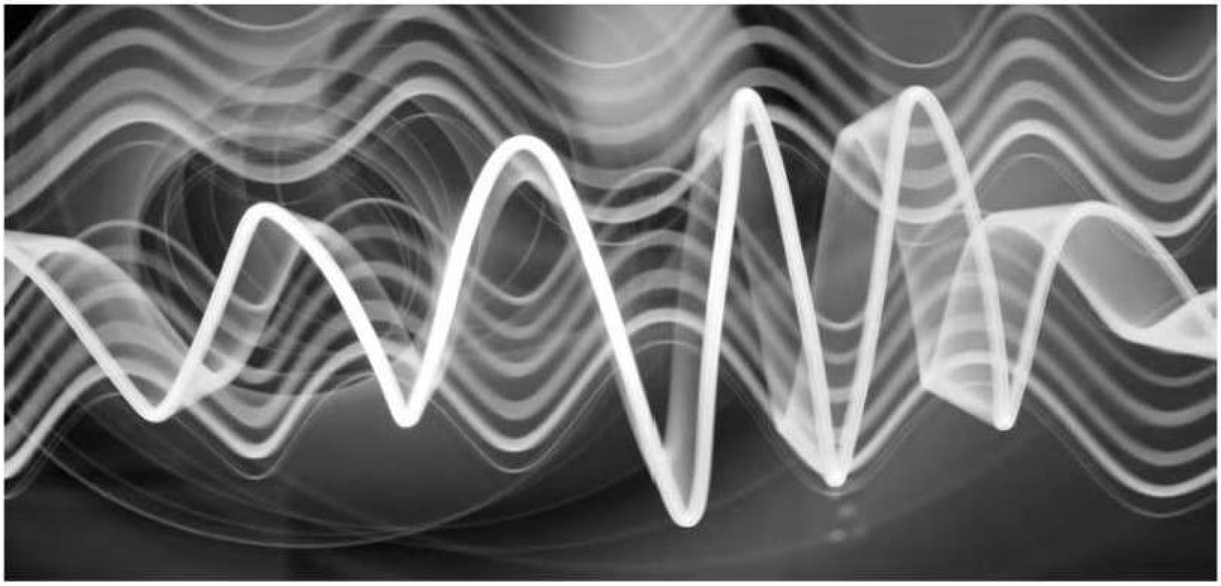
PHYSICS

UNIT 4



WAVE PARTICLE DUALITY AND THE QUANTUM THEORY

3



SYLLABUS CHECKLIST

SCIENCE UNDERSTANDING – WAVE PARTICLE DUALITY AND THE QUANTUM THEORY

- ☐ light exhibits many wave properties; however, it cannot only be modelled as a mechanical wave because it can travel through a vacuum.
- ☐ a wave model explains a wide range of light-related phenomena, including reflection, refraction, dispersion, diffraction and interference; a transverse wave model is required to explain polarisation.
- ☐ electromagnetic waves are transverse waves made up of mutually perpendicular, oscillating electric and magnetic fields.
- ☐ oscillating charges produce electromagnetic waves of the same frequency as the oscillation; electromagnetic waves cause charges to oscillate at the frequency of the wave.
- ☐ atomic phenomena and the interaction of light with matter indicate that states of matter and energy are quantised into discrete values.
- ☐ on the atomic level, electromagnetic radiation is emitted or absorbed in discrete packets called photons. The energy of a photon is proportional to its frequency. The constant of proportionality, Planck's constant, can be determined experimentally using the photoelectric effect and the threshold voltage of coloured LEDs.

  This includes applying the relationships:

  $c = f\lambda$, $E = hf = \dfrac{hc}{\lambda}$, $E_k = hf - W$, *de Broglie* $\lambda = \dfrac{h}{p}$
- ☐ a wide range of phenomena, including black body radiation and the photoelectric effect, are explained using the concept of light quanta.

- ☐ atoms of an element emit and absorb specific wavelengths of light that are unique to that element; this is the basis of spectral analysis.

  This includes applying the relationships:

  $\Delta E = hf,\ E_2 - E_1 = hf$

- ☐ the Bohr model of the hydrogen atom integrates light quanta and atomic energy states to explain the specific wavelengths in the hydrogen spectrum and in the spectra of other simple atoms; the Bohr model enables line spectra to be correlated with atomic energy-level diagrams.

- ☐ on the atomic level, energy and matter exhibit the characteristics of both waves and particles. Young's double slit experiment is explained with a wave model but produces the same interference and diffraction patterns when one photon at a time or one electron at a time are passed through the slits.

3.1 THE NATURE OF LIGHT

What is light?

Light is a form of energy with which we are all familiar. Its energy can keep us warm, allow us to see and most importantly ensures the growth of plants. The properties of light such as reflection and refraction are quite well understood but the nature of light, that is, what it actually is, is not so clear. Light, in fact, is usually described as being both wave-like and particle-like in nature.

Theories of light

The properties of light cannot be satisfactorily explained by any single theory. At the commencement of the 20th century the wave theory of light was well supported by all the available experimental evidence of that time. However, the discovery of the photoelectric effect showed that light also has a particle-like nature. The nature of light can therefore only be fully explained using both the wave and particle theory (sometimes referred to as wave-particle duality).

Young's double slit experiment

In 1801 Thomas Young demonstrated the wave-like nature of light by illuminating two narrow slits with a distant light source and observing the pattern formed on a screen placed behind them. The interference pattern produced had strong similarities to that which occurs where water or sound waves are treated in the same manner. The results of this experiment could not be explained by the then generally accepted particle theory of light suggested as probable by Newton. Hence this experiment marked a very important milestone in the theory of the nature of light.

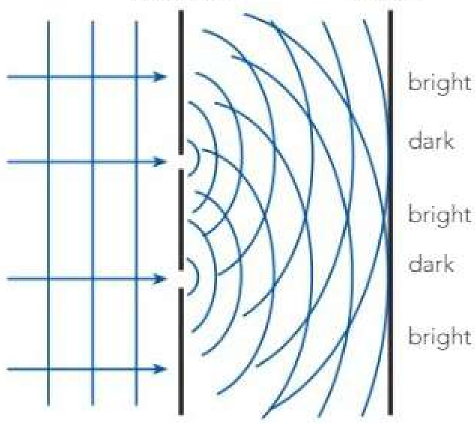


Figure 3.1 *Double Slit Interference Pattern. Each slit acts as a source of waves. These then combine to form either bright spots through constructive interference (antinodes) or dark spots through destructive interference (nodes).*

Question 3.1

(a) How could you ensure that a parallel light beam reached the double slits?

(b) To what do the bright spots of the light interference pattern correspond to if compared to a similar interference pattern for:

(i) Water

(ii) Sound

(c) What result might have been predicted by the particle model of light when doing Young's double slit experiment?

Electromagnetic Radiation

Young's double slit experiment in 1801 had shown that light had wave-like properties. A further development in the model for light occurred in 1864 when James Clerk Maxwell put forward the idea that light was electromagnetic in nature.

Essentially his theory proposed that an oscillating electric charge (or current) will produce an oscillating magnetic field which will in turn produce an oscillating electric field. This resulting oscillating electric field would then regenerate a changing magnetic field. The process becomes self sustaining, thus producing an electromagnetic wave which moves through space away from the original oscillating charge.

This mathematical theory also predicted that the speed of the wave would be 3.00×10^8 m s^{-1}, the speed of light in a vacuum. Maxwell also suggested that there would be other forms of electromagnetic radiation other than light. Electromagnetic waves in the form of radio waves were in fact propagated experimentally for the first time through air in 1886 by Heinrich Hertz.

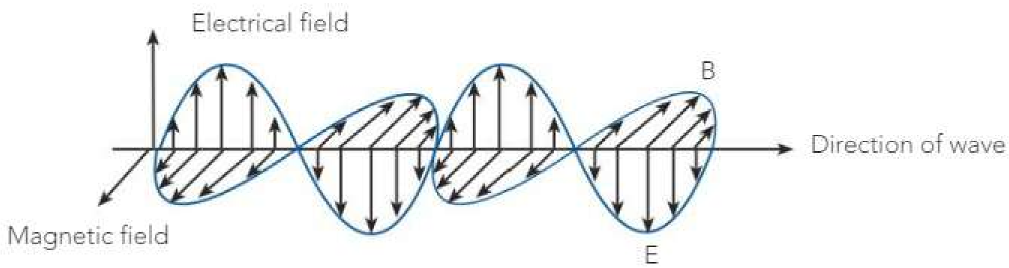


Figure 3.2 Electromagnetic waves consist of oscillating electric and magnetic fields at right angles to each other. They are transverse in nature and travel at the speed of light in a vacuum.

Properties of light and electromagnetic radiation

The properties of light are the same as those for all electromagnetic radiation:

- Light travels in straight lines. It can travel through a vacuum or transparent media.
- Speed of light in a vacuum is 3.00×10^8 m s^{-1}. This is a maximum speed.
- Light travels at different speeds in different media. This can cause refraction.
- Surfaces reflect light. Angle of incidence equals angle of reflection.
- Light diffracts when travelling through narrow openings or around the edge of a barrier.
- Light creates interference patterns in a similar manner to water waves.
- Light can cause electrons to be ejected from some metal surfaces.

The visible spectrum

Light is the small part of the electromagnetic spectrum which is visible to the eye. It can be separated into its component colours by passing it through a glass prism as shown in Figure 3.3. The prism causes dispersion since different wavelengths of light are refracted by different amounts.

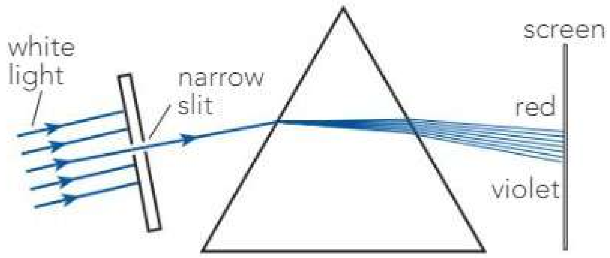


***Figure 3.3** Dispersion of white light by a prism. Different colours are refracted by different amounts. Red light, which has a longer wavelength, is refracted less than violet light.*

The electromagnetic spectrum

Although not visible to our eye, there exists other radiation on either side of the spectrum. If, for example, a thermometer was placed just above the red part of the spectrum it would show a temperature rise. This is due to the existence of infra-red radiation in that region. Similarly, by other means of detection, we can show the presence of a very large electromagnetic spectrum.

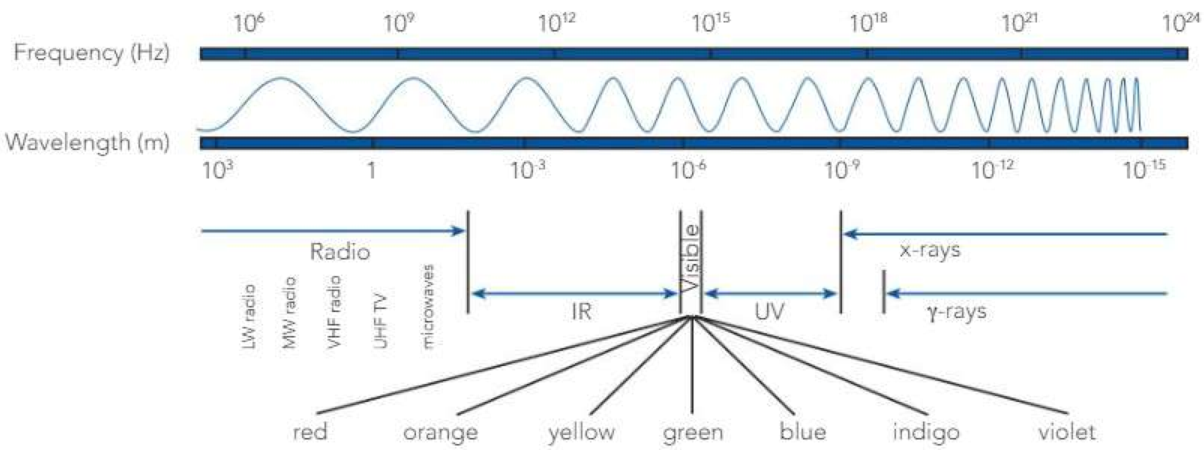


***Figure 3.4** The Electromagnetic Spectrum.*

Colour, frequency and wavelength

We have seen how a prism can disperse white light into different colours and in fact each corresponds to a different frequency and wavelength. There is virtually an infinite number of colours, each slightly different and each of a different frequency.

The wave equation gives us the relationship between the frequency and wavelength of the different colours. The relationship is given as:

$$c = f\lambda$$

c = speed of light in a vacuum
= 3×10^8 m s^{-1} for all e/m radiation
λ = wavelength (m)
f = frequency (Hz)

Red light has a longer wavelength (and lower frequency) than blue light (see Table below).

Table 3.1 Typical wavelengths and frequencies for different e/m radiation.

e.m. radiation	λ (m)	f (Hz)	$c = \lambda f$
Radio wave (1080 AM)	278.0	1.08×10^6	3.0×10^8
Micro wave	0.125	2.40×10^9	3.0×10^8
Red light	7.0×10^{-7}	4.3×10^{14}	3.0×10^8
Green light	5.5×10^{-7}	5.5×10^{14}	3.0×10^8
Blue light	4.7×10^{-7}	6.4×10^{14}	3.0×10^8
Violet light	4.2×10^{-7}	7.1×10^{14}	3.0×10^8
Ultra violet light	1.0×10^{-8}	3.0×10^{16}	3.0×10^8
X-Rays	1.0×10^{-10}	4.3×10^{18}	3.0×10^8

Worked Example 3.1

A television station transmits its vision signal on 527.25 MHz and its sound signal on 532.75 MHz. What are the wavelengths of each of these signals?

$c = 3.0 \times 10^8$ m s^{-1}

$f_v = 5.2725 \times 10^8$ Hz

$f_s = 5.3275 \times 10^8$ Hz

$\lambda_v = ?$

$\lambda_s = ?$

$c = \lambda f$

$\therefore \lambda_v = \frac{c}{f} = \frac{3 \times 10^8}{5.2725 \times 10^8}$

$= 0.5690$ m

Also $\lambda_s = \frac{c}{f} = \frac{3 \times 10^8}{5.3275 \times 10^8}$

$= 0.5631$ m

Wavelengths are just over half a metre in length.

Question 3.2

Radio broadcasts from overseas are typically in the 2 to 20 MHz range and are often referred to as shortwave transmissions.

(a) Why are they called shortwaves?

___

(b) Is this term appropriate when considering the whole e/m spectrum. Why?

___

___

The photoelectric effect

The discovery of the photoelectric effect by Heinrich Hertz in 1887 led to the reinstatement of a particle model for light. Hertz noticed that sparks induced in a coil by oncoming radio waves were brighter if the coil was illuminated by UV light. It was found through later investigations by physicists such as JJ Thompson and Philipp Lenard that when light shone on a metallic surface, electrons were emitted. The emission of the electrons (and their kinetic energy) was found to be dependent on the frequency of the light.

Lenard investigated the photoelectric effect in more detail by shining light of various frequencies and intensity on cleaned metal surfaces enclosed in an evacuated tube. The general features of his apparatus are shown below. The metal electrodes were connected to an external variable DC voltage. He was able to vary the frequency of the light falling on the metal surface under investigation using colour filters.

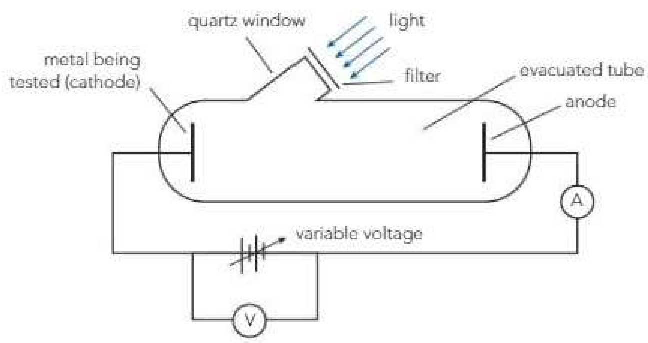


Figure 3.5 *The photoelectric effect. In 1902 Lenard used an experimental arrangement similar to that above to investigate the effect of shining light of different intensities and frequencies onto metal surfaces. The emission of electrons was found to be dependent on the frequency of the light.*

Lenard tested, in turn, the effect of using different metals, varying light frequency and intensity and varying the retarding voltage. Note above how the collector plate is connected to the negative terminal of the battery. His findings can be summarised as follows.

- A current would only occur above a minimum frequency, *threshold frequency*, for any given metal. Most importantly if the light was not above this frequency the effect could not be observed no matter how bright a light was used.
- When a current did occur its magnitude was proportional to the light intensity.
- When a negative voltage was applied to the collector electrode the current was reduced. At the stopping voltage there was no current.
- The stopping voltage varied for different metals and depended on light frequency. Light intensity, similarly to the first point, had no effect on stopping voltage.

The results of the photoelectric effect could not be explained by the wave theory of light. For example, the wave theory predicts that the photoelectric effect would occur at any frequency given light of sufficient intensity. This would occur, given wave energy to be continuous and additive. However this was not the case. Similarly, the existence of threshold frequencies was not able to be explained using wave theory.

Further, the wave theory predicts that an increase in the intensity of the light source would result in an increase in the kinetic energy of the photoelectrons. This, again, was not the case as there was simply an increase in the number of electrons ejected (photocurrent).

A satisfactory explanation of the experimental results of the photoelectric effect was only possible if light was considered to consist of quanta, that is, discrete packets of energy. This idea was put forward by both Planck and Einstein and by 1905 the concept of the photon was born.

Question 3.3

Which results from the photoelectric effect experiment could not be explained using the wave theory of light. Explain.

____

____

A particle model of light – photons

Max Planck first proposed the idea of light being made up of small packets of energy or quanta in 1900, when investigating the energy coming from hot bodies (blackbody radiation). He proposed that the radiation from the hot body was not continuous but made up of discrete bundles whose energy was proportional to the frequency of the radiation. The energy of these bundles, which we now call photons, can be determined using the expression $E = hf$, or when combined with the wave equation, using $E = hc/\lambda$.

$$E_{ph} = hf = \frac{hc}{\lambda}$$

E_{ph} = energy of photon (J)
h = Planck's constant
= 6.63×10^{-34} J s
f = frequency of radiation (Hz)
λ = wavelength of radiation (m)

Worked Example 3.2

(a) The light from a yellow light globe has a typical wavelength of 580 nm. Determine the energy of each photon of yellow light emitted by the globe.
(b) If we assume that the yellow light is being emitted at the rate of 2.00 W determine the number of photons being emitted every second.

(a) E_{ph} = ?
$h = 6.63 \times 10^{-34}$ J s
$\lambda = 5.80 \times 10^{-7}$ m
$c = 3.00 \times 10^{8}$ m s^{-1}

$$E_{ph} = hf = \frac{hc}{\lambda} = \frac{(6.63 \times 10^{-34})(3.00 \times 10^{8})}{(5.80 \times 10^{-7})} = 3.43 \times 10^{-19} \text{ J}$$

(b) Power = Energy/Time = 2.00 J s^{-1}
This means that 2.00 J of energy are emitted every second.

Hence, number of photons emitted per second.

$$= \frac{2.00}{3.43 \times 10^{-19}}$$

$$= 5.83 \times 10^{18} \text{ photons.}$$

Question 3.4

Three studio lamps are set up to give the three primary colours red, green and blue. Each lamp gives a light output of 500 W. The wavelengths of the light emitted are 670 nm, 530 nm and 470 nm respectively. Determine:

(a) Which colour lamp will emit photons of greatest energy? Briefly explain why and calculate the value of this photon energy.

____

____

(b) Which colour lamp will emit the greatest number of photons per second? Briefly explain why and calculate this number.

____

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Photoelectric effect – Einstein's equation

Building on the concept of photons proposed by Planck, Einstein developed a theory to explain the photoelectric effect. He considered that electrons held within a metal required a specific amount of energy to become free of that metal. The energy needed to just free an electron is called the work function of that metal (W). Einstein reasoned that this was related to the threshold frequency for that metal.

When individual photons hit a metal surface all their energy is absorbed by an electron. If this photon energy is less than the work function of the metal then the electron is not able to escape; if it is just equal to the work function it will escape the surface but have no kinetic energy. Where the photon energy is greater than the work function the escaping electron carries the excess energy as kinetic energy. Experimentally this excess kinetic energy can be determined by measuring stopping voltage and applying W = qV.

The energy transfer in the photoelectric effect can be stated mathematically as follows. This is often referred to as Einstein's photoelectric equation.

$$E_k = hf - W$$

E_k = kinetic energy of ejected electron (J)
h = Planck's constant
f = frequency of incident photon (Hz)
W = metal work function (J)

** Work function is often given in eV   1eV = 1.60 × 10⁻¹⁹ J*

Points to note

- One photon will eject only one electron.
- The colour (frequency) of the light determines the energy of its photons. Violet light for example consists of more energetic photons than red light.
- A bright light has more photons than a dull light (not photons of higher energy)

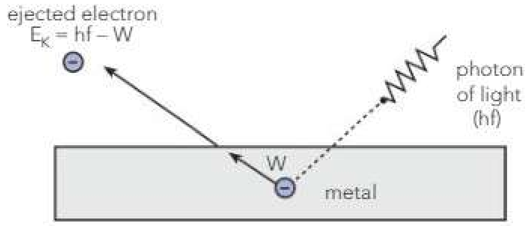

Figure 3.6 Photoelectric effect – Energy transfers. An electron absorbs all the energy of the incident photon. Some of the energy is used to overcome the work function of the metal (W), while the remainder is retained as kinetic energy by the ejected electron.

Worked Example 3.3

Ultraviolet light of wavelength 410 nm shines on a clean surface of the metal calcium. The work function for this metal is 2.87 eV. Show that:

(a) Photoelectrons will be emitted from its surface.
(b) The maximum kinetic energy of these emitted electrons.

(a)

$E_{ph} = ?$

$h = 6.63 \times 10^{-34}$ J s

$\lambda = 4.30 \times 10^{-7}$ m

$c = 3.00 \times 10^{8}$ m s^{-1}

1 eV $= 1.6 \times 10^{-19}$ J

$W = 2.87$ eV

$$E_{ph} = hf = \frac{hc}{\lambda}$$

$$= \frac{(6.63 \times 10^{-34})(3.00 \times 10^{8})}{(4.10 \times 10^{-7})}$$

$$= 4.85 \times 10^{-19} \text{ J}$$

In eV $$E_{ph} = \frac{4.85 \times 10^{-19}}{1.6 \times 10^{-19}}$$

$$= 3.03 \text{ eV}$$

Since the photon energy is greater than the work function photoelectrons will be emitted.

(b)

$$E_{k(max)} = hf - W$$

$$= 3.03 - 2.87$$

$$= 0.16 \text{ eV}$$

Worked Example 3.4

Photoelectrons are ejected from the surface of magnesium metal by a light whose wavelength is 275nm. It is found that the photoelectron current can be reduced to zero by applying a stopping voltage of at least 0.860 V. Determine:

(a) The energy of the incident photons in J and eV.
(b) The maximum kinetic energy of the photoelectrons.
(c) The work function of magnesium metal.
(d) The threshold frequency for this metal.

(a)

$E_{ph} = ?$

$h = 6.63 \times 10^{-34}$ J s

$\lambda = 2.75 \times 10^{-7}$ m

$c = 3.00 \times 10^{8}$ m s^{-1}

1 eV $= 1.6 \times 10^{-19}$ J

$W = ?$

$$E_{ph} = hf = \frac{hc}{\lambda}$$

$$= \frac{(6.63 \times 10^{-34})(3.00 \times 10^{8})}{(2.75 \times 10^{-7})}$$

$$= 7.23 \times 10^{-19} \text{ J}$$

In eV $$E_{ph} = \frac{7.23 \times 10^{-19}}{1.6 \times 10^{-19}}$$

$$= 4.52 \text{ eV}$$

(b) The stopping voltage allows us to calculate the maximum energy (kinetic) of the ejected photoelectrons. The work done by the electrical field in stopping the electrons is given by:

$$W = qV \text{ (where } q \text{ is the charge on an electron)}$$

$$\text{Hence } E_{k(max)} = qV = (1.6 \times 10^{-19})(0.860) \text{ J}$$

$$\text{or simply} = (1 \text{ e})(0.860) = 0.860 \text{ eV}$$

(c) To find the work function (W) we have:

$$E_{k(max)} = hf - W$$

$$\text{Hence } W = hf - E_{k(max)} = 4.52 - 0.860$$

$$= 3.66 \text{ eV}$$

(d) We can find the threshold frequency by considering the work function of the metal. At the threshold frequency the electrons are able to reach the surface of the metal but have zero kinetic energy and cannot leave it. In this case the incident photon energy is exactly equal to the work function.

$$E_{k(max)} = hf - W$$

$$0 = hf - W \quad \text{hence} \quad hf = W$$

$$hf = 3.66 \text{ eV} = (3.66)(1.6 \times 10^{-19}) = 5.86 \times 10^{-19} \text{ J}$$

$$f = \frac{5.86 \times 10^{-19}}{6.63 \times 10^{-34}}$$

Threshold frequency = 8.83×10^{14} Hz

Question 3.5

A clean surface of lithium metal was tested with light of different wavelengths in order to produce photoelectrons. It was found that the longest wavelength that would achieve this effect was 429 nm. Determine:

(a) The energy of the incident photons that will just produce photoelectrons.

____

(b) The work function of lithium metal.

____

(c) The maximum energy of emitted photoelectrons if a light of 350 nm was directed on to the lithium metal.

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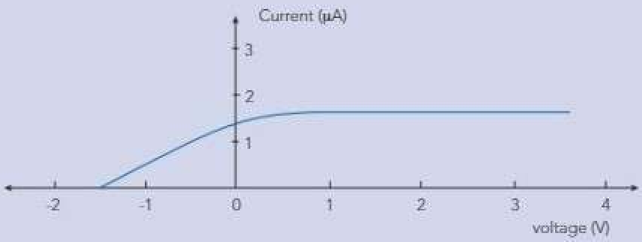
Question 3.6

An experiment to investigate the photoelectric effect was carried out using a photocell containing a zinc metal cathode. Ultraviolet light of 2.42×10^{-7} m wavelength was directed onto the zinc cathode. The light intensity was kept constant while the voltage applied to the anode was varied. The results of the variation in photocurrent that occurred with changes in voltage are graphed below.



Answer the following.

(a) From the graph determine the stopping voltage.

____

(b) How might this stopping voltage be affected, if at all, by the following (give reasons):

(i) An increase in light intensity

____

(ii) An increase in light wavelength

____

(c) The experiment was repeated using the same light source but at twice the intensity. On the graph above sketch the likely result. Explain this result.

____

____

(d) Determine:

(i) The photon energy of the light used in this experiment.

____

(ii) The maximum kinetic energy of the photoelectrons.

____

____

(iii) The work function for zinc metal.

____

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Wave particle duality – Matter waves

As we have seen light has both wave-like and particle-like characteristics. Many of its properties can be readily explained by both the wave theory and particle theory. However neither theory can satisfactorily explain all properties.

For example, light interference patterns from diffraction demonstrate the wave-like nature of light, but cannot be explained by the particle theory. However the photoelectric effect indicates a particle-like nature of light which cannot be explained by the wave theory. The quantum theory considers wave-like and particle-like behaviour for both light and matter.

In 1924 Louis de Broglie first suggested the idea that particles might behave like a wave. He reasoned that if light waves have particle-like properties then the reverse should be true. His hypothesis became an important part of the developing theory of quantum mechanics.

The wavelengths predicted by Broglie's theory were very small for large objects moving slowly and hence difficult to observe. However, for fast moving particles such as electrons, it was possible to detect them experimentally by diffraction. This was shown to be the case in 1927 by Davisson and Germer.

The de Broglie equation for the wavelength of a particle is as follows.

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

λ	=	wavelength (m)
h	=	Planck's constant
p	=	momentum (kg m s^{-1})
m	=	mass (kg)

Worked Example 3.5

Determine the de Broglie wavelength for the following and compare their magnitudes.

(a) A 58.0 g tennis ball with a speed of 25.0 m s^{-1}.

(b) An electron moving with a speed of 0.010 c (1.0% of the speed of light).

(a) $\lambda = ?$

$h = 6.63 \times 10^{-34}$ J s

$m = 5.80 \times 10^{-2}$ kg

$v = 25.0$ m s^{-1}

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

$$= \frac{(6.63 \times 10^{-34})}{(5.80 \times 10^{-2})(25.0)}$$

$$= 4.57 \times 10^{-34} \text{ m}$$

This is an extremely small wavelength and difficult to detect.

(b) $\lambda = ?$

$h = 6.63 \times 10^{-34}$ J s

$m = 9.11 \times 10^{-31}$ kg

$v = (0.010)\ (3.00 \times 10^{8})$

$= 3.00 \times 10^{6}$ m s^{-1}

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

$$= \frac{(6.63 \times 10^{-34})}{(9.11 \times 10^{-31})(3.00 \times 10^{6})}$$

$$= 2.43 \times 10^{-10} \text{ m}$$

This wavelength is comparable to X-ray wavelengths and can be readily detected and measured.

Worked Example 3.6

Electrons in an X-ray tube are accelerated towards a metal target by a voltage of 45.0 kV. Determine the following:

(a) The maximum kinetic energy attained by the electrons.
(b) The velocity of the electrons as they reach their target.
(c) The momentum and wavelength of the electrons on reaching their target.

(a) The increase in kinetic energy of the electrons in the X-ray tube is given by:

$E_k = ?$

$q = 1.6 \times 10^{-19}$ C

$V = 4.50 \times 10^4$ V

$h = 6.63 \times 10^{-34}$ J s

$W = qV = \Delta E_k$

Hence $\Delta E_k = (1.6 \times 10^{-19})(4.50 \times 10^4)$

$= 7.20 \times 10^{-15}$ J

$m = 9.11 \times 10^{-31}$ kg

(b) $\Delta E_k = \frac{1}{2} mv^2$

$\Delta E_k = 7.20 \times 10^{-15}$

$$v^2 = \frac{(7.20 \times 10^{-15})(2)}{(9.11 \times 10^{-31})}$$

$v = 1.26 \times 10^8$ m s^{-1}

(c) $p = mv = (9.11 \times 10^{-31})(1.26 \times 10^8)$

$= 1.15 \times 10^{-22}$ kg m s^{-1}

$$\lambda = h/p = \frac{(6.63 \times 10^{-34})}{1.15 \times 10^{-22}}$$

$= 5.76 \times 10^{-12}$ m

Question 3.7

Determine which of the following has the greatest de Broglie wavelength.

(a) A bullet of mass 145 g travelling at 350 m s^{-1} or an alpha particle of mass 6.64×10^{-27} kg moving at 8.25×10^5 m s^{-1}.

____

(b) An electron accelerated from rest by an electrical field to a +25.0 V potential or a neutron travelling at 0.150 c.

____

3.2 SPECTRA

Bohr model

In 1913 Neils Bohr proposed a theory of the atom which was a modification of the Rutherford model. It was able to explain more clearly the behaviour of electrons in atoms and was consistent with the quantum theory. Its main points were:

- Atoms consist of a positive nucleus surrounded by fast moving negatively charged electrons.
- Electrons can only exist in specific energy levels.
- Energy, in the form of photons, is emitted whenever an electron moves from a high energy level to a lower one. This photon has a frequency given by $E_2 - E_1 = hf$.

$$\Delta E = E_2 - E_1 = hf$$

E_2 = Energy at level 2
E_1 = Energy at level 1
h = Plank's constant
= 6.63×10^{-34} J s
f = frequency of emitted photon (Hz)

The Bohr model of the hydrogen atom

In developing his theory, Neils Bohr was particularly keen on being able to explain the spectra be observed from a hydrogen discharge tube. This consisted of four distinct lines, and their existence could not be explained by Rutherford's planetary model of the atom.

He proposed that the spectra was due to the movement of excited electrons in the hydrogen atoms "falling back" to their ground state level. The electrons of the atom must have initially being excited by the collisions of the atoms with the electrons accelerated by the discharge tube.

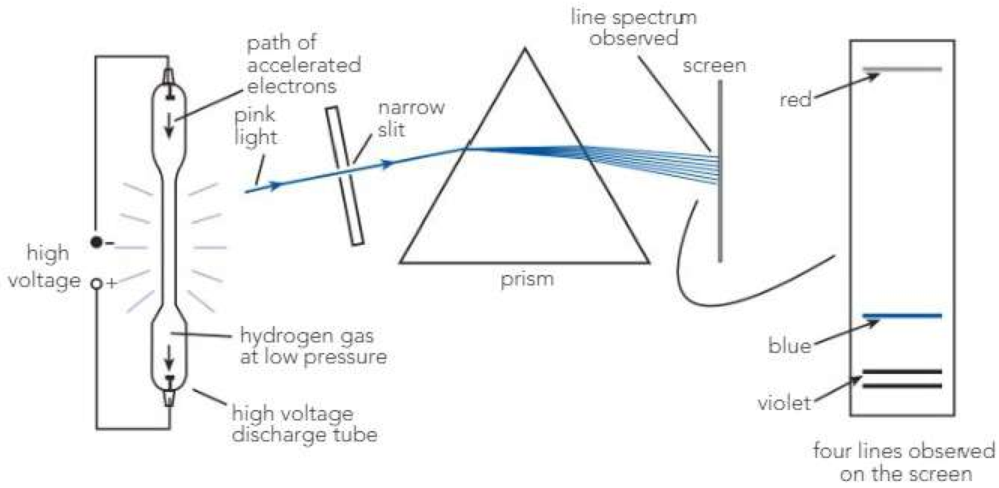


Figure 3.7 Observing the line emission spectrum for hydrogen.

Bohr used his observations of the hydrogen spectra and the quantum theory to determine the energy of each energy level in the hydrogen atom.

Mathematically, Bohr assumed that $E_n \propto \frac{1}{n^2}$, n being the level number.

The first five levels were predicted to be −13.6 eV, −3.40 eV, −1.51 eV, −0.85 eV and −0.54 eV. These are usually illustrated on an energy level diagram.

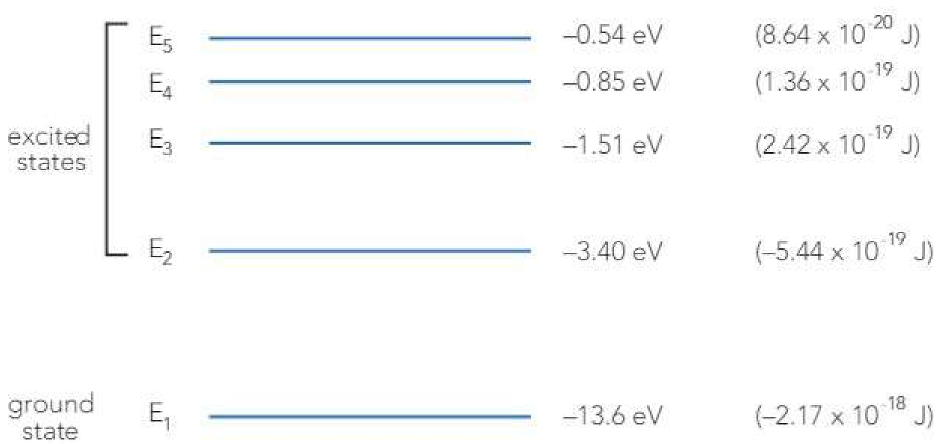


Figure 3.8 Energy levels of a hydrogen atom. It can be shown that $E_n \propto \frac{1}{n^2}$, n being the level number.

Note: 1 eV = 1.6×10^{-19} J

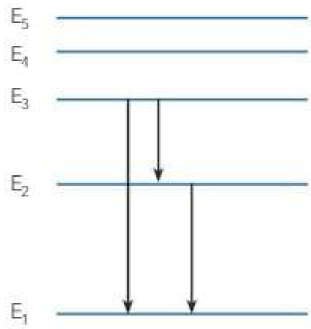
Worked Example 3.7

The electron in a hydrogen atom has been excited to the third level and after a short time returns to the ground state.

(a) Show the possible downward transitions of this electron.
(b) Determine the energy of the photons emitted in each case.
(c) What is the longest wavelength possible for the photons emitted?

(a) There are three possible downward electron transition as shown below.

(b) Photon energies possible:



i) $E_3 - E_1 = -1.51 - (-13.6)$ eV
$= 12.09$ eV

ii) $E_2 - E_1 = -3.40 - (-13.6)$ eV
$= 10.2$ eV

iii) $E_3 - E_2 = -1.51 - (-3.40)$ eV
$= 1.89$ eV

(c) The longest wavelength photon would be the one with the least energy (least frequency).

$E = hf$ Use $c = f\lambda$

$\therefore E = \dfrac{hc}{\lambda}$ *Note: energy must be in Joules.*

$$\therefore \lambda = \frac{hc}{E} = \frac{(6.63 \times 10^{-34})(3 \times 10^{8})}{(1.89 \times 1.6 \times 10^{-19})}$$

$$\lambda = 6.58 \times 10^{-7}\,\text{m}$$

This wavelength in fact corresponds to the red line observed in the spectra for hydrogen (see Figure 3.10).

Question 3.8

(a) If the ground state electron of a hydrogen atom is excited to the fifth energy level (E5) how many possible downward transitions are there from this level?

____

(b) Which electron transition would give the shortest wavelength?

____

(c) Calculate the wavelength of the photons given up by an E_4 to E_2 electron transition.

____

____

____

(d) Check Figure 3.8 and Table 3.1 to verify the colour of light this photon belongs to.

____

Energy levels and spectra

Atoms in their normal state may be excited by:

- being heated (thermally excited)
- being bombarded by fast moving particles such as electrons
- absorbing photons of a specific frequency.

In their excited state electrons remain in energy levels higher than their normal ground state for a very short time. When these electrons return to their ground state they emit photons whose energy corresponds to the difference in energy levels.

There are many possible transitions. Electrons may return to the ground state by a series of steps provided that there are energy levels in between. If atoms are sufficiently excited, then a large number of electron transitions are possible leading to a corresponding number of lines in the observed emission spectrum for that substance.

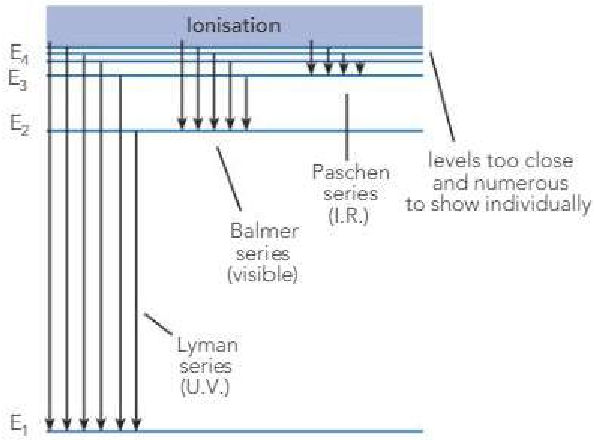


Figure 3.9 Line emission spectra from a hydrogen atom. Each electron transition (represented by an arrow) leads to one line in the spectra of hydrogen as shown in the figure below. Only four lines are visible.

Figure 3.10 Hydrogen line emission spectrum. Only 4 lines are in the visible region.

Question 3.9

(a) The Lyman series occurs in the ultraviolet region and is not visible. Which line in this series has the longest wavelength?

____

(b) Use the data from Figure 3.8 to determine this wavelength.

____

____

(c) Determine the longest wavelength line from the Paschen series.

____

____

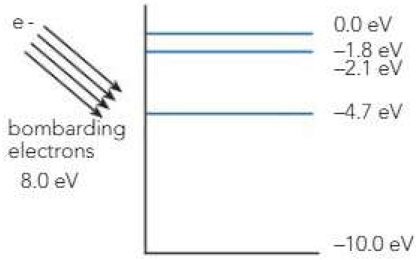
Spectra due to bombardment by electrons

Worked Example 3.8

When atoms are bombarded by electrons the bombarding electrons give up some (or all) of their energy to the electrons of the atom and are themselves scattered with reduced energy. A stream of electrons of energy 8.0 eV is used to bombard atoms of an element with the energy levels. Calculate:

(a) The energies of the scattered electrons.

(b) The possible energies of the photons emitted.



(a) Scattered electrons can have the following energies:

8.0 – 0	=	8.0 eV *(elastic collision)*
8.0 – (10.0 – 4.7)	=	2.7 eV
8.0 – (10.0 – 2.1)	=	0.1 eV *(elastic collision)*
8.0 – (10.0 – 1.8)	etc. not possible	

Scattered electron energies are 8.0 eV, 2.7 eV, 0.1 eV

(b) Possible photon energies:

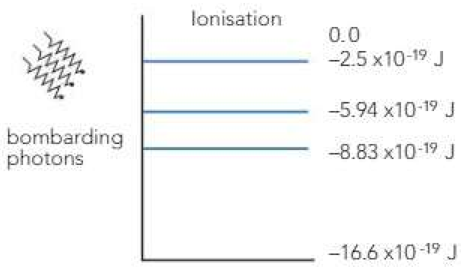
$E_3 - E_1$	=	-2.1 – (-10.0)	=	7.9 eV
$E_3 - E_2$	=	-2.1 – (-4.7)	=	2.6 eV
$E_2 - E_1$	=	-4.7 – (-10.0)	=	5.3 eV

Photon energies are 2.6 eV, 5.3 eV, 7.9 eV. Transitions from E_4 or higher are not possible since bombarding electrons have insufficient energy.

Spectra due to bombardment by photons

Worked Example 3.9

When atoms are bombarded by photons an interaction occurs only if the photon can be completely absorbed. That is, the photon energy must correspond exactly to the difference between a ground state and a possible empty excited state. Alternatively the photon may ionise the atom! Some of the energy levels of a mercury atom are shown at right.



The ground state is -16.6×10^{-19} J.

(a) What energy photons may be absorbed by atoms of mercury assuming the existence of only the levels shown?

(b) What energy photon is required to cause ionisation of the atom?

(c) If the atom is ionised what is the maximum frequency of photon that will then be emitted?

(d) How many lines would appear in the emission spectrum of this atom? (Assume that only the levels shown exist).

(a) Photons are absorbed when an electron in the ground state (-16.6×10^{-19} J) is given the exact energy to go to any of the higher levels.

Photon energies absorbed will be:

$(16.6 - 8.83) \times 10^{-19}$ J	=	7.77×10^{-19} J
$(16.6 - 5.94) \times 10^{-19}$ J	=	10.66×10^{-19} J
$(16.6 - 2.50) \times 10^{-19}$ J	=	14.1×10^{-19} J
$(16.6 - 0) \times 10^{-19}$ J	=	16.6×10^{-19} J and higher

(b) Ionisation will be caused by photon energies of 16.6×10^{-19} J or higher.

(c) An electron falling from an energy level of 0.00 J (infinity), to the ground state will give up 16.6×10^{-19} J of energy. A photon of this energy will be emitted by the atom.

$$E_\infty = 0 \qquad E_\infty - E_1 = hf$$

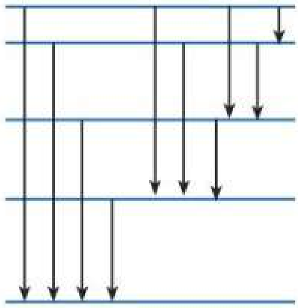
$$E_1 = -16.6 \times 10^{-19}\,\text{J} \qquad f = \frac{16.6 \times 10^{-19}}{6.63 \times 10^{-34}}$$

$$h = 6.63 \times 10^{-34}\,\text{Js} \qquad f = 2.50 \times 10^{15}\,\text{Hz}$$

$$f = ?$$

This photon frequency corresponds to the ultra-violet range.

(d)



Ten lines are possible in the line emission spectrum.

Question 3.10

If a stream of electrons having 8.00×10^{-19} J of energy bombarded the atom used in Worked Example 3.9 what would be:

(a) the scattered electron energies observed?

(b) the photon energies emitted?

Question 3.11

The atom in Worked Example 3.9 is bombarded with photons of the following energies. Describe in each case what would occur. Energy of photons used:

(a) 10.0×10^{-19} J

(b) 10.66×10^{-19} J

(c) 20.00×10^{-19} J

Question 3.12

Why are photons less likely to cause line emission spectra than an electron of the same energy?

Types of spectra

Spectra are classified into two main types, emission and absorption spectra. The essential difference in the two types of spectra is the means by which it was produced in the first place.

- **Emission spectra** is that which is obtained by the dispersion of light coming directly from the source. This may be from the glowing gas in a discharge tube or an incandescent (glowing) solid such as a globe filament.
- **Absorption spectra** is that which is obtained by the dispersion of light that has passed through some absorbing material. In this type of spectra we tend to see black lines superimposed onto a continuous spectrum which represents the absence of light within the spectrum. The solar spectrum contains a series of black lines in an otherwise continuous spectrum.

Emission spectra

Emission spectra may be either line emission, band emission or continuous emission.

- **Line emission:** If gaseous atoms are excited by fast moving electrons (such as in a gas discharge tube) then light of specific frequencies is emitted. When viewed through a spectroscope we see distinct lines which are characteristic of the atoms of that element.
- **Band emission:** This is similar to line emission spectra except that the spectra is due to the excitation of gaseous molecules (rather than atoms). High pressure glowing gas or salts in a flame will give bands of fine lines when viewed through a spectrometer.

- **Continuous emission.** When light from a hot incandescent solid, such as white hot iron, is viewed through a spectroscope a continuous spectrum is seen.

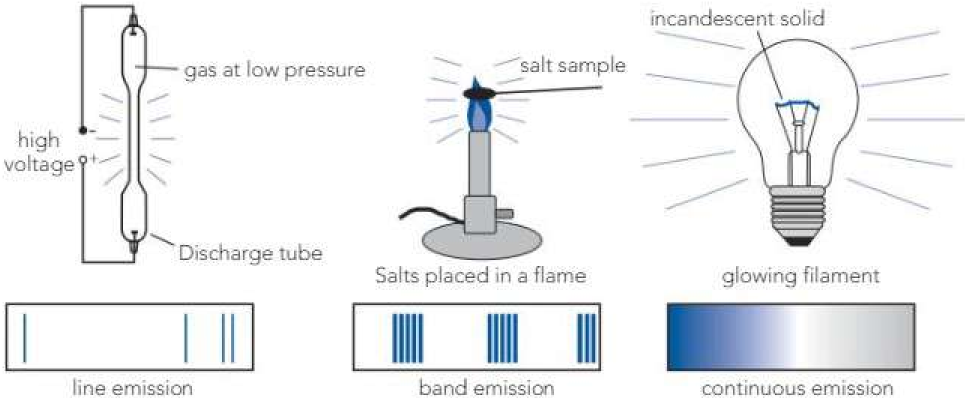


Figure 3.11 Types of emission spectra. Excited gaseous atoms result in line emission. Band spectra is more typical of large molecules. Each band consists of many discrete lines very close together.

Absorption Spectra

Absorption spectra may be either line or band absorption.

- **Line absorption:** When white light is passed through a vapour or some low pressure gas, photons of the frequencies corresponding to the line emission spectrum of that gas will be absorbed. This means that black lines (or an absence of light) will be seen where bright lines would have appeared in an emission spectrum.

  The solar spectrum consists of a continuous emission spectrum crossed by many absorption lines. These black lines are called Fraunhofer lines after their discoverer. They correspond to the emission lines of gases in the sun's outer atmosphere and to some extent the earth's atmosphere.

- **Band absorption:** This occurs in a similar manner to line absorption when light passes through coloured glass or coloured liquid solutions such as potassium permanganate. Dark bands are visible within an otherwise continuous spectrum.

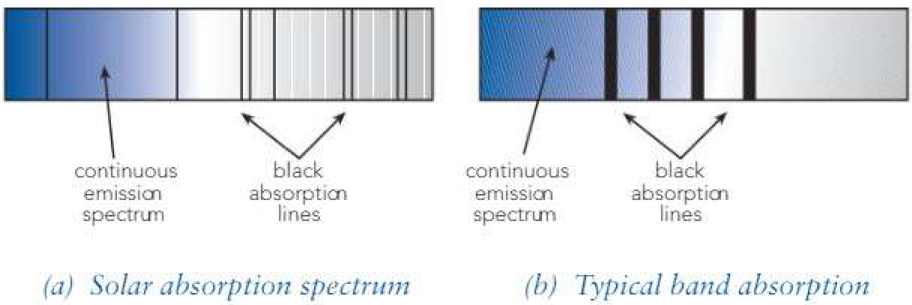


Figure 3.12 Typical absorption spectrum.

Question 3.13

When you look at a hydrogen gas discharge tube you can see a pinkish glow of light. Its visible spectrum however, consists of four distinct lines. Explain.

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Question 3.14

The black absorption lines in the solar spectrum give scientists valuable information about both the sun's and earth's atmospheres. Explain.

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Fluorescence

Fluorescent materials have the ability to absorb ultraviolet light and re-emit it as visible light. This interesting and useful phenomenon relies on the particular energy levels of the atoms of the substance. When the atoms are excited to a higher energy level they may return to the ground state by a series of smaller jumps. This releases photons whose lower energy often corresponds to the visible range. Some common examples of fluorescence are:

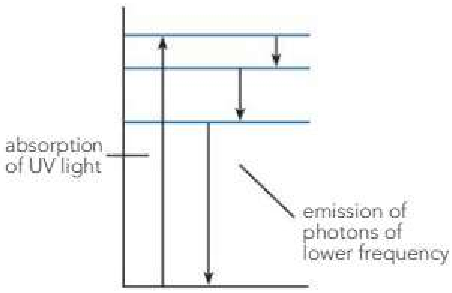


__Figure 3.13__ Fluoresence. An electron is excited to a higher level by absorbing UV light. As it returns to the ground state photons are emitted which are in the visible range.

- **Fluorescent minerals.** Fluorite, which gives the effect its name, and calcite, are two common fluorescent minerals. If ultraviolet light shines on them they will glow. Fluorite appears as fluorescent blue and calcite as fluorescent red, pink, and yellow.
- **Fluorescent tubes.** These are similar to discharge tubes in that a stream of fast moving electrons excites the atoms of the low pressure gas inside the tube. The excited atoms then release ultra-violet light which is absorbed by the white powdered material which is coated on the inside of the tube. This material fluoresces and re-emits the ultra-violet light as visible light.
- **Fluorescent ink.** This is sometimes referred to as invisible ink and is often used for invisible signatures or messages. When an ultra-violet light ("black light") shines onto the ink it becomes visible due to fluorescence.

Band gaps in solids

As we have seen, electrons in isolated atoms occupy specific energy levels or shells. The outermost energy level that they occupy is called the valency shell. In a solid however, the energy levels of the many atoms combine to form allowable energy bands separated by forbidden gaps.

For conduction to occur in solids the electrons from the valence band must move up through an energy gap to the conduction band. In metals this gap is very small and conduction occurs readily. Insulators have large band gaps which limit conduction. Semiconductors have relatively small band gaps and this allows their conducting properties can be readily modified by doping them with suitable impurity materials. Diodes, and in particular light emitting diodes, are a good example of this property.

Light emitting diodes – LEDs

A light emitting diode (LED) is a chip of semiconducting material containing small amounts of impurities so as to create a p-n junction. When a small forward voltage is applied it emits light from this junction. The colour of light produced depends on the particular combination of impurities used. These determine the energy gap of the semiconductor chip and hence the energy of the photons emitted.

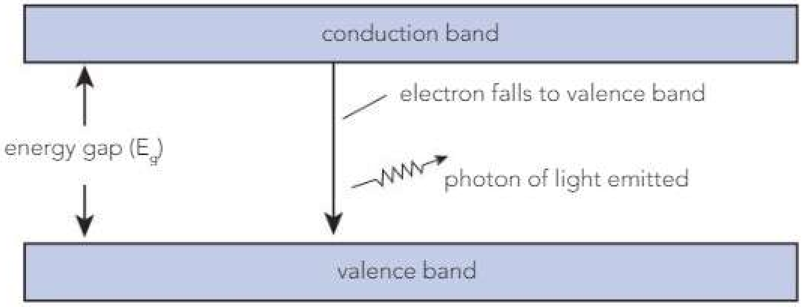


Figure 3.14 Light from an LED. When a small forward voltage is applied to an LED the movement of electrons at the p-n junction causes some electrons in the conduction band to fall to the valence band. The spontaneous emission of photons occurs.

As illustrated in Figure 3.14 above we can see that the photon energy is dependent on the energy gap (E_g). We can determine the wavelength of the radiation using our previous formulae for photon energy as follows.

$$E_{ph} = hf = \frac{hc}{\lambda}$$

$$\lambda = \frac{hc}{E_g}$$

λ	=	wavelength of radiation (m)
h	=	Planck's constant (J s)
c	=	velocity of light (m s^{-1})
E_g	=	energy gap (J)

Worked Example 3.10

(a) An LED using indium gallium nitride (InGaN) has a band gap of 3.25 eV. Determine the wavelength of the light it emits when a suitable small voltage is applied to it.

(b) A yellow light of about 590 nm wavelength is required. Determine the energy gap suitable in an LED to produce this light.

(a)

λ = ?

E_g = 3.25 eV = 5.20×10^{-19} J

h = 6.63×10^{-34} J s

c = 3.00×10^{8} m s^{-1}

$$\lambda = \frac{hc}{E_g} = \frac{(6.63 \times 10^{-34})(3.00 \times 10^{8})}{(5.20 \times 10^{-19})} = 3.83 \times 10^{-7}\ \text{m} \quad \text{or} \quad 383\ \text{nm}$$

(b)

Similarly

$$E_g = \frac{hc}{\lambda} = \frac{(6.63 \times 10^{-34})(3.00 \times 10^{8})}{(5.90 \times 10^{-7})}$$

Suitable energy gap (E_g) $= 3.37 \times 10^{-19}$ J or 2.11 eV

Production of X-rays

X-rays are high frequency electromagnetic waves (or photons) which are produced when high speed electrons strike a metal target. They were first discovered by Roentgen in 1895 while experimenting with a discharge tube. He realised that they were some kind of very penetrating ray but knew little else about them and so decided to call them X-rays.

X-rays are produced in an X-ray tube where:

- electrons are accelerated to very high velocities by voltages of about 50 kV.
- the electrons strike a metal target (usually tungsten) and cause very short wavelength photons to be emitted ($\approx 10^{-11}$ m).

The electrons often undergo several collisions with the metal target while giving up their energy. Each collision results in some loss of energy which results in photons of that energy. Several photons of different energies are produced in this way.

An X-ray spectrum from an X-ray tube will also show characteristic peaks which are related to the metal in the atom. Energetic incoming electrons will sometimes remove electrons from the lower levels (say K shell) of the target metal atoms. Electrons from higher levels within the atom quickly fall to the vacated orbital and consequently release high energy photons (X-rays) of a specific frequency.

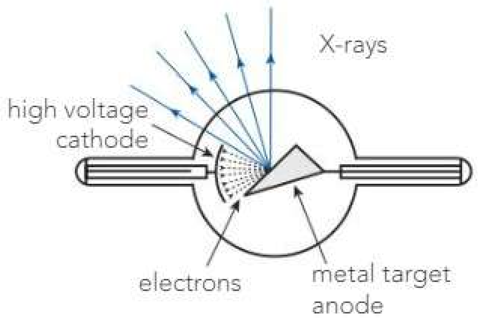


Figure 3.15 X-ray tube.

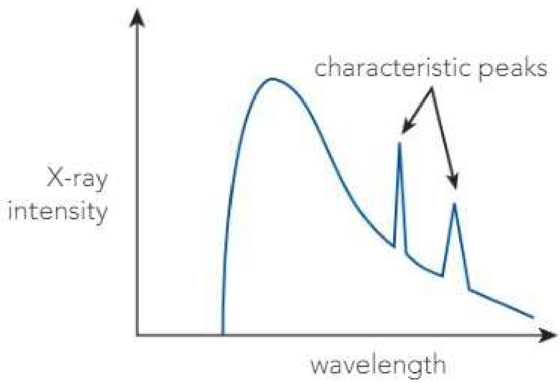


Figure 3.16 X-ray spectrum.

Question 3.15

When ultraviolet light shines on calcite it fluoresces in a variety of colours (red, pink and yellow). In terms of electron transitions explain clearly how this is possible.

___

___

___

Question 3.16

The spectrum from an X-ray tube usually has distinctive peaks which vary with the target metal used. Explain the presence of these peaks.

___

___

___

Worked Example 3.11

A typical X-ray tube is operated at 50 kV. Calculate:

(a) The kinetic energy of the electrons accelerated towards the target anode.

(b) The maximum frequency of the X-ray photons produced.

(a)

V	=	50×10^3 V	W	=	Vq
q	=	1.6×10^{-19} C	$\therefore E_K$	=	$(5 \times 10^4)(1.6 \times 10^{-19})$
E_K	=	?		=	8×10^{-15} J
f	=	?			

This is the kinetic energy of the electrons when they strike the metal target.

(b) Photon energy

$$E = hf$$

$$\therefore f = \frac{E}{h} = \frac{8.0 \times 10^{-15}}{6.63 \times 10^{-34}} = 1.21 \times 10^{19}\text{ Hz}$$

The maximum possible frequency of the X-rays will be $\approx 1.21 \times 10^{19}$ Hz.

Question 3.17

(a) Using the frequency from the previous problem determine the wavelength of a typical X-ray.

(b) How does this compare with the typical wavelength of light? (e.g. blue/green light of wavelength 5×10^{-7} m)

REVIEW QUESTIONS

Chapter 3: Wave particle duality and the Quantum theory

The Nature of Light

1. In Young's double slit experiment it is possible to show that light waves do diffract. Does this evidence support the wave theory or the particle theory of light? Explain your answer.

2. Ultraviolet radiation is far more damaging to the human skin than infrared radiation. What is the likely reason for this? Explain.

3. A microwave oven is rated at 850 W and the wavelength of its radiation is 12.25 cm. Determine:
   (a) the frequency of this radiation,
   (b) the energy of each photon,
   (c) the number of photons it produces each second.

4. Two beams of light, one blue ($\lambda \approx 4.8 \times 10^{-7}$ m) and the other yellow ($\lambda \approx 5.9 \times 10^{-7}$ m) are both rated at 100 W.
   (a) Which beam will emit the greatest number of photons per second?
   (b) Determine the ratios:

   (i) $\dfrac{\text{Photon energy of blue light}}{\text{Photon energy of yellow light}}$

   (ii) $\dfrac{\text{No. photons of blue light}}{\text{No. photons of yellow light}}$

5. One of the TV channels in Perth transmits its programs as follows:
   (i) vision signal 209.24 MHz at 10 kW
   (ii) audio signal 214.74 MHz at 1.0 kW

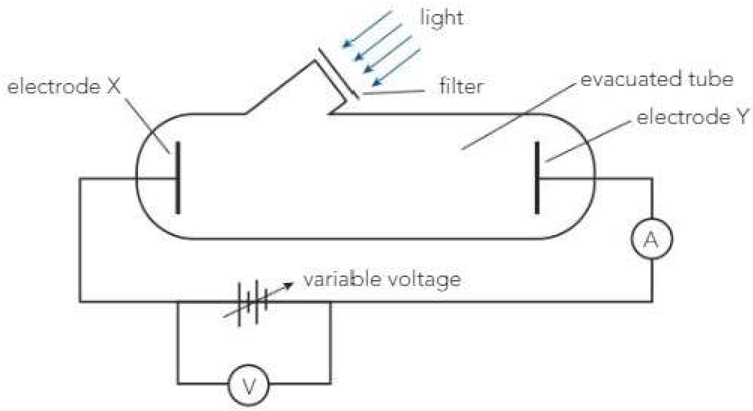
   (a) Determine the wavelengths of each of these signals.
   (b) Which signal consists of photons of higher energy? Calculate this energy.
   (c) How many photons per second leave the sound transmitter?

6. Domestic microwave ovens operate on a frequency of 2450 MHz while air traffic control radar operates at approximately 2800 MHz. Compare the wavelengths and photon energies of these two microwave sources by determining appropriate ratios.

7. The primary radar system for tracking aircraft approaching airports is within the S-Band of frequencies, that is, between 2700 and 2900 MHz. Peak output power is 600 kW during pulses of 1.00 μs duration.
   (a) If a frequency of 2800 MHz is used determine:
      (i) the wavelength of the radar pulses,
      (ii) the photon energy associated with these microwaves.
   (b) How many photons are transmitted in a single radar pulse?

8. A typical continuous wave laser using a helium/neon gas mixture emits light of 6.33×10^{-7} m wavelength.
   (a) Determine the frequency of this light. To what colour does it correspond?
   (b) What are the photon energies being emitted?
   (c) If this laser can emit 5×10^{18} photons per second what is its power rating?

9. The experimental arrangement shown below is similar to that used by Lenard to investigate the photoelectric effect. Answer the following questions.



(a) Which electrode contains the test metal? Is this the anode or cathode?
(b) Explain the purpose of the filter and why it is necessary.
(c) While testing a particular metal with yellow light ($\lambda \approx 590$ nm) a current of 1.35 mA was recorded at the ammeter. The voltage setting for the anode was constant at 1.50 V.

Describe what change, if any, would occur to the current flowing through the ammeter if any of the following was done. Give a brief explanation for your answer.

(i) A yellow light of double intensity was used.
(ii) Blue light ($\lambda \approx 470$ nm) of the same intensity as the yellow light was used.
(iii) The voltage for the anode was changed to a constant value of 3.0 V.

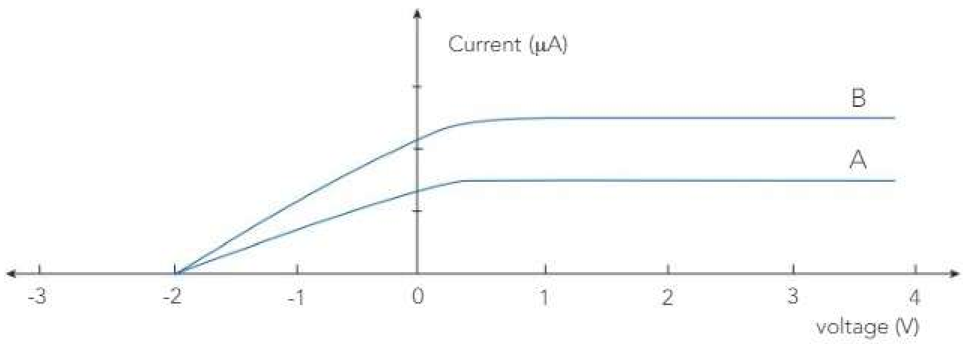
10. An unknown metal was tested with an experimental arrangement similar to that in the previous question. It was found that a photo current could be produced with green or violet light but not with yellow light.

Two other colours tested were red and blue light. Are these colours likely to produce a photocurrent? Explain your answer.

11. In an experiment using a photocell with a lead metal cathode a photocurrent was produced when a light of wavelength 260 nm is used. It was found that the photoelectron current could be reduced to zero by applying a stopping voltage of at least 0.550 V. Determine:

(a) The energy of the incident photons.
(b) The maximum kinetic energy of the photoelectrons.
(c) The work function of lead metal.
(d) The threshold frequency for this metal.

12. An experiment to investigate the photoelectric effect was carried out using a photocell containing a potassium metal cathode. Ultraviolet light of 290 nm wavelength was directed onto the lithium cathode. The results of the variation in photocurrent that occurred with changes in voltage are graphed below. Results were obtained for two different light intensities A and B.



Answer the following.

(a) The graph shows two curves, A and B. Which one relates to the higher intensity light? Explain your answer.

(b) The experiment was repeated using a light source of a slightly longer wavelength but of the same light intensities as previously. On a copy of the graph above sketch the likely result. Explain this result.

(c) From the graph determine the stopping voltage. Use this to find:

(i) The maximum kinetic energy of the photoelectrons.

(ii) The work function for potassium metal.

(iii) The threshold frequency for this metal.

13. Louis de Broglie first suggested that particles can behave like a wave. This phenomenon is not easily observable for everyday objects.

(a) Explain why it was difficult to verify the de Broglie's theory.

(b) Determine the de Broglie wavelength for the following and comment.

(i) A person of mass 71.0 kg running at 12.0 m s^{-1}

(ii) A 1.25 tonne car moving at 60.0 km h^{-1}

(iii) An electron accelerated from rest by 150 V.

14. An LED containing gallium arsenide phosphide (GaAsP) is listed as having a band gap of 2.25 eV.

(a) Explain what is meant by a band gap when referring to LEDs.

(b) Determine the wavelength of the light this LED will emit when in use.

(c) Check Table 3.1 to see what approximate colour this is. If a red colour is required instead, should an LED with a larger or smaller band gap be used?

Spectra

15. The Bohr Theory of the atom states that electrons can only exist in specific energy levels. If an atom absorbs energy, its electrons are temporarily at a higher energy level and the atom is said to be in an excited state.

(a) Describe three ways by which an atom can be caused to be in an excited state.

(b) By what process can an atom lose its excited state? To what state does it go to?

16. Bohr predicted the energy levels of a hydrogen atom by using the relationship:

$$E_n = \frac{-13.6 \text{ eV}}{n^2} \qquad n = 1, 2, 3, \ldots.$$

(a) Use this relationship to find the energies of the fifth and sixth energy level of the hydrogen atom (E_5, E_6).

(b) Determine the wavelength of a photon that would be emitted by an electron transition from E_6 to E_5.

(c) In which part of the electromagnetic spectrum does this photon belong?

17. The first four energy levels of an atom are shown below.

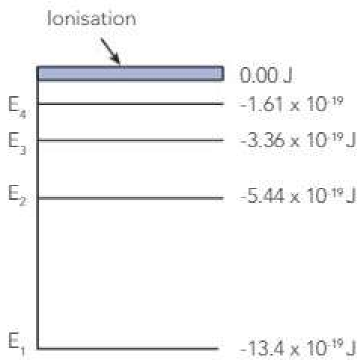
(a) Why are the energies indicated as negatives?

(b) What minimum energy would be required to:

(i) cause this atom to attain an excited state,

(ii) cause this atom to become ionised?

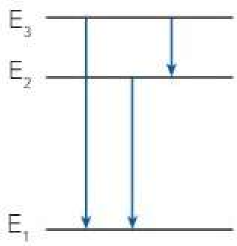
(c) If the atom is excited to the E_3 level, what are the possible photon energies emitted thereafter?
Determine the maximum frequency of these photons.



18. The first three energy levels of a sodium atom are shown below. The electron transition between E_2 and E_1 result in visible light ($\lambda \approx 5.89 \times 10^{-7}$ m) while that between E_3 and E_1 results in ultraviolet light ($\lambda \approx 3.88 \times 10^{-7}$ m).

(a) Determine the wavelength of the photon which would be released by an electron transition between E_3 and E_2.

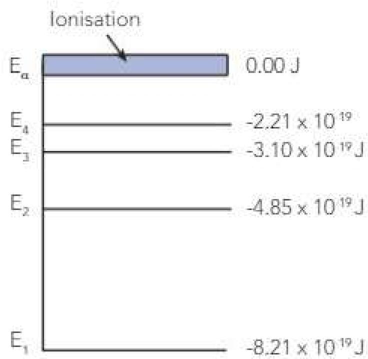
(b) To which region of the e/m spectrum does this photon belong?



19. A few of the energy levels of an atom are shown right.

(a) If this atom is in the ground state what minimum frequency photon will cause it to be ionised?

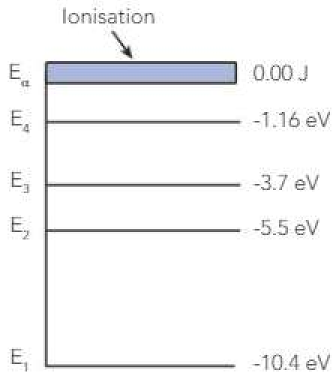
(b) How many different frequency photons are possible when ionised atoms of this element return to the ground state? Show each possible transition that results in the emission of a photon on the diagram.



(c) Determine the longest wavelength in the emission spectrum of this atom.

20. The first four energy levels of a hydrogen atom are –13.6 eV, –3.4 eV, –1.5 eV and –0.85 eV.
(a) If this atom is bombarded by photons with energies up to 12.0 eV, which photon energies would be absorbed?
(b) If this atom was instead bombarded by electrons with energies up to 12.0 eV how would the interaction between the atom and the electrons be different to that with the photons?
(c) If this atom was in an excited state with its electron at the E_3 level, what would be the highest frequency photon it could emit as it returned to the ground state?

21. The first four energy levels of a mercury atom are shown at right. In an experiment, atoms of mercury are bombarded with a stream of electrons whose energy of 7.5 eV. Determine:
(a) the possible energies of the scattered electrons,
(b) the possible energies of the photons emitted,
(c) the electron energy that is required to ionise atoms of mercury.



22. Atoms of mercury are to be bombarded with photons. Use the energy levels shown in the previous question to answer the following:
(a) What would occur if a stream of photons of 7.5 eV were used to bombard mercury atoms?
(b) If all photon energies up to 10.0 eV were used, which photons would be absorbed?
(c) In this latter case which photon energies would be emitted?

23. Minerals such as calcite and fluorite can often be fluorescent due to the presence of rare earth elements which can absorb short wavelength light and then re-emit it at longer wavelengths.
In one such occurrence photons of 1.15×10^{15} Hz are absorbed and then the energy is released in two separate photons. If one of the photons emitted has an energy of 2.07 eV determine:
(a) The energy of the other photon emitted,
(b) The wavelengths of the two photons emitted,
(c) The part of the e/m spectrum or colour that these photons belong to.

24. When taking chest X-rays the voltage required can be a high as 120 kV. The current drawn is 100 mA while the duration of the X-ray is 0.040 s. Determine:
(a) The kinetic energy of the electrons accelerated towards the target anode.
(b) The maximum possible frequency of the X-rays produced.
(c) Assuming that the average photon energy is half of the maximum energy, calculate the number of photons you are exposed to during a typical chest X-ray.

4 SPECIAL RELATIVITY

SYLLABUS CHECKLIST

SCIENCE UNDERSTANDING – SPECIAL RELATIVITY

- ☐ observations of objects travelling at very high speeds cannot be explained by Newtonian physics. These include the dilated half-life of high-speed muons created in the upper atmosphere, and the momentum of high-speed particles in particle accelerators
- ☐ Einstein's special theory of relativity predicts significantly different results to those of Newtonian physics for velocities approaching the speed of light
- ☐ the special theory of relativity is based on two postulates: that the speed of light in a vacuum is an absolute constant, and that all inertial reference frames are equivalent
- ☐ motion can only be measured relative to an observer; length and time are relative quantities that depend on the observer's frame of reference

  This includes applying the relationships:

$$l = l_o\sqrt{(1 - \frac{v^2}{c^2})} \qquad t = \frac{t_o}{\sqrt{(1 - \frac{v^2}{c^2})}} \qquad u = \frac{v + u'}{1 + \frac{v u'}{c^2}} \qquad u' = \frac{u - v}{1 - \frac{u v}{c^2}}$$

- ☐ relativistic momentum increases at high relative speed and prevents an object from reaching the speed of light

  This includes applying the relationships:

$$p_v = \frac{m v}{\sqrt{(1 - \frac{v^2}{c^2})}}$$

- ☐ the concept of mass-energy equivalence emerged from the special theory of relativity and explains the source of the energy produced in nuclear reactions

This includes applying the relationships:

$$E = \frac{m c^2}{\sqrt{(1 - \frac{v^2}{c^2})}}$$

4.1 FRAMES OF REFERENCE AND RELATIVE MOTION

All motion is relative. But relative to what? In our normal everyday experience we usually consider motion relative to the ground. However the motion of a body can be viewed from different frames of reference.

For example, when two cars are both travelling in the same direction on a freeway and at the same speed, their velocity relative to each other is zero. If the cars were in adjoining lanes the occupants of each car would view the others from their own frame of reference and perceive zero motion. Interestingly if one of the cars then changed their speed slightly, relative to the ground, the passengers in the adjoining car may think that it is their car that has changed speed. Of course if they look outside at their surroundings they would see that their motion relative to the ground has not changed.

These observations are best explained by considering the concept of *inertial reference frames*. This idea was first introduced by Galileo and later expanded on by Newton. Frames of reference which are non-accelerating, that is, they have a constant velocity or are at rest, are called inertial reference frames.

The *principle of relativity* states that the laws of physics are the same in all inertial frames and do not depend on their velocity. For example, if you bounce a ball inside a train moving at constant velocity it will behave exactly the same as it would if you did it at home in your family room. The fact that the train is moving makes no difference to the physics of the situation. No frame of reference gives results that are different to another.

Galileo further stated that you cannot measure the velocity of your frame of reference without comparing it to another. For example, you would not be able to tell the train is moving without looking outside. He also stated that there is no absolute frame of reference, that is, there is no reference frame with zero velocity. Hence all motion is relative.

Figure 4.1** (a) **Relative motion.
You are walking towards the front of a bus at 4.0 kmh^{-1} while the bus is travelling due East at 60 kmh^{-1}. Your velocity relative to the bus (your frame of reference) is 4.0 kmh^{-1} East. However your velocity relative to the ground, as may be viewed by an onlooker standing on the side of the road, is 64.0 kmh^{-1} East.

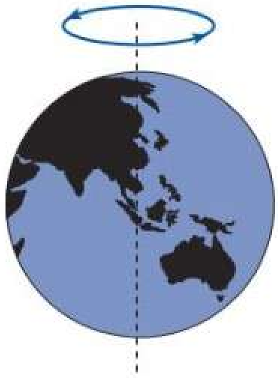


Figure 4.1 (b) Relative motion. *The Earth is spinning on its axis, from West to East, once every 23 h and 56 min. This means that a point on the equator is moving at approximately 1675 kmh^{-1} relative to "space". This is without considering the motion of the Earth as it orbits the sun and as it moves as part of the motion of our solar system and our galaxy.*

Relative velocities

Reference frames (co-ordinate systems) are a useful concept in comparing measurements, such as velocities, made by two observers moving relative to each other. If we consider two reference frames S and S´, as shown below, each point in S (x, y, z) has a corresponding point in S´ (x', y', z').

Consider an event occurring in frame S´ as viewed by an observer in frame S. If frame S' is moving away from frame S with a velocity v as shown in Figure 4.2, then the relation between the corresponding points is given by:

$$x = x' + vt' \qquad y = y' \qquad z = z' \qquad t = t'$$

This is known as the *Galilean transformation*. In this case it simply indicates that point x' has moved away from x, in the x direction by an amount vt. It is assumed that the reference frames were both at the origin at $t = 0$, the clocks are synchronised and that they are running at the same rate. The Galilean transformation only holds for velocities much less than the speed of light as we shall see later.

From the equations above it is possible to show that:

$$u = v + u'$$

u' = velocity of an object moving in frame S´
u = velocity of that same object as viewed from frame S
v = relative velocity between frames S and S´

The inverse of the equation above, $u' = u - v$, applies for an object moving in frame S as seen from frame S´. Essentially these equations show that we can simply add the velocities as vectors.

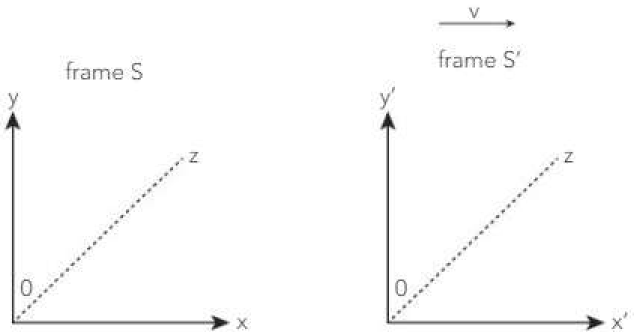


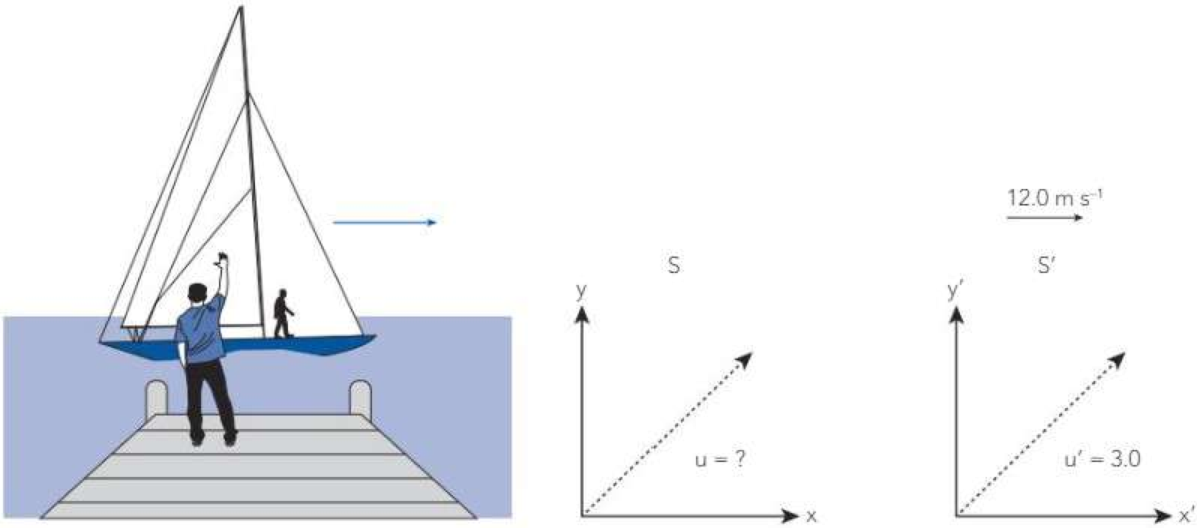
Figure 4.2 *Two reference frames (co-ordinate systems) are shown. Reference frame S´ is moving away from frame S with a velocity v. From the point of view of S´, S is moving away with a velocity of –v.*

Worked Example 4.1

Matt is watching a sailboat from a nearby jetty as it moves directly away from him at 12.0 m s^{-1} due east. He waves to his friend John who is walking to the front of the sailboat at 3.0 m s^{-1}. Answer the following using the Galilean equations and then also by using vectors.

(a) Determine John's velocity relative to Matt.

(b) A little later John turns around and begins to run to the back of the sailboat at 5.0 m s^{-1} to wave to Matt. Determine Matt's velocity relative to John.



Using the Galilean transformation equation

(a) We consider Matt to be in one reference frame, S, and the ferry boat and John in S´ as shown above. We will nominate east as a positive direction. Hence we have:

u = the velocity of John relative to Matt. = ?

v = the velocity of frame S' relative to frame S. = 12.0 m s^{-1}

$u´$ = the velocity of John relative to frame S´. = 3.0 m s^{-1}

To solve: $u = v + u´$

John's velocity relative to Matt u = 12.0 + 3.0 = 15.0 m s^{-1} east

(b) We need to use the inverse equation as we are looking for Matt's velocity in S as seen from S´.

$u´$ = the velocity of Matt relative to John. = ?

v = the velocity of frame S relative to frame S´. = - 12.0 m s^{-1}

u = the velocity of John relative to frame S' = - 5.0 m s^{-1}

To solve: $u´ = u - v$

Matt's velocity relative to John u = - 5.0 – (- 12) = 7.0 m s^{-1} east

Using vectors

(a) As above and east positive $u = v + u´$

u = ?

v = 12.0 m s^{-1} $\xrightarrow{12}$

$u´$ = 3.0 m s^{-1} $\xrightarrow{3}$

$\xrightarrow{12}\xrightarrow{3}$

$\xrightarrow[15]{}$

= 15 m s^{-1} east

(b) $u' = ?$

$v = -12.0 \text{ m s}^{-1}$ $\xleftarrow{-12}$

$u = -5.0 \text{ m s}^{-1}$ $\xleftarrow{-5}$

$u' = u - v$

$\xleftarrow{-5}\xrightarrow{7}$

$\xrightarrow[-(-12)]{}$

$= 7\ m\ s^{-1}$ *east*

Question 4.1

For the following assume that you are in a bus which is moving at 50 km h^{-1} due West while you are moving towards the front of the bus at 2.0 km h^{-1}. There is also a car travelling at 70 km h^{-1} which has just passed the bus travelling in an opposite direction and now some distance away.

Determine your velocity relative to:

(a) the bus ________________________________

(b) the ground ________________________________

(c) the car ________________________________

Question 4.2

An aircraft is flying at 650 km h^{-1} relative to the ground and heading due North. Determine the velocity of the aircraft as viewed by an observer on the ground if the aircraft encounters a 100 km h^{-1} wind from:

(a) the North ________________________________

(b) the South ________________________________

(c) the West ________________________________

The Speed of Light

As we know the speed of light is extremely fast. Early attempts to measure it proved difficult due to the very small time intervals involved and lack of precise timing equipment. Galileo attempted to measure the time delay between uncovering a bright lantern on one hilltop and seeing a lantern on an opposing hilltop uncovered by an assistant in response. The time delay was not measurable.

In 1676, the Danish astronomer Olaus Roemer provided the first real estimate of the speed of light when he made careful observations of the time between eclipses of Jupiter's moon Io. The times were measurably shorter when Jupiter was closest to Earth. He argued that this time difference was due to the lesser distance light had to travel when Jupiter was closer. Using estimates of the Earth's orbit about the Sun and the observed time difference of the eclipses a value for the speed of light of 2.26×10^8 m s^{-1} was obtained.

Much more accurate measurements of the speed of light were made during the 19th century by Fizeau, Foucault and other scientists with values close to 3.0×10^8 m s^{-1}. Albert Michelson achieved very precise measurements using an intense light source and a rapidly rotating octagonal mirror. A light beam was deflected by the rotating mirror to a stationary mirror on a mountainside some 35 km away. The reflected beam returned to the rotating mirror and was visible to an observer for particular rotation frequencies. The rotation frequency and distances involved were used to calculate the speed of light. His experiments were carried out with improving accuracy over many years, 1877 to 1927, with a final result of 2.99796×10^8 m s^{-1}. The accepted value today is 2.997925×10^8 m s^{-1} although for our calculations we will simply use 3.00×10^8 m s^{-1}.

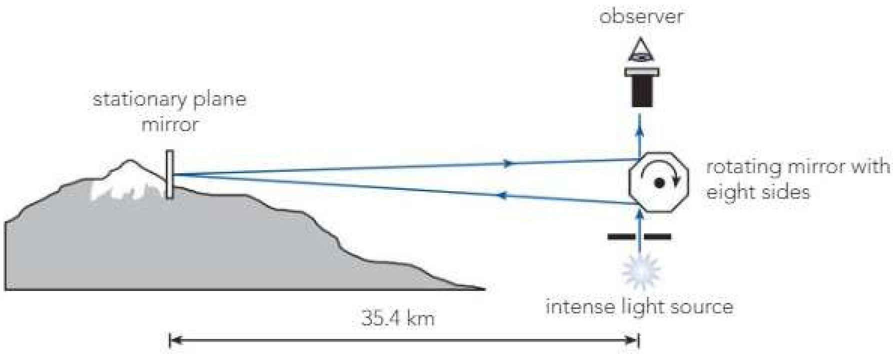


Figure 4.3 Measuring the speed of light. An intense beam of light is reflected off one of the sides of a rapidly rotating octagonal mirror to a stationary mirror some 35.4 km away. The returning beam of light will be reflected by one of the other sides of the octagonal mirror to an observer for a particular rotational frequency.

Question 4.3

Galileo attempted to measure the time taken for light from a lantern to travel to a distant hill and back.

(a) If we assume that the hills were 8.00 km apart calculate the time interval that Galileo was trying to measure.

___

(b) Suggest two main reasons why a value for the speed of light could not be determined.

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The Michelson and Morley experiment

The wave theory of light was well established in the later part of the 19^{th} century. In 1864 Maxwell proposed that in fact light was an electromagnetic wave which travels at 3.0×10^8 m s^{-1} in a vacuum. His theory also showed that this speed was independent of any motion of the source or the observer, an idea which did not fit with classic relativity theory. It was thought that the speed of light would depend on your frame of reference.

An assumption held by physicists at the time was that a medium must exist for light waves to travel through, just as air acts as a medium for sound waves. They called this proposed but undetected medium the *luminiferous aether*. Perhaps it could explain why the speed of light was the same for any observer.

In 1887 Michelson and Morley carried out an ingenious experiment to try and detect this aether. Using an array of mirrors they compared the time taken by a beam of light to travel identical distances in different directions. If the aether existed, through which the Earth was travelling at about 30 km s^{-1}, then the time taken for light to travel back and forth in the direction of the aether should be slightly longer than at right angles to it. No such difference could be found.

The instrument used by Michelson and Morley was a very sensitive interferometer which worked by splitting a light beam with a half silvered mirror and allowing the resulting two beams to travel to the observer by two equidistant paths at right angles to each other. As the two light beams recombined an interference pattern was produced which would indicate any path difference. A path difference of a whole number of light waves would result in a bright fringe whereas one including half waves would give a dark fringe.

We can see that the interferometer used had the capability of detecting any aether if present. Yet repeated experiments consistently gave a null result. This was unexpected and led to further experiments in the hope of finding this elusive aether and also to various explanations as to why it was unobserved. It was some years later, in 1905, that a theory consistent with the Michelson-Morley result was proposed by Einstein.

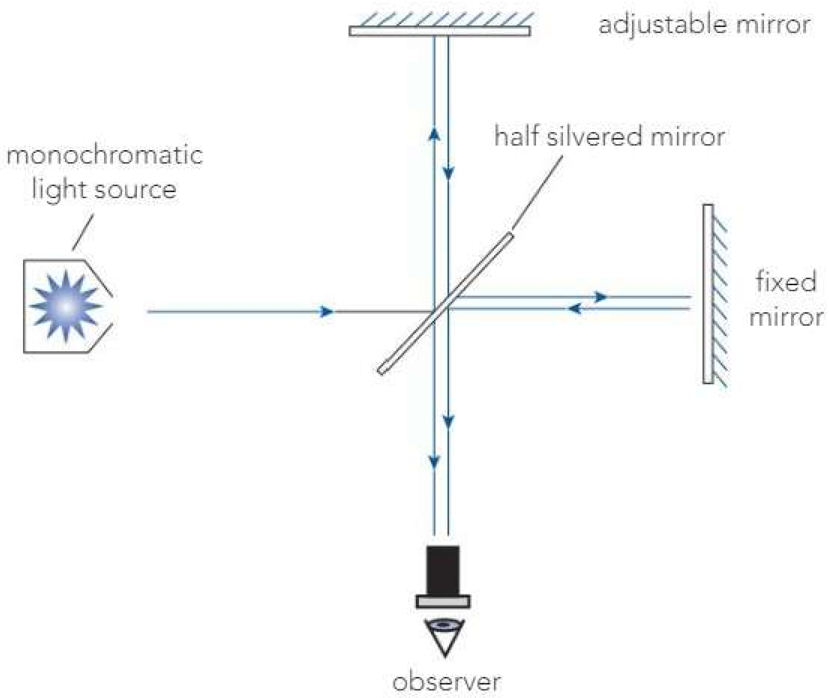


Figure 4.4 A simplified diagram of the Michelson-Morley interferometer. A monochromatic beam of light is split by the half silvered mirror. As the two light beams reach the observer an interference pattern is observed which varies with any path difference. Note that the two paths are at right angles.

4.2 THE SPECIAL THEORY OF RELATIVITY

In 1905 Albert Einstein announced his Special Theory of Relativity. This introduced many new concepts such as how time is affected by motion in space (space-time) and how mass and energy are related (mass-energy equivalence). The theory also proposed that there is no absolute frame of reference in the universe.

Einstein's theory is now well established. It is more often associated with the explanation of the behaviour of particles moving at speeds close to that of light but it just as accurately applies to every day motion around us. At low speeds, those much less than the speed of light, both Newton's laws and Einstein's theory are in agreement. Hence Newton's laws are essentially correct at non relativistic speeds and work very well to describe everyday motion and planetary motion.

Einstein's theory is based on two fundamental assumptions or postulates:

First postulate – The laws of physics are the same in all inertial (that is, non-accelerated) frames of reference. This statement simply means the laws of physics are the same whether a particular frame of reference is stationary or in uniform relative motion to another.

For example, if you juggle a tennis ball inside a moving bus it will behave the same as when the bus is stationary. Or if you were to carry out some physics experiments in the cabin of a fast moving train you would get exactly the same results as when the train is moving at a slower speed or stationary. However this postulate does not apply if there is any acceleration.

Second postulate – The speed of light is the same in all inertial frames of reference. Its value, c, is the same for all observers and does not depend on the relative motion of the source or the observer. This statement challenges our normal experience of relative velocity since the speed of light is always the same to an observer despite any relative movement towards or away from the light source.

For example, consider the following thought experiment illustrated below in Figure 4.5. You are in a spaceship travelling at half the speed of light, $0.5c$, away from a light source such as the sun. To your surprise you would find that the speed of the light going past you would still be c. If you then turned around and travelled towards the light source at half the speed of light you would find, incredibly, that the speed of the light coming towards you has not changed and would still be c.

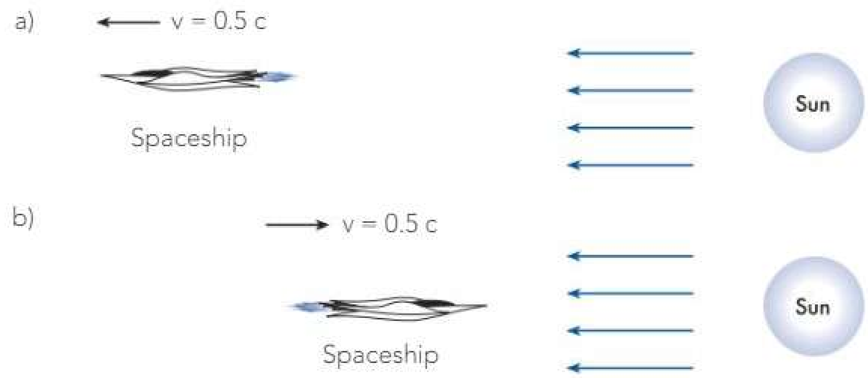


Figure 4.5 *(a) The speed of light is constant. An imaginary spaceship travelling away from the Sun with a speed of 0.5c would measure the speed of light going past it to be* 3.0×10^8 *m s*$^{-1}$ *or c. (b) If the spaceship then turns and moves towards the Sun with a speed of 0.5c then remarkably the measured speed of the light it is encountering from the Sun is still* 3.0×10^8 *m s*$^{-1}$ *or c.*

The idea that the speed of light is constant regardless of the motion of either the source or the observer is in agreement with the results of the Michelson-Morley experiments carried out in 1887. Einstein reasoned that the constancy of the speed of light unifies space and time. We will see that this also leads to the not so easily understood ideas of *time dilation* and *length contraction*.

Time Dilation

Einstein considered that motion through space affected and slowed our motion through time. This effect, called time dilation, is not noticeable at the usual speeds we encounter but is very significant at speeds closer to the speed of light.

To illustrate this idea we can consider the following hypothetical situation. A racing driver has two mirrors set up on opposing sides of his speeding car so that pulses of bright light can be reflected back and forth as in Figure 4.6. He has a watch which is able to accurately measure the time taken for these pulses of light to travel from one mirror and back again.

A stationary observer watches the car speeding past and is also able to make accurate measurement of the time taken for the light pulses to travel from one mirror and back again. However, each person will have had a different view of the motion of the light beam.

From his frame of reference, the driver sees the light pulse move back and forth in the same line while the stationary observer sees the light move through a longer triangular path. Since the speed of light is constant for both viewers it means that the time measured by the stationary observer must be longer.

The time measured by the driver is referred to as *proper time* as it is measured in the drivers inertial reference frame. The stationary observer would measure a longer time for the same event. Of course this time dilation is only observable when inertial reference frames are moving at near light speeds relative to each other.

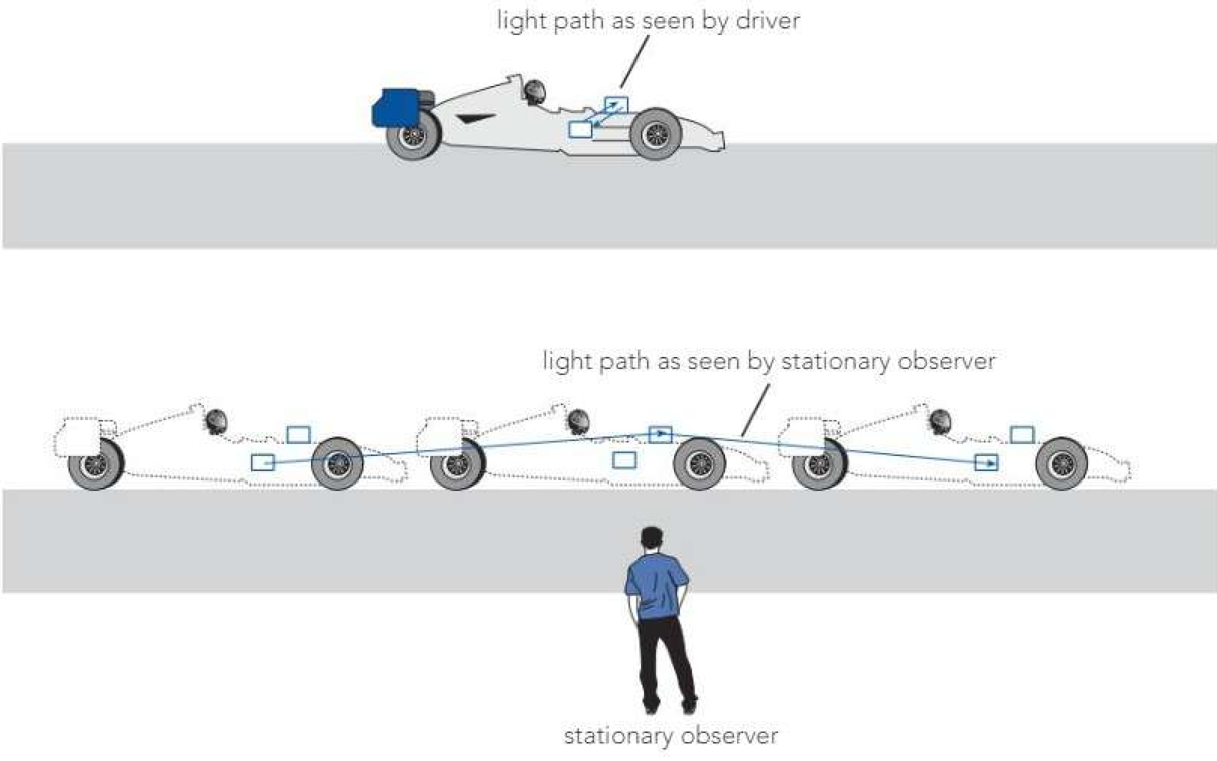
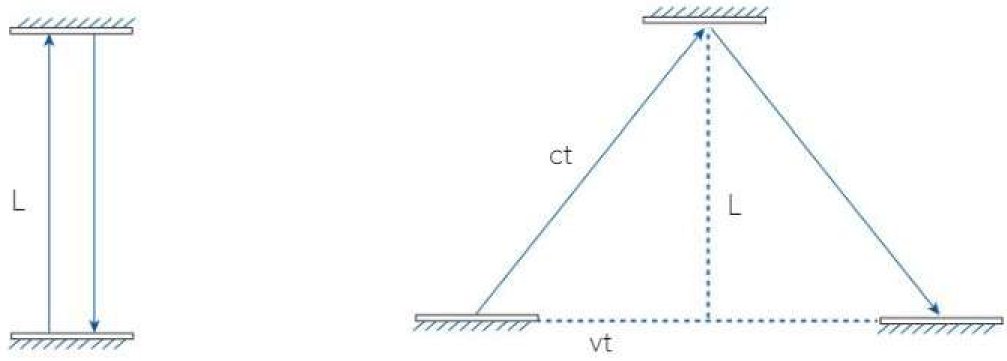


Figure 4.6 *(a) A speeding driver measures the time light pulses take to travel from one mirror and back again. He sees the path of the light as being directly back and forth in one line. His time measurement is referred to as proper time as it is measured within his inertial reference frame. (b) The path of the light as viewed by a stationary observer is longer and follows a triangular path. Since the speed of light is constant for both observers the time measured by the stationary observer is longer. The stationary observer would consider the driver's watch as being slow.*

Calculating time dilation

We can consider the hypothetical situation shown in Figure 4.6 in a mathematical way using geometry. The diagram below shows the path taken by the light pulse from one mirror to the other as seen by the driver and the stationary observer.

For the driver the light travels a distance L in a time of t_o. For the stationary observer the distance is the hypotenuse of a right triangle in a time of t. The base of the triangle is the distance travelled by the driver to the right at a velocity v. In both cases the speed of light is c and hence the distance $L = ct_0$ and the hypotenuse $= ct$.



Considering first half of light path:

For the driver:			For the stationary observer:		
distance	=	L	distance	=	ct
time	=	t_o	time	=	t
light speed	=	c	light speed	=	c

Figure 4.7 Time dilation – comparing observations mathematically.

From the diagram above, Figure 4.7, we can see using Pythagoras that:

$$(ct)^2 = L^2 + (vt)^2$$
$$c^2t^2 = c^2t_o^2 + v^2t^2$$
$$t^2 = t_o^2 + \left(\frac{v^2}{c^2}\right) t^2$$

This can be shown (see question 4.4) to give the time dilation equation below.

$$t = \frac{t_o}{\sqrt{(1 - \frac{v^2}{c^2})}}$$

t_o = time measured in the moving frame of reference (proper time)
t = time measured by a stationary observer
v = velocity of moving frame of reference
c = velocity of light (same in both cases)

Worked Example 4.2

A spaceship passing by Earth sends a signal pulse of 1.00 s duration every 5.00 minutes. The velocity of the spaceship is 0.40 c. For a stationary observer on Earth, find:
(a) The time duration of these signals
(b) The frequency of the signals.

(a) The pulse time duration measured on the spaceship, t_o, is 1.00 s. To the observer on Earth the spaceship clock will appear slow. The time duration, t, as measured on Earth is given by the dilation formula.

$$t = \frac{t_o}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$= \frac{1.00}{\sqrt{1 - \frac{(0.40c)^2}{c^2}}}$$

$$= \sqrt{\frac{1.00}{0.84}}$$

$= \quad 1.09$ s (pulse duration)

(b) The arrival of the pulses on Earth will also appear to be further apart. The time would be longer by the same factor as shown.

Time between pulses on Earth $= 5.00 \times 1.09 = 5.45$ m

Frequency of signals on Earth will be one every 5.45 minutes.

Question 4.4

(a) Use the information from Figure 4.7 and Pythagoras to show that:

$$t = \frac{t_o}{\sqrt{1 - \frac{v^2}{c^2}}}$$

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(b) Hannah observes Chelsea's spaceship going past at a velocity of 0.25 c. She waves to Chelsea at the rate of 40.0 waves per minute. Use the dilation formulae to determine how many waves per minute Chelsea would see.

____

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Length contraction

Like time, length measurements are different for inertial reference frames with relative motion between them. *Proper length* is the length measured in the observer's frame of reference. The length of a moving object will always appear shorter (in the direction of the motion only) when measured by a stationary observer.

Again, to illustrate the concept, we can consider the hypothetical situation of our racing driver set up with two mirrors racing past a stationary observer. Importantly, in this case, the mirrors are set up in the line of motion of the car. Pulses of bright light are reflected back and forth as shown in Figure 4.8.

This time we are interested to see if the measured length, L, between the mirrors, is the same for the driver as it is for the stationary observer. The actual measurement of length is made indirectly by noting the time taken for each light pulse journey. This is done since it is not possible to measure the position of the two end points simultaneously and allows for the fact that the mirror positions change during measurements.

For the driver, the light travels a distance $2L_o$ in a time of t_o hence the length is given by ct_o. This is the proper length. Similarly, for the stationary observer, the light travels a length of $ct_1 + ct_2$ in total time t. In both cases the speed of light, c, is used.

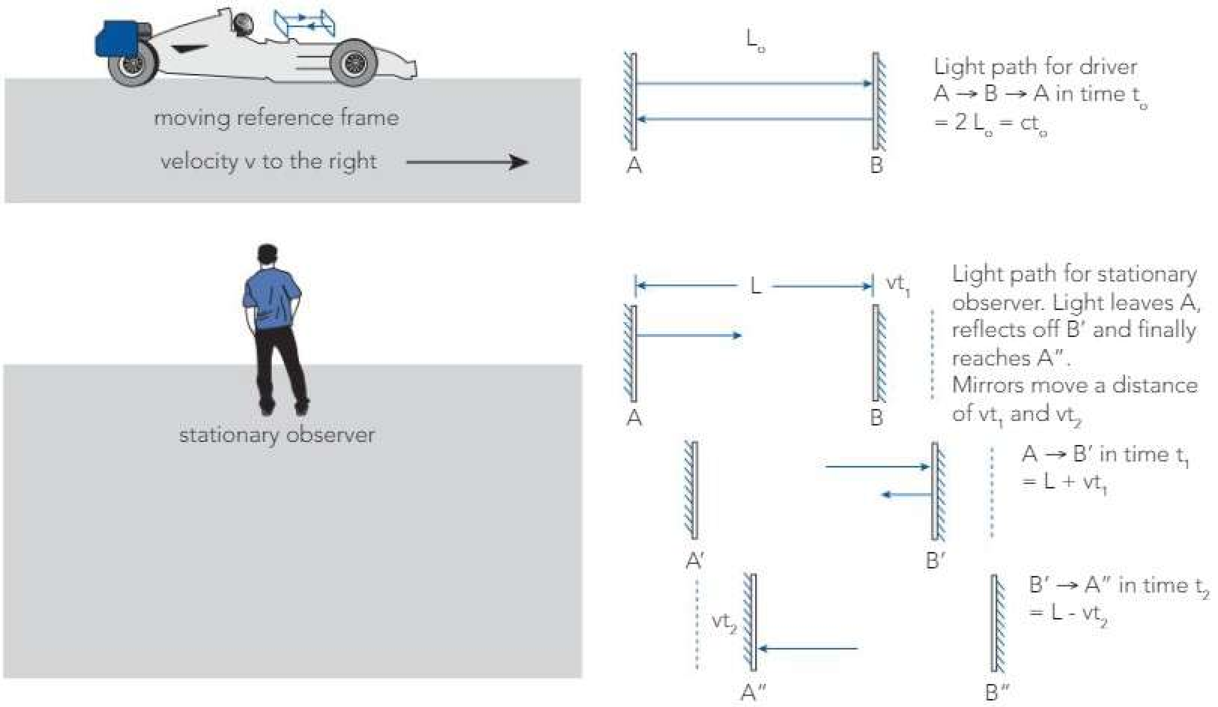


Figure 4.8 Length contraction – comparing observations mathematically.

From the diagram above we can see that:

For the driver – the total distance light travelled in the time interval to is:

In time t_o $A \rightarrow B \rightarrow A = 2L_o = ct_o$

For the stationary observer – the total distance light travelled in the time intervals t_1 and t_2 are:

In time t_1 $A \rightarrow B' = ct_1 = L + vt_1$

In time t_2 $B' \rightarrow A'' = ct_2 = L - vt_2$

Where vt_1 and vt_2 are the distances that the mirrors moved.

$$\text{Total time} \quad t = t_1 + t_2 = \left(\frac{L}{c-v}\right) + \left(\frac{L}{c+v}\right) = \frac{(c+v)L + (c-v)L}{(c-v)(c+v)}$$

$$t = \frac{2\,cL}{c^2 - v^2} = \frac{2\,L}{(c)\left(1 - \frac{v^2}{c^2}\right)}$$

By applying the time dilation equation to the above (see question 4.5) we will get the *Lorentz equation* as shown below.

$$l = l_o\sqrt{1 - \frac{v^2}{c^2}}$$

l_o = length measured in the moving frame of reference (proper length)
l = length measured by a stationary observer
v = velocity of moving frame of reference
c = velocity of light (same in both cases)

Worked Example 4.3

A spaceship passing by Earth at a velocity of 0.55 c is 120 m long and 25.0 m wide.

(a) For a stationary observer on Earth what will be the apparent dimensions of the spaceship?

(b) To an observer on the spaceship Earth appears to be quite egg-shaped rather than spherical. Give a reason for this observation. By what factor would the Earth appear longer than wider?

(a) The length of the spaceship would be shorter since it is moving in that direction. The width will not change as there is no relative movement to the Earth in that direction.

$$
\begin{aligned}
l &= l_o\sqrt{(1 - \frac{v^2}{c^2})} \\
&= (1.20 \times 10^2)(\sqrt{1 - (\frac{0.55c}{c})^2} \\
&= (1.20 \times 10^2)(\sqrt{0.698}) \\
&= 1.00 \times 10^2 \text{ m}
\end{aligned}
$$

The dimensions of the spaceship will appear to be 100 m long by 25.0 m wide.

(b) To an observer on the spaceship the Earth appears to be moving past them with a velocity of 0.55c. Hence it will appear smaller in the direction of their relative motion.

The Earth's diameter in this direction will be reduced by a factor given by the Lorentz equation:

$$
\begin{aligned}
l &= l_o\sqrt{(1 - \frac{v^2}{c^2})} \\
l &= l_o(\sqrt{1 - (\frac{0.55c}{c})^2} \\
l &= 0.835\, l_o
\end{aligned}
$$

The Earth's ellipsoid shape will be in the ratio of 1.00 for the major axis (unchanged) to 0.835 for its minor axis.

Since $\frac{1.00}{0.835} = 1.20$ The Earth appears 1.20 times longer than wider.

Question 4.5

(a) Use the information from Figure 4.8 and Pythagoras to show that:

$$l = l_o\sqrt{1 - \frac{v^2}{c^2}}$$

(b) An electron gun accelerates electrons to a velocity of 7.50×10^7 m s^{-1} after which they coast to a target 350 mm away. In the frame of reference of the electrons determine their distance to the target.

(c) The time they take to reach the target.

Velocity transformation

When we have relative motion between two reference frames, say S and S´, we can use the transformation equations to determine the velocity of an object moving in one reference frame, say S´, as viewed from the other, S. The relativistic velocity transformation equations are as follows.

$$u = \frac{v + u'}{1 + \frac{v u'}{c^2}}, \quad u' = \frac{v + v}{1 - \frac{u v}{c^2}}$$

u'	=	velocity of an object moving in frame S´
u	=	velocity of that same object as viewed from frame S
v	=	relative velocity between reference frame S and S´
c	=	velocity of light

At velocities that are very much smaller than c the transformation equations shown above simply reduce to a case of adding velocities. The value of $\frac{uv}{c^2}$ would essentially be zero.

We would arrive at: u = v + u' and the inverse u' = u − v

These equations are of course the *Galilean transformations* which we used earlier in this chapter. Their use gives very close to true results at low speeds and they are commonly used for classical physics problems. At higher velocities however, the results they give are only approximations at best, or not correct at all. In comparison, *the relativistic equations* apply and are true at all velocities.

Worked Example 4.4

(a) Max is watching a very fast car, A, moving away from him on a long straight road at 70.0 m s^{-1}. A second car, B, is also moving in the same direction but is further in front of car A. Car B is moving away from car A at a rate of 60.0 m s^{-1}.
Determine the velocity of car B as seen by Max.

(b) Let us suppose instead, that Max is watching two spaceships from Earth in a similar situation to that above. Spaceship A is moving away at 0.70c as seen from Earth and spaceship B is moving away in the same direction at 0.60c as seen by spaceship A.

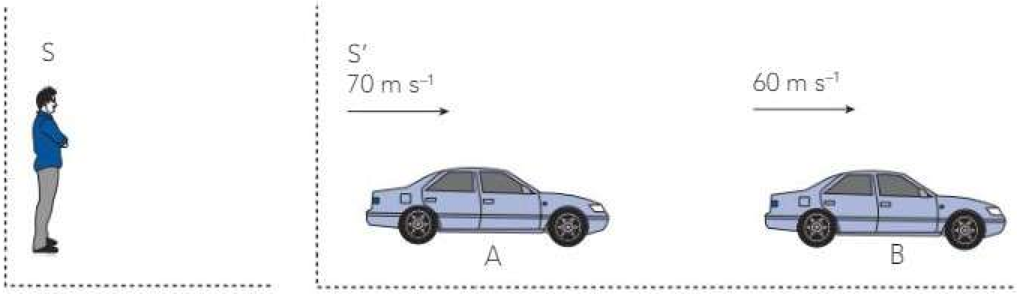
Determine the velocity of spaceship B as seen by Max on Earth.

(a) This problem is easily solved using the Galilean transformation equation since the velocities are so much less than c. We consider Max to be in one reference frame and the two cars in another, which is moving away at 70.0 m s^{-1}. Hence we have:

u = the velocity of car B relative to Max. = ?

v = the velocity of car A relative to Max. = 70.0 m s^{-1}

u' = the velocity of car B relative to car A. = 60.0 m s^{-1}

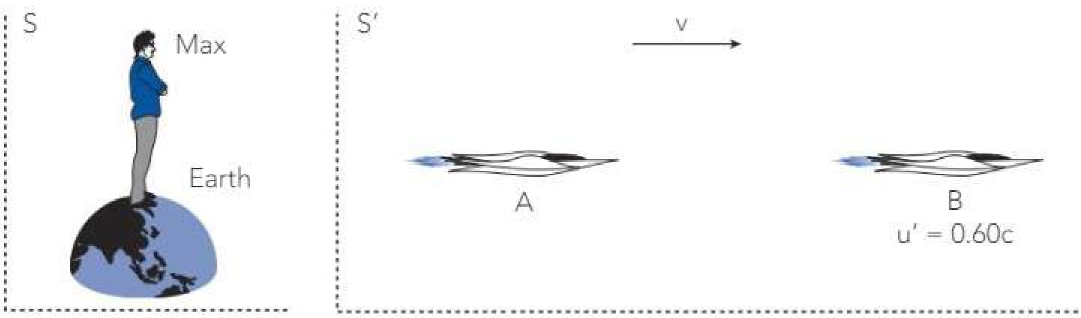


$$u = v + u'$$

$$u = 70.0 + 60.0 = 130 \text{ m s}^{-1}$$

The velocity of car B relative to Max is 130 m s^{-1}

(b) Only relativistic velocity equations will give a correct answer here. As before, consider Max on Earth to be in one reference frame, S, and the two spaceships in reference frame S′. Reference frame S′ is moving at a velocity of 0.70c away from frame S. Hence the velocity of spaceship A will be zero in its reference frame and that of spaceship B will be 0.60c. It is best to visualise the problem as shown below.



u = the velocity of B relative to S = ?

u' = the velocity of B relative to S′. = 0.60c

v = the velocity of S′ relative to S = 0.70c

$$u = \frac{(v + u')}{1 + (\frac{vu'}{c^2})}$$

$$u = \frac{(0.70c + 0.60c)}{1 + (\frac{(0.70c \times 0.60c)}{c^2})}$$

$$u = \frac{(1.30c)}{1 + 0.42}$$

$$u = 0.92c$$

The velocity of spaceship B will be 0.92c relative to Max on Earth. Note that this is less than c and quite a different answer to what we would get with classical physics formulae. No object can travel at greater than the speed of light.

Question 4.6

In the Worked Example 4.4 (a) we used the Galilean transformation formula to calculate the relative velocity of car B with respect to Max. Repeat the calculation with the same data but use the relativistic formulae to determine the relative velocity of car B with respect to Max. Comment on your result.

Question 4.7

In the Worked Example 4.4 (b), spaceship B was moving away from spaceship A. In our new situation spaceship B turns around and is heading towards spaceship A. As seen by Max on Earth spaceship A is still moving away at 0.70c but spaceship B is moving towards Earth at 0.50c.

Determine the velocity of spaceship B as seen by spaceship A.

Relativistic Momentum

We know from classical physics that the momentum of a body is defined as the product of its mass and velocity.

That is: $p = mv$

When an external force or impulse is applied to a body its velocity and momentum will increase. In classical physics it would seem that this could be done without limit simply by continually applying a force. However this cannot be the case as velocity has an ultimate limit of c. In fact as the velocity approaches that of the speed of light it takes an ever greater force to change the momentum as it approaches an infinite value.

Einstein showed that in fact momentum is relativistic and can be determined from the following equation.

$$p_v = \sqrt{\frac{m\,v}{1 - \frac{v^2}{c^2}}}$$

p_v = relativistic momentum (kg m s^{-1})
m = mass (kg)
v = velocity (m s^{-1})
c = velocity of light (3.0×10^8 m s^{-1})

Alternatively the above equation indicates that mass is a relative quantity. It increases with speed and becomes extremely large as it approaches the speed of light. So similarly to the above equation we have:

$$m = \sqrt{\frac{m_o}{1 - \frac{v^2}{c^2}}}$$

where m is the relativistic mass and m_o the rest mass.

We can see from the equation that when the velocity is much less than c the relativistic mass is equal to the rest mass; that is, $m = m_o$.

Similarly the relativistic momentum formula above reduces to p = mv for very low speeds.

Relativistic Energy and Mass Energy Equivalence

Perhaps the most interesting and well known aspect of Einstein's special theory of relativity is that mass can simply be thought of as a form of energy. Einstein concluded that mass and energy are equivalent. A loss of mass will produce energy and it takes energy to produce mass. In nuclear reactions such as the explosion of an atomic bomb for example, a small loss of mass results in the release of large amounts of energy.

Einstein was able to show that the total relativistic energy of a moving body is given by the following.

$$E = \sqrt{\frac{m\,c^2}{1 - \frac{v^2}{c^2}}}$$

E = total relativistic energy (rest energy + kinetic energy – see below) (J)
m = mass (kg)
v = velocity (m s^{-1})
c = velocity of light (3.0×10^8 m s^{-1})

If we apply this expression to a body at rest, that is, where $v = 0$, then the value of $(\frac{v^2}{c^2})$ also becomes zero.

The expression then becomes Einstein's famous equation for the equivalence between mass and energy.

That is: $E_o = m\,c^2$ where E_o is the rest energy associated with a mass m at rest.

We can see then that a body's total relativistic energy is made up of its rest energy and any relativistic kinetic energy due to motion. The kinetic energy can be determined from the difference between total energy and rest energy as follows:

since $$E = mc^2 + E_k$$

then $$E_k = \frac{m c^2}{\sqrt{1 - \frac{v^2}{c^2}}} - mc^2$$

This last expression for relativistic kinetic energy looks a little complex but it can be shown that for very low speeds it simplifies to the familiar $E_k = \frac{1}{2} mv^2$. However at high speeds this classical physics formula gives much lower values than is the case. In fact we can see from the relativistic formula that as the velocity of a particle approaches c its kinetic energy becomes extremely large.

This again indicates that it is not possible for a body to travel at the speed of light. If that were the case the relativistic energy would be infinite.

Worked Example 4.5

An electron is placed in an electric field and accelerated to a velocity of 0.95c.

(a) Determine the relativistic momentum of the electron at this speed.

(b) Compare this value with that predicted using a non-relativistic formula.

(a) The relativistic momentum is given by:

$$p = \frac{m v}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$p = \frac{(9.11 \times 10^{-31})(0.95 \times 3 \times 10^8)}{\sqrt{1 - (\frac{(0.95c)^2}{c^2})}}$$

$$p = \frac{2.596 \times 10^{-22}}{\sqrt{1 - 0.9025}}$$

$$p = 8.32 \times 10^{-22} \text{ kg m s}^{-1}$$

(b) The non-relativistic value for momentum is given by:

$$p = mv$$

$$p = (9.11 \times 10^{-31})(0.95 \times 3 \times 10^8)$$

$$p = 2.596 \times 10^{-22} \text{ kg m s}^{-1}$$

This value for momentum is approximately $\frac{1}{3}$ of the actual value. The equation $p = mv$ is only applicable at velocities which are very much less than the speed of light.

Worked Example 4.6

A proton in the same electric field is accelerated to a velocity of 0.75c. Determine for this velocity:
(a) The total energy of the proton.
(b) The protons kinetic energy.

(a) The total energy of the proton is given by

$$E = \frac{m c^2}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$= \frac{(1.67 \times 10^{-27})(3.0 \times 10^8)^2}{\sqrt{1 - (\frac{(0.75c)^2}{c^2})}}$$

$$= \frac{1.50 \times 10^{-10}}{\sqrt{1 - 0.5625}}$$

$$= 2.27 \times 10^{-10} \text{ J}$$

(b) The protons kinetic energy is given by

$$E_k = \text{total energy - rest energy}$$

$$= 2.27 \times 10^{-10} - mc^2$$

$$= 2.27 \times 10^{-10} - (1.67 \times 10^{-27})(3.0 \times 10^8)^2$$

$$= 7.69 \times 10^{-11} \text{ J}$$

Question 4.8

The rest mass of an alpha particle is 6.64×10^{-27} kg. It is accelerated to a velocity of 8.50×10^7 m s^{-1}. Determine:

(a) The relativistic momentum of the alpha particle.

______

______

______

(b) Its total energy

______

______

______

(c) Its kinetic energy

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______

______

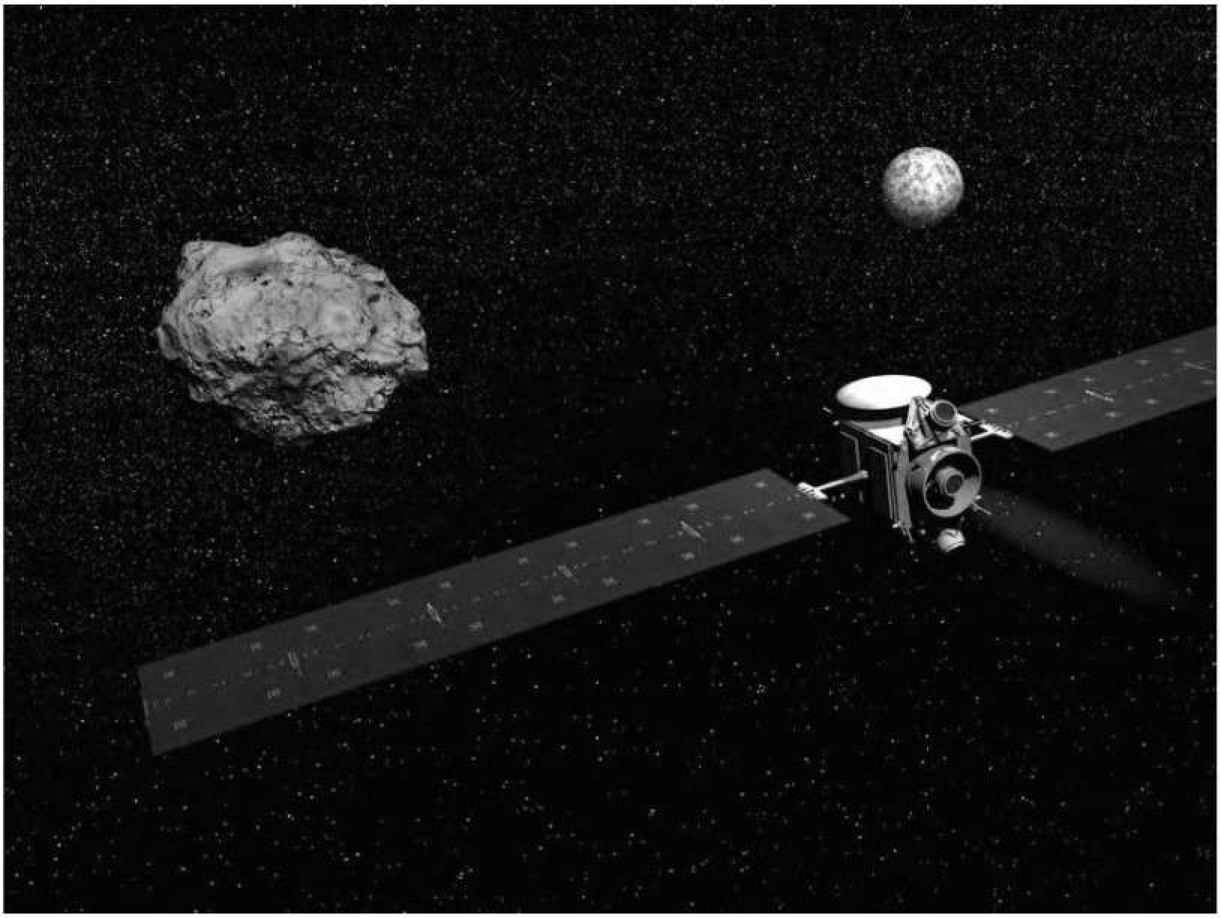
(d) Can this particle be accelerated to reach the speed the speed of light? Explain.

Question 4.9

One of the largest asteroids, Vesta, has a mass of 2.60×10^{18} kg. It orbits the sun at a mean speed of 19.3 km s^{-1}. Based on this information determine:

(a) The rest energy of Vesta

(b) Its total energy



REVIEW QUESTIONS

Chapter 4: Special Relativity

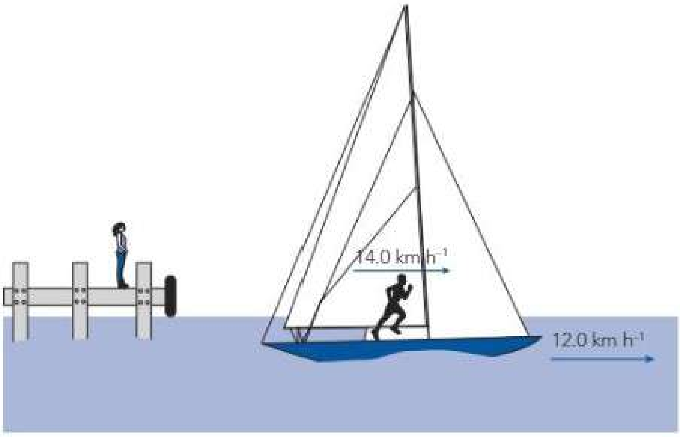
Relative Motion – Frames of Reference

1. (a) What is meant by an inertial reference frame? Give two examples.
   (b) Is the Earth an inertial reference frame?

2. You are sitting in a very quiet moving train where there are no windows.
   (a) Are you able to tell if you are moving, if at all? Explain.
   (b) Are you able to tell if you are accelerating, if at all? Explain.

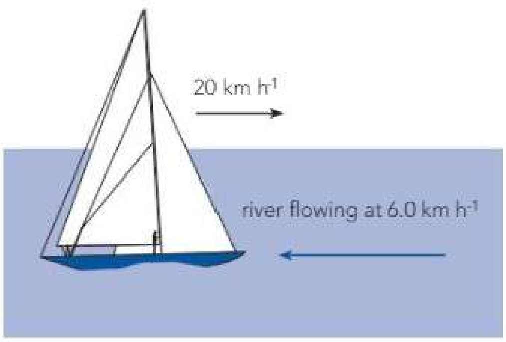
3. In his principle of relativity, Galileo stated that there is no absolute frame of reference. Explain what is meant by this statement.

4. Sarah is watching Max from a jetty as the boat he is on moves away steadily at 12.0 km h^{-1}. Max is running along the deck towards the front of the boat at 14.0 km h^{-1}.



   Use Galilean transformation equations to determine:
   (a) how fast Max is moving as seen by Sarah.
   (b) Sarah's velocity as seen by Max if he now runs towards the back of the boat at the same speed.

5. Frank's yacht is moving East at 20 km h^{-1} relative to the water. The river is flowing West at 6.0 km h^{-1}.
   (a) Determine the yacht's velocity relative to the bank.
   (b) If Frank now heads the yacht due North, at the same speed relative to the water, what will be his velocity relative to the bank?

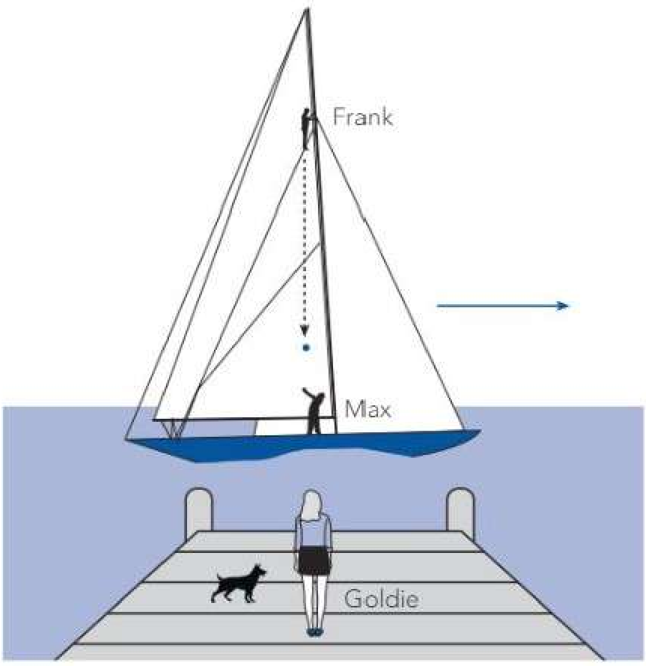


6. A glider is released into the air with a velocity of 75 km h^{-1} due North. It then encounters a 25.0 km h^{-1} wind from the East.
   (a) Determine the glider's velocity relative to the ground.
   (b) How far West of it's release point will the glider be after 10.0 minutes, assuming no other change to its velocity?

7. A boat is heading due North, directly across a river 625 m wide at a velocity of 16.0 m s^{-1} relative to the water. The river is flowing at 4.00 m s^{-1} in an Easterly direction.
   (a) Determine the velocity of the boat relative to the shore.
   (b) How long will it take the boat to reach the opposite side of the river?
   (c) How far down stream will the boat have reached?

8. (a) For the previous question determine the direction the boat should have taken if it wanted to reach a point located directly across from its starting position on the opposite side of the river.
   (b) How long would it take to cross the river in this case?

9. Frank is near the top of the mast of his sailing boat as he drops a ball to Max who is directly below him. The ball reaches Max 1.22 s later. Goldie is watching from a nearby jetty when the boat sails past at 6.00 m s^{-1} in an Easterly direction.

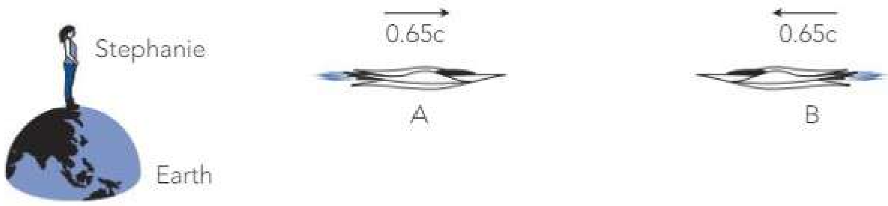


   (a) Determine the vertical velocity of the ball as it reaches Max.
   (b) Determine the velocity of the ball as seen by Goldie.
   (c) Describe the trajectory of the ball as seen by:
   (i) Frank (ii) Max (iii) Goldie.

10. In the Michelson-Morley experiment of 1887 a beam of light was split into two and then the two light beams travelled at right angles to each other before reaching an observer.

   (a) How was the light beam split into two?
   (b) What was the aim of the Michelson-Morley experiment?
   (c) Why were the two light beams made to travel at right angles to each other?
   (d) What was the result of the experiment?

11. Stephanie is located on Earth and monitoring the movements of two spaceships. As seen from Earth both spaceships are travelling at 0.65 c. Space ship A is travelling directly away from Earth while space ship B, which is further away, is travelling towards Earth.

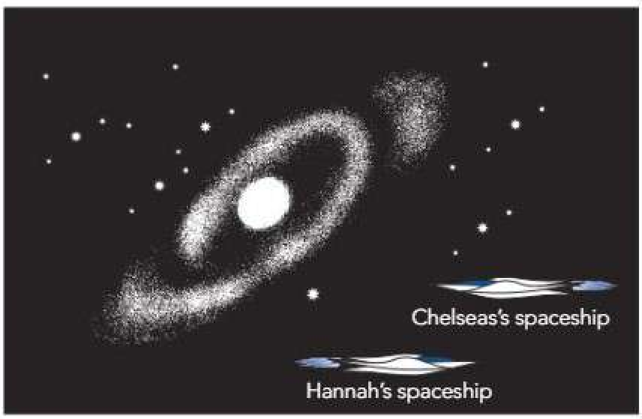


(a) Determine the velocity of spaceship B as seen from spaceship A.
(b) Space ship A is 145 m long in its own frame of reference. What length will it appear to be to:
   (i) an observer on spaceship B
   (ii) Stephanie on Earth.

12. You are sitting at the viewing window of a space station when you see an approaching spaceship and its flashing light. From your viewpoint, which of the following are affected and if so in what way?
(a) The speed of the light reaching you.
(b) The duration of the light flashes reaching you.
(c) The frequency of the light reaching you.

13. The approaching spaceship in the previous question, 12, is moving at 0.82 c and its light flashes for 2.0 s every minute. Determine from the viewpoint of the space station:
(a) the time duration of the flashes
(b) the time between flashes.

14. Chelsea is travelling in her spaceship towards the Andromeda galaxy at a speed 0.20c when she encounters Hannah's spaceship travelling in the opposite direction at the same speed. As viewed from Chelsea's spaceship comment on the following.
(a) The speed of Hannah's spaceship.
(b) The speed of Hannah's clock.
(c) The length of Hannah's spaceship.
(d) The speed of light reaching Chelsea's paceship from Andromeda.



15. Referring to the previous question, 14, Chelsea decides to take a well earned 30.0 minute nap on her way to Andromeda. Her bed is 1.80 m long. As viewed from Hannah's spaceship, determine:
   (a) how long Chelsea slept.
   (b) the length of her bed.

16. A space ship is travelling directly towards the Earth at 0.90c and as it approaches it notes that its shape appears circular. As the space ship gets closer to the Earth it decides to pass by, still moving at 0.90c, and continue on its journey. Surprisingly, the Earth's shape appears quite different as it goes past.

   (a) What shape will the Earth appear from the spaceship as it goes past?
   (b) Explain this change in shape.

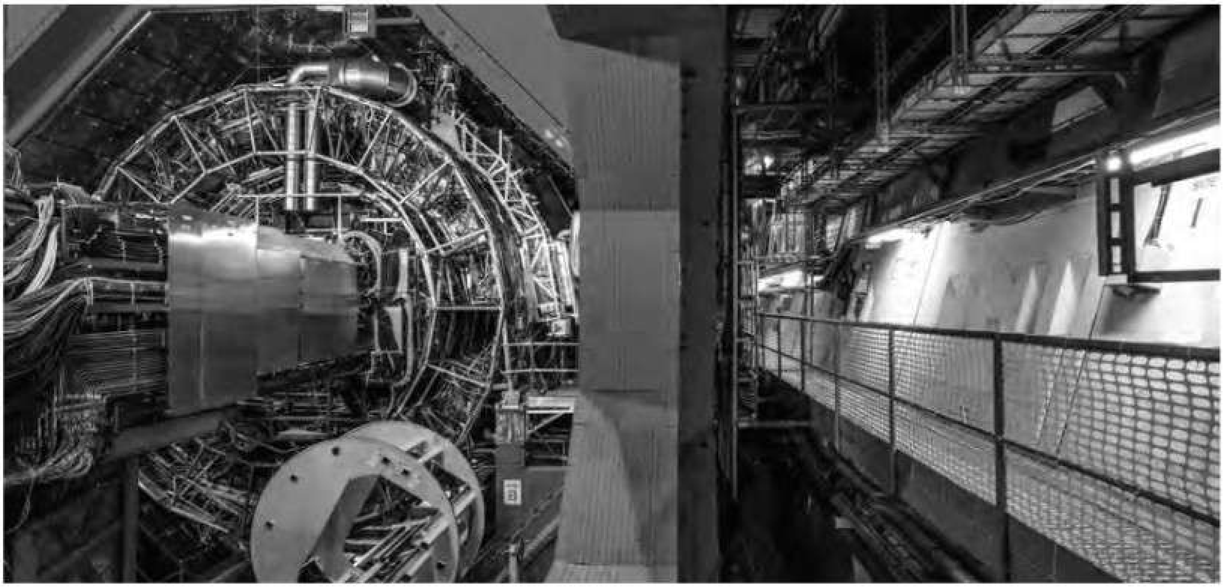
17. An electron is accelerated in an electric field to a velocity of 0.45 c.
   (a) Determine the momentum of the electron at this velocity.
   (b) Determine its momentum if the velocity is doubled to 0.90 c.
   (c) Compare the results and comment.

18. A proton has a mass of 1.67×10^{-27} kg.
   (a) Determine its rest energy.
   (b) If it is accelerated to a velocity of 0.80 c, determine its:
      (i) total energy
      (ii) kinetic energy.

19. A particle is travelling at 0.95 c in a particle accelerator which is 2.0 km long.
(a) How long does the particle accelerator appear to be in the particles frame of reference?
(b) How long would it take the particle to traverse the accelerator as seen from:
   (i) an observer in the laboratory
   (ii) the particles frame of reference.

20. Explain what is meant by each of the following terms related to Einstein's special theory of relativity:
   (a) time dilation
   (b) length contraction
   (c) proper time
   (d) proper length
   (e) mass energy equivalence.

5 THE STANDARD MODEL



SYLLABUS CHECKLIST

SCIENCE UNDERSTANDING – THE STANDARD MODEL

- ☐ the expansion of the universe can be explained by Hubble's law and cosmological concepts, such as red shift and the Big Bang theory.
- ☐ the Standard Model is used to describe the evolution of forces and the creation of matter in the Big Bang theory.
- ☐ high-energy particle accelerators are used to test theories of particle physics, including the Standard Model.

  This includes applying the relationships:

  $$\frac{m v^2}{r} = q v B$$

- ☐ the Standard Model is based on the premise that all matter in the universe is made up from elementary matter particles called quarks and leptons; quarks experience the strong nuclear force, leptons do not.
- ☐ the Standard Model explains three of the four fundamental forces (strong, weak and electromagnetic forces) in terms of an exchange of force-carrying particles called gauge bosons; each force is mediated by a different type of gauge boson.
- ☐ Lepton number and baryon number are examples of quantities that are conserved in all reactions between particles; these conservation laws can be used to support or invalidate proposed reactions. Baryons are composite particles made up of quarks.

5.1 THE UNIVERSE

Our ideas of what constitutes the universe have changed markedly over the centuries. In ancient times there were many different theories but most, like Aristotle, considered the Earth to be the centre of the universe. During the second century Ptolemy, a Greek astronomer, consolidated this idea of a *geocentric* model of the universe with a detailed theory which could explain, often in complicated ways, the then known movements of celestial bodies. His theories remained the basis of astronomical studies until the sixteenth century.

A major advance occurred in 1543 when Nicolaus Copernicus proposed a *heliocentric* model with the planets revolving around the sun. Further advances followed in our understanding of the cosmos through the work of scientists such as Galileo, Kepler and Newton. Of great significance was the ability to observe the universe in greater detail with the advent of telescopes and more recently the understanding of spectra.

In 1905 Einstein announced his *Special Theory of Relativity* including his concept of space-time. This had implications of our understanding of the universe since we could no longer think of space as an infinite expanse in which all things existed. Instead both space and time exist within the universe. Hence the universe is all that exists around us, such as planets, stars and galaxies as well as all space and all time.

Figure 5.1 *The Universe is all that exists around us, such as our world, planets, stars and galaxies as well as all space and all time.*

The Big Bang Theory

During the 20th century scientists have been able to gather much more detailed information about the cosmos. The analysis and interpretation of this data has shown that the universe is expanding and that distant galaxies in particular are moving away at great speed.

Using mathematical modelling and the measured velocities of these receding galaxies the Big Bang theory suggests that the universe expanded from an infinitely dense single point some thirteen billion years ago. The Standard Model provides a means of understanding the forces and creation of matter suggested by the Big Bang theory.

Some of the significant discoveries and ideas that have contributed to the Big Bang theory include the following:

- In 1912 Vesto Slipher used spectroscopic analysis of a distant spiral nebula and found that the spectral lines were all closer to the red end of the spectrum. This so called red shift indicated that the nebula was moving away from the milky way (see Doppler effect).
- In 1915 Albert Einstein published his General Theory of Relativity. This allowed scientists to consider possible new models of the universe. In particular Alexander Friedmann derived the Friedmann equations which showed that the universe is expanding.

- In 1924 Edwin Hubble measured the distance to the nearest spiral nebulae and showed that in fact they were spiral galaxies. He was also able to use the red shift measurements already made by Slipher and others to estimate the distances to other galaxies. More importantly in 1929 he discovered that the more distant galaxies were moving away at a greater rate (see Hubble Law).
- In 1931 Georges Lemaitre, a Belgian physicist, suggested that since the galaxies are moving apart in forward time then at some time in the past they all originated from a single point, a "primeval atom". He proposed that the universe formed when this "primeval atom" blew apart.
- In 1948 George Gamou further developed the idea of the Big Bang theory and proposed that the universe was the result of an explosion some 13 billion years ago. The beginning universe was extremely dense and hot.
- In 1965 the detection of cosmic microwave radiation gave the Big Bang theory greater acceptance as it had been predicted by this theory. Until this discovery, many scientists such as Fred Hoyle, supported the *steady state theory* of the universe. This rival theory suggested the universe is infinite and has always existed. However observational evidence continues to support the Big Bang theory.

Improved telescope technology and analysis of data are giving cosmologists a greater understanding of our universe. Interestingly it appears that expansion of the universe is increasing at a greater rate.

As to the future of the universe the answer may lie with the Friedmann equations which nearly a century ago were used to predict the expansion of the universe. There are several solutions and scenarios based on these equations. The universe may eventually stop expanding and then crunch back on itself, it may simply keep expanding forever or it may keep expanding at a slower rate that avoids any implosion. More accurate measurement of cosmological constants may help in providing a clearer solution using the Friedmann equations.

The Doppler Effect

If you listen to the sound of an ambulance siren as it goes past you along the road the pitch of the sound appears to change. This apparent change in frequency due to the relative movement between the sound source and the observer is called the Doppler effect. When the sound source is moving towards the listener the apparent frequency will be higher as more waves reach the listener per second. At lower frequency is heard when the sound source is receding.

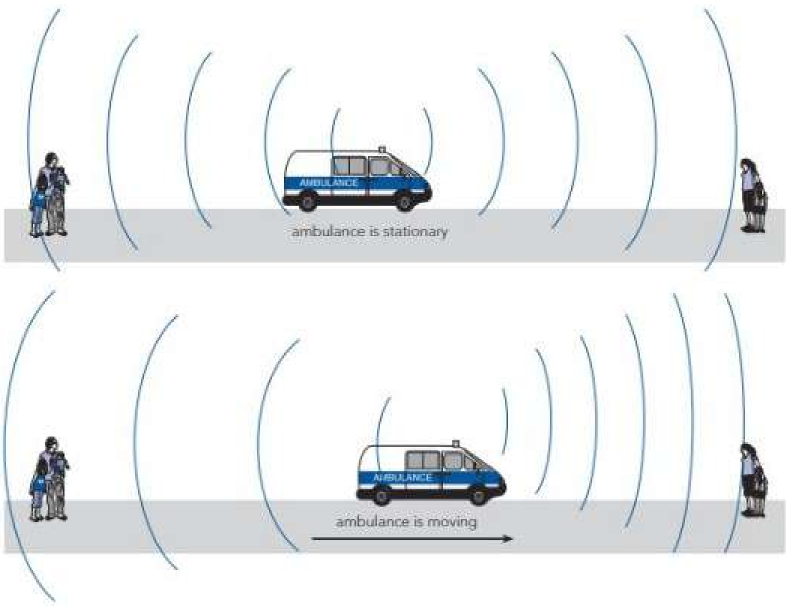


Figure 5.2 *The Doppler effect. The apparent frequency will be higher when the sound source is moving towards you as the sound waves bunch up closer together. The opposite occurs if the sound source is moving away from you.*

The Red Shift

The Doppler effect can also be observed with light. When a light source is moving towards us there will be an increase in the apparent frequency, or colour, of the light. This is referred as a *blue shift*. If the light source is moving away from us then there is a decrease in frequency and a consequent *red shift*.

The use of the Doppler effect has been very important in determining if stars are moving away or towards us. The light from the stars is analysed using a spectroscope and the characteristic spectral lines are compared with those of known gases tested in the laboratory. In 1912 Vesto Slipher used this technique to observe a distant spiral nebula. He found that all of the expected spectral lines, as say like from a close star like our sun, had moved towards the red end of the spectrum.

Accurate measurement of such a red shift can be used to calculate the velocity with which a star is moving away from us or towards us in the case of a blue shift. The movement of stars of course could be tangential to the Earth in which case the Doppler effect would not occur and other techniques would be needed to measure velocity.

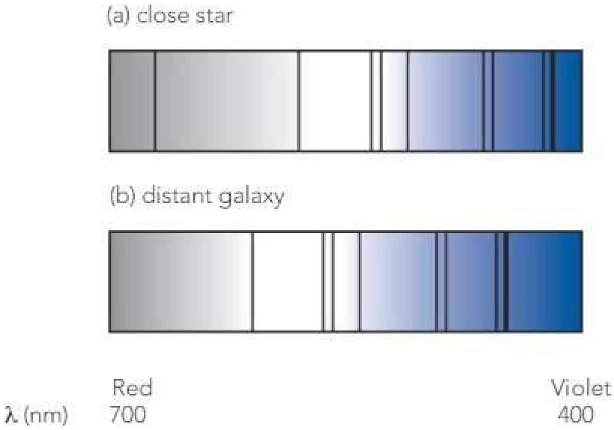


***Figure 5.3** The red shift in the spectra from distant galaxies. The Doppler effect in the light from receding distant galaxies causes the frequency of the light to be reduced (wavelength is increased) and spectral lines are all closer to the red end of the spectrum.*

Hubble's Law

Edwin Hubble investigated the red shift of distant galaxies and found that the further they were from our solar system the more rapidly they were moving away. By graphing the red shift versus estimated distances to different galaxies he found that a linear relationship exists. This linear relationship is called Hubble's Law. It can be stated as "the speed of recession of a galaxy is proportional to its distance from the Earth".

Mathematically it can be stated as:

$$v \propto d \quad \text{or} \quad v = Hd$$

Where H is Hubble's constant (the gradient of the velocity versus distance graph). This linear relationship holds well for distant galaxies but not for closer ones. The accurate measurement of distances to galaxies and determination of the value of H is difficult. Interestingly the value of 1/H is an indication of the age of the universe.

Measurement of Distances to Stars

The distance to stars and galaxies is measured by viewing them from different positions and finding the parallax angle. The position of a nearby star will appear to change relative to a fixed background such as very distant stars. Using as large a baseline as possible, that is the distance between the two points a particular star is viewed from, the angle of parallax will be a measure of the distance to the star (see Figure 5.4).

The distances to stars and galaxies are so large that astronomers use a more meaningful set of units rather than kilometres. The astronomical unit (AU), the light year and the parsec (pc) are all distance units used in astronomy.

- **The astronomical unit (AU)**
  This is the average distance from the Earth to the Sun. 1 AU = 1.496×10^8 km. Interestingly this distance is used in defining the parsec (see Figure 5.4). The AU unit is particularly useful in stating distances within our solar system.

- **The light year**
  This is the distance travelled by light in a vacuum in one year. 1 light year = 9.46×10^{12} km. The light year is particularly useful in stating distances to the stars. For example the distance to Alpha Centauri is 4.3 light years. This measurement not only tells us the distance to a star but the time taken for the light to reach us. Hence when we view the light from Alpha Centauri we are viewing the light that left the star 4.3 years ago.

- **The parsec (pc)**
  This is the distance to a star that would have a parallax of 1 second of arc (1/3600 of a degree) using the average distance from the Earth to the Sun as a baseline (see Figure 5.4). 1 pc = 3.086×10^{13} km. This is 3.26 light years. This unit is very useful when measuring astronomical distances using parallax.

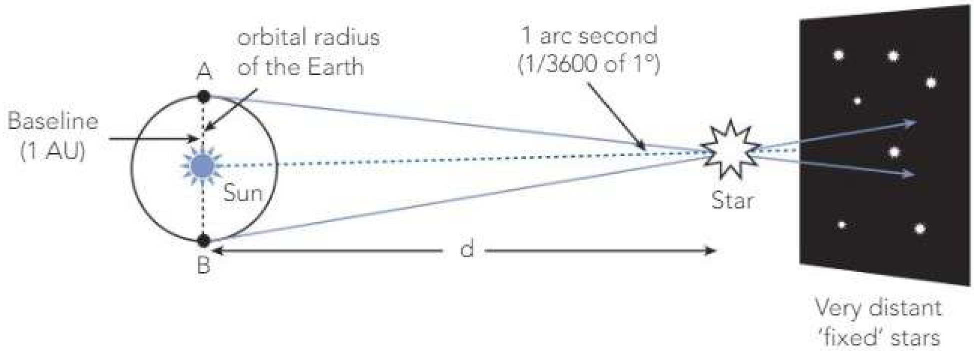


Figure 5.4 The parsec. One parsec is the distance that would subtend 1 arc second of angle using the average Earth Sun distance (1 AU) as the baseline. The star under observation appears to move against a "fixed" back ground of very distant stars. 1 parsec (pc) is 3.26 light years or 3.086×10^{13} km.

Worked Example 5.1

The distance to the star Rigel is approximately 276 parsec. Determine what this distance is in km and in light years.

(a)

$$\begin{aligned} 1 \text{ pc} &= 3.086 \times 10^{13} \text{ km} \\ \text{distance to Rigel is} &= (276)(3.086 \times 10^{13}) \text{ km} \\ &= 8.52 \times 10^{15} \text{ km} \end{aligned}$$

(b)

$$\begin{aligned} 1 \text{ light year} &= 9.46 \times 10^{12} \text{ km} \\ \text{distance to Rigel is} &= \frac{8.52 \times 10^{15} \text{ km}}{9.46 \times 10^{12} \text{ km}} \\ &= 900 \text{ light years.} \end{aligned}$$

Question 5.1

Antares is the red star in the constellation of Scorpio which is 250 light years from our solar system. What would be this distance in:

(a) km?

____

(b) parsec?

____

Question 5.2

The following table gives some typical astronomical distances in one unit of measurement. Complete the table to show all measurements in all three units.

	Distance (km)	Distance (AU)	Distance Light years	Distance Parsec (pc)
Earth–Moon distance	3.84×10^5			
Earth–Sun distance	1.50×10^8			
Pluto–orbit Sun distance		39.4		
Distance to Proxima Centauri		2.67×10^5		
Expanse of Milky Way			1.50×10^5	
Edge of observable universe			1.30×10^{10}	

5.2 MATTER

Matter

To understand the nature of matter we must firstly review the model of the structure of atoms. Our modern concept of the atom is based on the work and theories of many scientists but in particular those of Ernest Rutherford and Neils Bohr. The Standard Model as we shall see gives our current understanding of elementary particles and forces.

During the earlier part of last century it was established that atoms have a dense positively charged centre (nucleus) surrounded by negatively charged particles (electrons). The Rutherford/ Bohr model of the atom suggests that:

- atoms are mostly empty space
- nearly all of their mass is concentrated in the nucleus
- protons and neutrons have approximately the same mass and are located in the nucleus
- electrons move around the nucleus in specific orbits dependent on their energy
- all the neutral atoms of a given element have the same number of protons (+ve charge) and electrons (–ve charge)
- when atoms lose or gain electrons they become ions (that is, charged atoms).

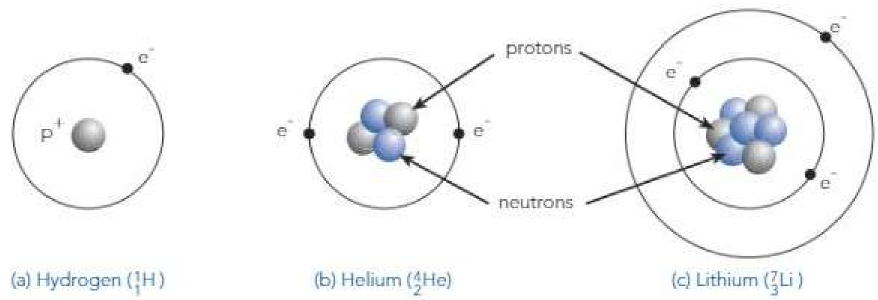


Figure 5.5 Rutherford/Bohr model of the atoms of the first three elements

Protons, neutrons and electrons

Protons, neutrons and electrons are the three particles that make up atoms. Protons and neutrons (collectively called nucleons) are similar in mass and are 1836 times heavier than electrons. They are held together in the nucleus by very strong nuclear forces.

Electrons and protons carry equal and opposite charges (1.60×10^{-19} coulomb). It is the electrostatic attraction between these two particles which keeps the electrons in orbit around the nucleus.

Table 5.1 Protons, neutrons, electrons and their properties

Particle	Symbol	Charge (C)	Mass (kg)
proton	^1_1p	$+1.60 \times 10^{-19}$	1.673×10^{-27}
neutron	^1_0n	neutral	1.675×10^{-27}
electron	$^0_{-1}e$	-1.60×10^{-19}	9.11×10^{-31}

We now know that protons and neutrons are themselves made up of fundamental matter particles called *quarks*. A great variety of matter particles have been discovered through the use of particle accelerators and these are grouped into two main types, leptons and hadrons. *Leptons* are particles such as electrons and neutrinos that are not influenced by the strong nuclear force. Particles that are influenced by the strong nuclear force such as protons and neutrons are called *hadrons*.

Quarks

The development of particle accelerators and sophisticated detectors has allowed scientists to study the nucleus of atoms more closely. These accelerators are used to fire beams of very fast moving electrons, protons or other particles at selected targets or at each other. The interactions between these high energy particles and their targets often resulted in the formation of short lived particles that do not exist as ordinary matter. More importantly these interactions provided proof that protons and neutrons are made up of smaller subatomic particles called quarks.

Protons and neutrons are each made up of three different quarks. Quarks are confined within the protons and neutrons by the strong nuclear force and cannot be isolated for separate observation. However it has been established that there are six different types of quarks.

Each type of quark is called a flavour and each is characterised by intrinsic properties such as mass, electric charge and spin. The six flavours are: up, down, charm, strange, top and bottom. A proton for example is composed of 2 up quarks and 1 down quark while a neutron is composed of 2 down quarks and 1 up quark (see Table 5.2).

The Neutrino

Neutrinos, like quarks, are one of the fundamental particles of nature. They are similar to electrons except that they carry no charge. This makes them difficult to detect as they are not affected by the electrostatic forces that influence electrons. Their existence was predicted many years before they were detected.

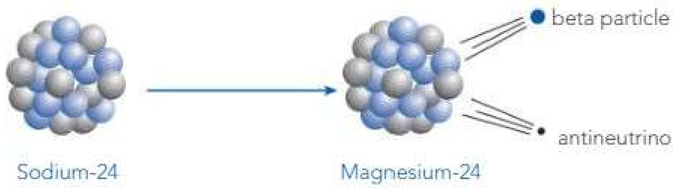
In 1931 Wolfgang Pauli suggested the existence of an undetected neutral particle that would explain the then unaccountable energy loss that occurred during beta decay experiments. In 1934 Enrico Fermi as part of his beta decay theory included and named the neutrino as the yet undiscovered particle involved in the decay process.

- A typical *beta minus* decay process is the decay of the sodium-24 isotope. A nuclear equation showing the particles involved (before the neutrino was considered) is shown below.

$$^{24}_{11}\mathrm{Na} \rightarrow \ ^{24}_{12}\mathrm{Mg} + \ ^{0}_{-1}\mathrm{e}$$

However careful measurements of the masses and energies involved resulted in an apparent energy loss during the process as indicated by the equation above. In fact, as suggested by Pauli, a neutral particle is also produced during the reaction. In this case an *antineutrino* is formed during the beta-minus decay and a more accurate way of indicating the process is as follows:

$$^{24}_{11}\mathrm{Na} \rightarrow \ ^{24}_{12}\mathrm{Mg} + \ ^{0}_{-1}\mathrm{e} + \ ^{0}_{0}\overline{\nu}$$



The process occurring within the nucleus of the atom is that a neutron is changing to a proton by emitting an electron at high speed. An antineutrino is also produced.

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

A typical *beta plus* decay process is the decay of the radioactive isotope phosphorus-30 as shown below. This results in the formation of a *neutrino* (as compared with the formation of an antineutrino during a beta minus decay).

Positrons

Beta plus particles, called *positrons*, were discovered in the early 1930s by C. P. Anderson while studying cosmic rays. They had the same mass as electrons but were positively charged. Positrons were also observed by Irene Curie and Frederick Joliot when bombarding various nuclei with alpha particles. The alpha particles were absorbed by the target atoms creating a new radioactive element which then emitted positrons. As we now know, neutrinos were also formed.

$$^{27}_{13}\text{Al} + {}^{4}_{2}\text{He} \rightarrow {}^{30}_{15}\text{P} + {}^{1}_{0}\text{n}$$

$$^{30}_{15}\text{P} \rightarrow {}^{30}_{14}\text{Si} + {}^{0}_{+1}\text{e} + {}^{0}_{0}\nu$$

The discovery of a particle fitting the expected characteristics of the neutrino was made in 1956 by Clyde Cowan and Fred Reines. It is now known that there are three different types of neutrinos, *electron neutrinos, muon neutrinos* and *tau neutrinos*. All neutrinos have an antimatter partner called an antineutrino.

Neutrino type	Charged particles related to it
ν_e	Electron
ν_μ	Muon
ν_τ	Tau

Question 5.3

(a) Although the existence of the neutrino was predicted in the early 1930s it was not detected and identified until nearly 30 years later. Why was the detection of the neutrino so difficult?

____

____

____

____

(b) Write equations for each of the following:

Beta minus decay
The carbon-14 nucleus is unstable and breaks down to produce a nitrogen-14 nucleus, a beta minus particle and an antineutrino.

____

(c) **Beta plus decay**
The magnesium-23 nucleus is unstable and breaks down to produce a sodium-23 nucleus, a beta plus particle and a neutrino. Write an equation for this beta plus decay.

____

The four fundamental forces

The many different forces that occur in nature can all be understood in terms of four fundamental interactions. These are the *strong, electromagnetic, weak* and gravitational interactions. In each case there are mediating particles or force carriers involved. These force carriers, called *bosons*, are exchanged during force interactions.

For example when two charged particles such as electrons are approaching each other there is a continual exchange of photons between the two, resulting in a repulsive force. In this case of an electromagnetic interaction, the *photon* is the mediating particle or force carrier. Other force carriers include gluons, for the strong nuclear force, W^+, W^-, *and Z particles*, for the weak nuclear force, and gravitons, for the gravitational force. Gravitons have not yet been observed. A summary of these interactions is shown below.

Interaction	Acts on	Mediating particle
Strong nuclear	Hadrons	Gluons
Electromagnetic	Charged particles	Photon
Weak nuclear	Quarks, leptons	W^+, W^-, Z^0 particles
Gravitational	All particles	Graviton (*Not observed)*

Feynman diagrams

Interactions between particles can be illustrated using Feynman diagrams. In these diagrams introduced by the American physicist Richard Feynman, matter particles are represented as solid arrows while force carriers may be wiggly lines, such as for photons, or dashed lines and curly lines for other force carriers. The lines meet at a point (vertex) which represents the interaction. Two typical interactions are illustrated below with Feynman diagrams. The first is the force interaction between two free protons approaching each other. As discussed above the mediating particle is a photon. If we imagine two protons approaching each other then the repulsive interaction (force) occurs through the continual exchange of photons.

As the protons get closer the exchange of these photons becomes more rapid and the force increases. The photons exchanged between the interacting particles have a very brief lifespan and are essentially 'virtual' photons. These are represented by wiggly lines in the diagram.

The second example shows the strong nuclear interaction between a proton and a neutron. The mediating particle or force carrier in this instance is a π meson.

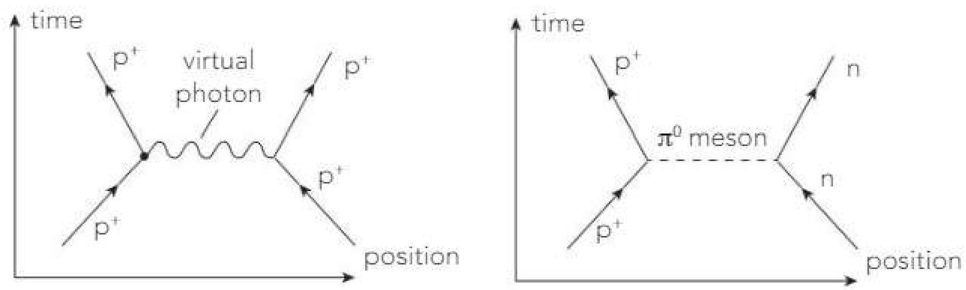


Figure 5.6 *Feynman diagrams for two typical particle interactions. The solid lines represent matter particles, fermions, and the wiggly or dashed lines the force carriers, bosons.*

The standard model

The four fundamental forces provide a means of classifying the very large number of sub-atomic particles that have been discovered. The nature of a particles interaction with fundamental forces and their general properties form the basis of how they are classified into the Standard Model. Hadrons for example are particles that interact through the strong nuclear force whereas leptons interact through the weak nuclear force.

The standard model is a combination of different models developed to explain the nature of particles and matter. In this model there are 12 fundamental matter particles, 6 leptons and 6 quarks. They are called fermions. There are also force carriers called bosons. These include photons, gluons and W^+, W^- and Z particles. A simplified view of the standard model is shown below.

Table 5.2 *A simplified view of the standard model. The fundamental particles of matter are leptons and quarks which are called fermions. The force carriers are called bosons and include photons, gluons and the W^+, W^- and Z particles. The Higgs boson particle has tentatively been confirmed to exist after experiments at CERN detected a Higgs boson like particle in July 2012.*

FERMIONS Matter particles, spin = 1/2, 3/2, 5/2, ...		**BOSONS** Force carriers, spin = 0, 1, 2, 3, ...	
Leptons & Quarks spin = 1/2		**Gauge Bosons** spin = 1	**Higgs Boson** spin = 0
Leptons 6 flavours or types e , ν_e μ , ν_μ τ , ν_τ	Quarks 6 flavours or types up, down, charm, strange, top, bottom	Electroweak interactions photons W^+, W^-, Z^0 particles Strong interactions gluons	*Higgs boson **A particle consistent with a Higgs Boson was first detected in 2012 and tentatively confirmed to exist in 2013.*

Fundamental particles

Our understanding of what are fundamental particles has continually changed as we have been able to see smaller and smaller particles. In the early 19th century Dalton's atomic theory considered the atom, as yet unseen, to be indivisible and therefore a fundamental particle. The discovery of the electron by Thompson in 1897 and work by Bohr and others in the earlier part of the 20th century established that there were three fundamental matter particles; the *proton*, *electron* and *neutron*. The photon was also understood as an energy particle.

The advent of particle accelerators and nuclear reactors in the latter part of the 20th century has allowed physicists to peer even more deeply into the sub-atomic world. Several hundred sub-atomic particles have now been identified some of which are extremely short lived.

Our current knowledge of all particles and their interactions is summarized in the Standard Model. In this model there are twelve fundamental matter particles, six leptons and six quarks. The leptons which include the electron and electron-neutrino are point particles with no structure and hence fundamental. Quarks, on the other hand, cannot exist separately but are the elementary particles that make up hadrons such as protons and neutrons.

Table 5.3 *Fundamental particles and their properties. There are twelve in total. Leptons exist as individual particles whereas quarks cannot be isolated for separate observation. Quarks are part of larger particles called baryons and mesons. Anti particles also exist for each lepton and quark. Their properties of charge and number are opposite to their counterpart.*

Leptons (spin ½)				Quarks (spin ½)			
Name	Symbol	Charge	Lepton No	Flavour (type)	Symbol	Charge	Baryon No
Electron	e	-1	1	Up	u	2/3	1/3
Electron-neutrino	ν_e	0	1	Down	d	-1/3	1/3
Muon	μ	-1	1	Charm	c	2/3	1/3
Muon-neutrino	ν_μ	0	1	Strange	s	-1/3	1/3
Tau	τ	-1	1	Top	t	2/3	1/3
Tau-neutrino	ν_τ	0	1	Bottom	b	-1/3	1/3

Quarks to Baryons and Mesons

Baryons and mesons, collectively called hadrons, are made up of quarks. Three different quarks make up a baryon whereas a quark and an anti-quark pair make up a meson.

Combining quarks

- 3 Quarks combine to give → Baryons e.g. Nucleons (p, n)
  - must be different — Hyperons (λ^+, λ^0, Ω^-, etc.)
- 2 Quarks combine to give → Mesons e.g. Pion-plus π^+
  - quark/anti-quark pair — Kaon-plus K etc.

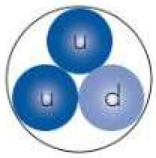
Although many combinations are possible the usual conservation rules apply as well as others. Some are:

- Charges must balance. For example the charge on a proton is +1, hence the charges on the three quarks it is composed of must also add up to +1.
- Baryon number for baryon particles must add to +1 and for antiparticles -1.
- For mesons the baryon number must add to zero.

Some common examples of how quarks make up particles are shown below.

1. Proton – quarks contained, u, u, d

u, u, d →



charge

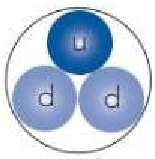
$$\left.\begin{array}{l} u = \frac{2}{3} \\ u = \frac{2}{3} \\ d = \frac{-1}{3} \end{array}\right\} = 1$$

baryon No

$$\left.\begin{array}{l} \frac{1}{3} \\ \frac{1}{3} \\ \frac{1}{3} \end{array}\right\} = 1$$

2. Neutron – quarks contained, u, d, d

u, d, d →



charge

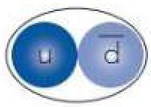
$$\left.\begin{array}{l} u = \frac{2}{3} \\ d = \frac{-1}{3} \\ d = \frac{-1}{3} \end{array}\right\} = 0$$

baryon No

$$\left.\begin{array}{l} \frac{1}{3} \\ \frac{1}{3} \\ \frac{1}{3} \end{array}\right\} = 1$$

3. Pion-plus (π^+) – quarks contained, u, $\overline{d}$

u, $\overline{d}$ →



charge

$$\left.\begin{array}{l} u = \frac{2}{3} \\ \overline{d} = \frac{1}{3} \end{array}\right\} = 1$$

baryon No

$$\left.\begin{array}{l} \frac{1}{3} \\ \frac{-1}{3} \end{array}\right\} = 0$$

$\overline{d}$ is an antiquark; charge and baryon number are opposite to d.

Question 5.4

Which of the fundamental forces of nature:

(a) acts on all particles? ______________________

(b) acts on hadrons? ______________________

(c) is mediated by photons? ______________________

(d) is mediated by Z particles? ______________________

Question 5.5

(a) Explain the difference between a fermion and a boson.

____

(b) How are baryons and mesons similar and how they are different?

____

Question 5.6

An antiproton has a charge and baryon number opposite to that of a proton. If it is made up of the three anti-quarks $\bar{u}$, $\bar{u}$, $\bar{d}$, verify that the resulting charge and baryon number will be correct.

____

____

Question 5.7

An unknown particle is made up of the three quarks u, d, s.

(a) Is this particle a baryon or a meson? ______________________

(b) Determine its charge and baryon number.

____

____

5.3 PARTICLE ACCELERATORS

Charged particles in electric fields

As we saw earlier in Chapter 2, when a charged particle is placed in an electrical field a force will be exerted on it. For example if an electron is placed between two charged parallel plates as shown below a force in the direction of the positive plate will act on the electron. The electron will accelerate and its velocity and kinetic energy will increase.

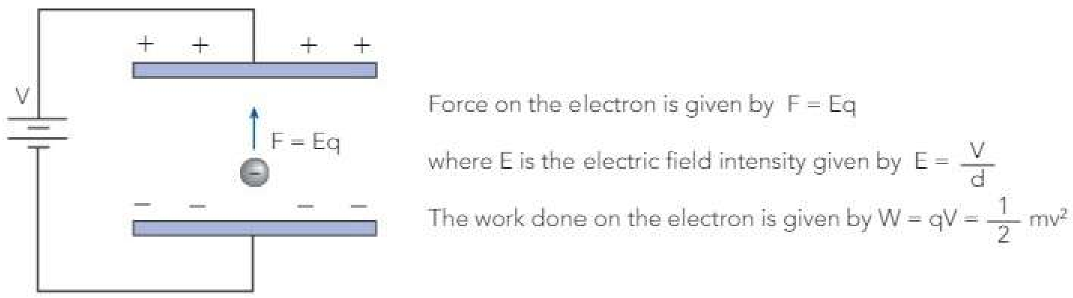


***Figure 5.7** Electron moving in an electrical field. The electron will accelerate in the direction of the positive plate. Its velocity and kinetic energy will both increase.*

The electron gun

The electron gun provides a high speed electron beam for use in such devices as the old style TV monitors or for particle accelerators. The gun consists of a low voltage heater element which allows electrons from a hot cathode to be accelerated to a high voltage anode. The cathode is coated with a metal which allows for the easy promotion of conduction electrons to its surface from which they are literally boiled off as they are attracted within the vacuum tube to the positive anode. The high speed electron beam continues through the small hole in the anode to a CRT screen or where required.

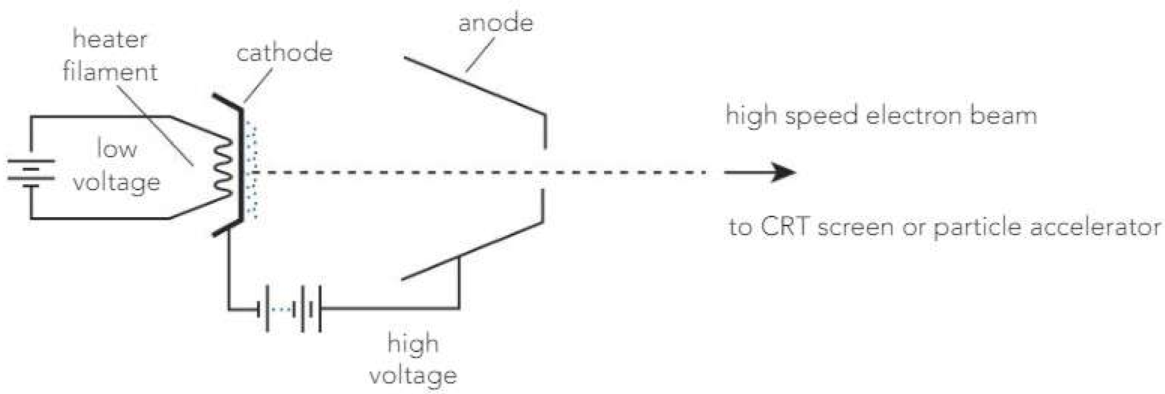


***Figure 5.8** An electron gun. A low voltage source supplies current to the heater filament. Electrons move to the surface of the hot cathode and are accelerated through the cone of the anode by the high positive voltage.*

The cathode ray oscilloscope (CRO)

As we saw in Chapter 2 the cathode ray oscilloscope can be described as a simple old style television monitor which can measure and display electrical information. It essentially displays voltage in a graphical form. Its most important component is the electron gun.

As we saw above the electron gun is made up of a hot cathode that supplies electrons and a positively charged anode that attracts them. The electron beam can be focussed using both electrical and field magnets.

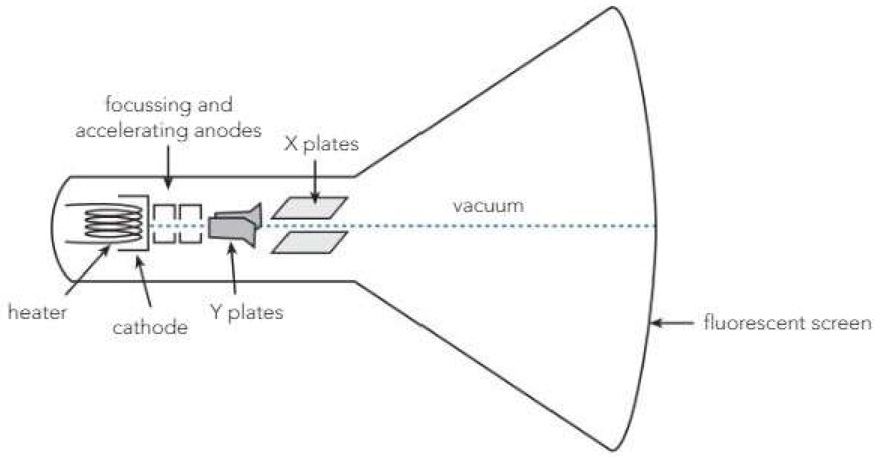


Figure 5.9 Simplified diagram of a CRO. The electron gun provides a beam of electrons which create a white spot on the fluorescent screen. The beam direction can be controlled by voltages applied to the X and Y plates thus creating a trace or picture on the screen.

Worked Example 5.2

An electron beam in a cathode ray oscilloscope is accelerated through 5.00 kV. Ignoring any relativistic effects. Determine:

(a) the velocity that the electrons achieve
(b) the time taken for them to reach the screen which is 32.5 cm from the anode
(c) the energy each electron gives upon hitting the screen.

(a)

$V = 5.00 \times 10^3$ V

$q = 1.6 \times 10^{-19}$ C

$W = ?$

$v = ?$

$m_e = 9.11 \times 10^{-31}$ kg

$$W = Vq = \frac{1}{2}mv^2$$

$$\therefore v^2 = \frac{2Vq}{m}$$

$$= \frac{(2)(5000)(1.60 \times 10^{-19})}{9.11 \times 10^{-31}}$$

$$v = 4.19 \times 10^7 \text{ m s}^{-1}$$

(b)

$v = 4.19 \times 10^7$ m s^{-1}

$s = 0.325$ m

$t = ?$

$$v = \frac{s}{t}$$

$$\therefore t = \frac{0.325}{4.19 \times 10^7}$$

$$= 7.76 \times 10^{-9} \text{ s}$$

(c) On colliding with the screen the electrons would give up all their kinetic energy in the form of light and heat.

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

$$= \frac{1}{2}(9.11 \times 10^{-31})(4.19 \times 10^7)^2$$

$$= 8.00 \times 10^{-16} \text{ J}$$

Worked Example 5.3

An electron beam in a cathode ray tube has a velocity of 9.15×10^6 m s^{-1} as it passes between two deflecting plates where the electric field intensity is 8.20×10^3 Vm^{-1}. The electron beam is at right angles to the electric field and is in its influence for 2.45×10^{-9} s. Ignoring any relativistic effects determine:

(a) the force exerted on each electron and consequent acceleration
(b) the lateral (sideways) velocity gained by the electrons
(c) the angle of deviation of the electron beam.

(a) $F = Eq = (8.20 \times 10^3)(1.6 \times 10^{-19}) = 1.31 \times 10^{-15}$ N

$a = \dfrac{F}{m} = \dfrac{1.31 \times 10^{-15}}{9.11 \times 10^{-31}} = 1.44 \times 10^{15}$ m s^{-2}

(b) $v = u + at$

$= 0 + (1.44 \times 10^{15})(2.45 \times 10^{-9}) = 3.53 \times 10^6$ m s^{-1}

(c) Using vectors

$\tan\theta = \dfrac{3.53 \times 10^6}{9.15 \times 10^6}$

$\theta = 21.1°$

The linear accelerator

An electron gun provides a fast beam of electrons but their velocity is limited by the voltage that can be safely and practically applied. It would seem that by simply using much higher voltages a very high speed electron beam could be produced. This is not the case. Apart from the practicality of using very high voltages on a single anode the limiting factor is the relativistic effects that become dominant at speeds close to the speed of light. A means of supplying energy to the electrons in stages has been found in the linear accelerator.

The linear accelerator (linac) consists of a series of tubes through which electrons travel in a straight line. The tubes are connected to an alternating voltage which effectively creates a series of changing cathodes and anodes in the electrons path. The voltage is alternated so that as the electrons leave one tube the next in line becomes positive and attracts it. The one it is leaving becomes negative and hence repels it.

The actual increase in velocity of the electrons occurs as they accelerate from one tube to the next, after which they coast, or drift, while they are within the tube. The length of each succeeding tube increases to match the increasing velocity of the electrons. This ensures that the change in polarity of the tubes due to the alternating voltage occurs exactly as they reach the end of the tube.

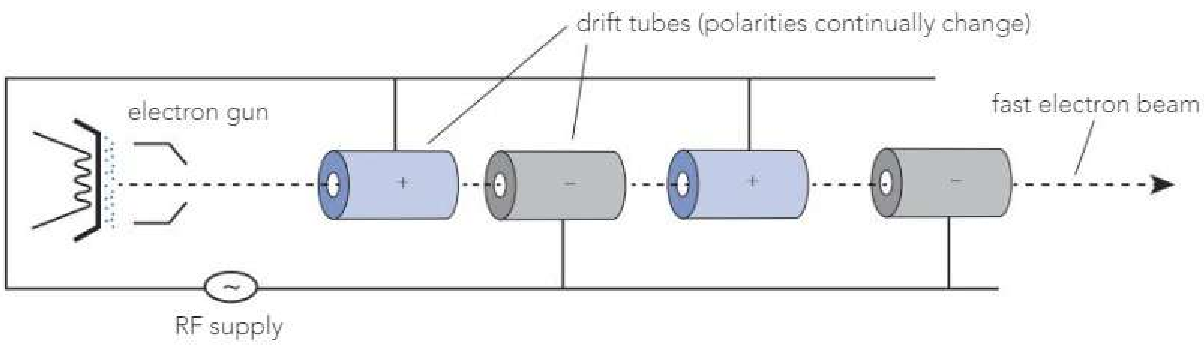


Figure 5.10 *A simplified diagram of a linear accelerator. The electrons travel in a straight line through the centre of a series of tubes connected to a high frequency alternating voltage. The frequency is timed so that the tubes act as a series of changing cathodes and anodes in the electrons path.*

The synchrotron

The Australian Synchrotron is a very large device that accelerates electrons to extremely high energies. These electrons, travelling at close to the speed of light, are made to travel in a circular path by the use of powerful magnets. The circular motion means that the electrons are effectively accelerating and this causes radiation to be emitted. This radiation, called synchronous radiation, is used to carry out a wide range of research.

The Synchrotron has many components beginning with the electron source and finishing at the end-station where the synchronous radiation is used for particular research. The Australian Synchrotron, which is located in Melbourne, takes up an area almost as large as a football oval. The main components of this synchrotron are as follows.

- **Electron gun:** Electrons are produced by emission from a hot tungsten cathode. They are accelerated in bunches to 90 keV.
- **Linear accelerator (linac):** This device uses a series of radio frequency cavities to further accelerate the electrons to velocities greater than 0.9999c.
- **Booster ring:** This large circular device, 130 m in circumference, boosts the energy of the electron beam from 100 Mev to 3 GeV. It contains a series of powerful magnets to keep the beam in circular motion and an RF cavity to provide energy.
- **Storage ring:** This is where the beam is 'stored' or allowed to circulate for many hours. Again this is a large device in order to allow sufficient curvature for the fast moving beam. The overall shape is circular although it actually consists of several straight sections followed by arcs. At each arc powerful magnets are used to bend the electron beam. This is where the synchrotron light is produced.
- **Beam lines and end-stations:** The synchrotron light (radiation) is directed down long pipelines, called beam lines, to areas where research takes place. These areas, called end stations, receive synchronous radiation of selected energies or wavelengths suitable for the particular investigation taking place. Available energies range from infrared to hard X-rays allowing a wide variety of investigative techniques.

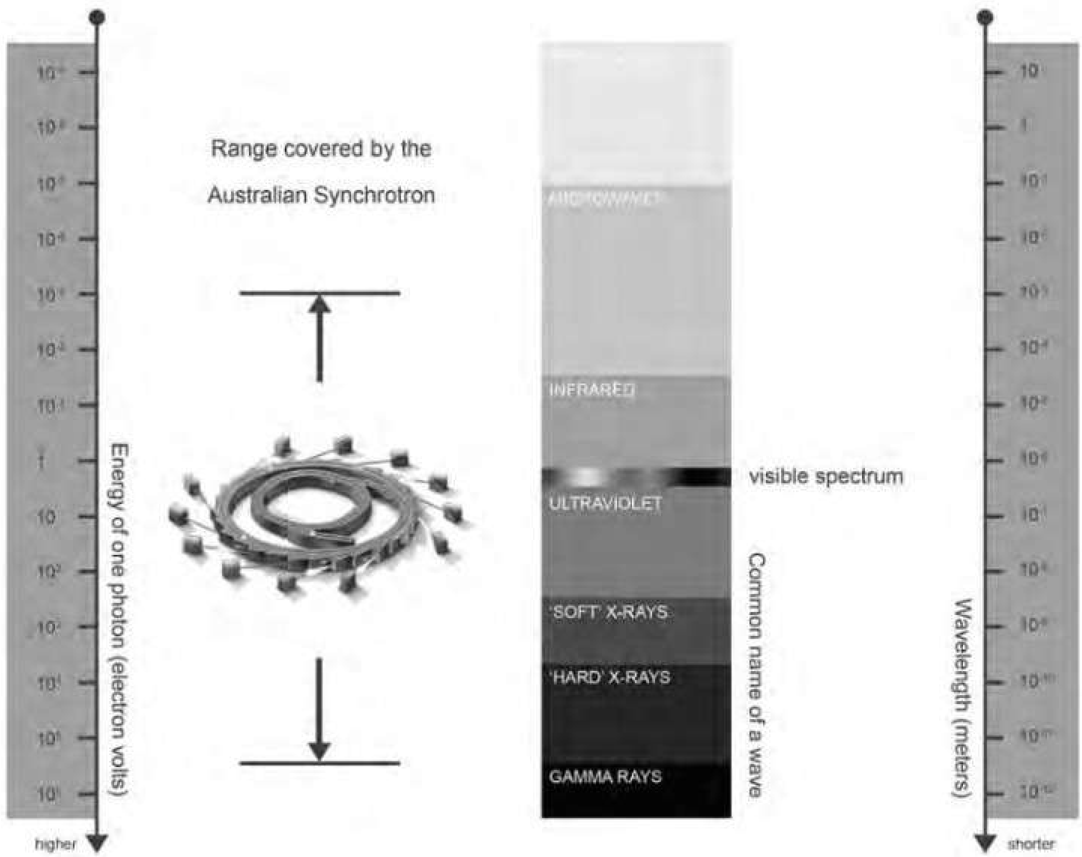


Illustration courtesy of the Australian Synchrotron

Question 5.8

(a) By what means are fast electrons produced in the electron gun at the Australian Synchrotron?

(b) How are the electrons accelerated in a linear accelerator?

(c) How are the very fast moving electrons in the booster ring of a synchrotron made to travel in a circular path?

(d) In which part of the Australian Synchrotron is synchrotron light produced? What causes this light?

Question 5.9

The first component of the Australian Synchrotron is an electron gun producing electrons by thermionic emission from a hot tungsten cathode. The electrons are accelerated by a 90.0 kV voltage towards the anode. Ignoring any relativistic effects determine the following.

(a) The maximum kinetic energy of the electrons in J and eV units.

(b) The maximum velocity of the electrons.

Question 5.10

The linear accelerator of the Australian Synchrotron is able to accelerate electrons to 99.9987% of the speed of light. Determine the energy of these electrons using the relativistic formula for total energy given in Chapter 4. Give your answer in J and MeV.

5.4 CHARGED PARTICLES IN MAGNETIC FIELDS

Interaction between charged particles and magnetic fields

As we saw in the chapter on Electromagnetism, a moving charge creates a magnetic field around itself. If the charge passes through an area which already has a magnetic field then there will be an interaction – that is a force will be exerted on the particle. The force will be at right angles to the motion of the particle (consistent with the right hand palm rule) and causes the particle to move in a circular path.

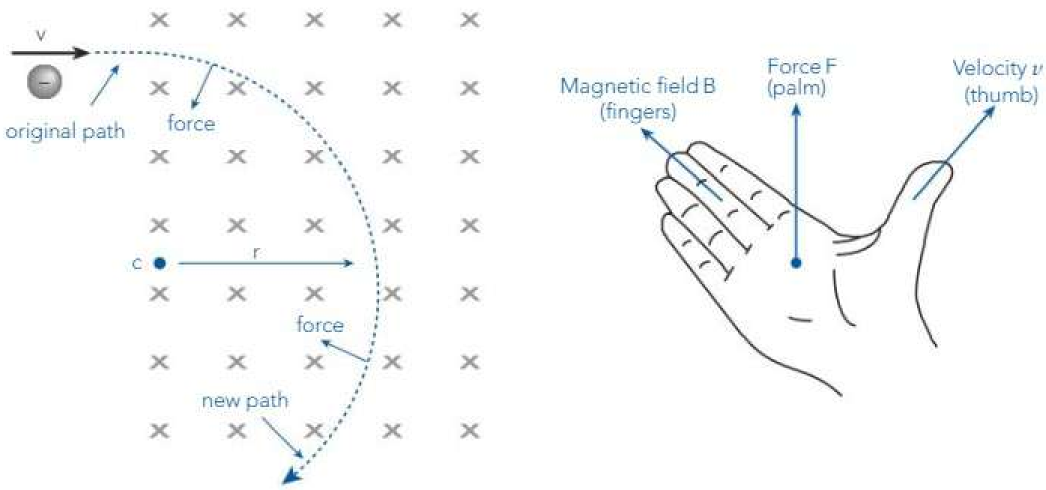


Figure 5.11 *Force on a moving charge. The right hand palm rule gives the direction of the force which is always at right angles to the movement. This causes circular motion.*

As we saw in Chapter 2 force on the charged particle is given by:

$$F = q\,v\,B$$

The charged particle will experience a force which is at right angles to its motion. If this motion was originally at right angles to the magnetic field then circular motion will result.

Since the force on the particle is always at right angles to its motion it is essentially a centripetal force. Hence we have:

$$F_c = \frac{mv^2}{r} = q\,v\,B \text{ which will give}$$

$$r = \frac{mv}{Bq}$$

r = radius of curvature (m)
m = mass of particle (kg)
v = velocity (m s^{-1})
B = magnetic field strength (T)
q = charge of particle (C)

We can see then that for a given magnetic field strength the circular path of a charged particle will depend on its *mass*, its *charge* and its *velocity.*

Worked Example 5.4

An electron initially at rest is accelerated horizontally due West through a potential difference of 22.0 kV. It then enters a vertical (upwards) magnetic field of 1.25×10^{-2} T. Determine:

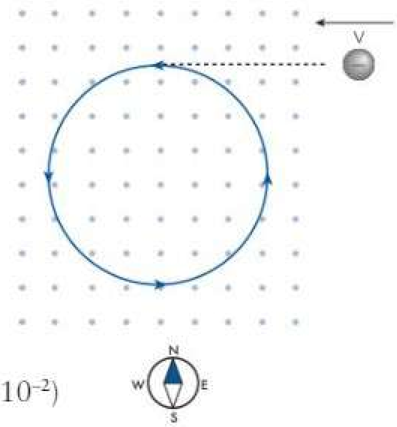
(a) The velocity achieved by the electron, ignoring any relativistic effect.
(b) The force exerted on the electron by the magnetic field.
(c) The radius of curvature of the electrons path in the magnetic field and its direction of motion.

(a) The electron will gain kinetic energy from the electrical work done on it.

i.e. $E_K = \frac{1}{2}mv^2 = Vq$

$$\therefore v^2 = \frac{2Vq}{m} = \frac{(2)(2.20 \times 10^4)(1.60 \times 10^{-19})}{9.11 \times 10^{-31}}$$

$$\therefore v = 8.79 \times 10^7 \text{ m s}^{-1}$$



(b)
$$F = qvB = (1.6 \times 10^{-19})(8.79 \times 10^7)(1.25 \times 10^{-2}) = 1.76 \times 10^{-13}\text{ N}$$

(c)
$$F_C = \frac{mv^2}{r} = 1.76 \times 10^{-13}$$

$$\therefore r = \frac{mv^2}{1.76 \times 10^{-13}} = \frac{(9.11 \times 10^{-31})(8.79 \times 10^7)^2}{1.76 \times 10^{-13}} = 4.00 \times 10^{-2}\text{ m}$$

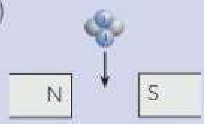
or more simply
$$r = \frac{mv}{Bq} = \frac{(9.11 \times 10^{-31})(8.79 \times 10^7)}{(1.25 \times 10^{-2})(1.6 \times 10^{-19})} = 4.00 \times 10^{-2}\text{ m}$$

Hence the electron would follow a circular path of 4.00 cm in an anticlockwise direction if viewed from above.

Question 5.11

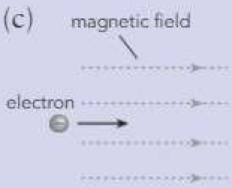
State or indicate the direction of the force acting on the charged particle in each case.

(a)

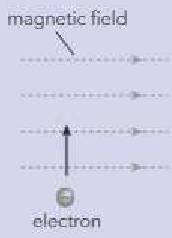


(b)

(c)



(d)



__________ __________ __________ __________

Question 5.12

Three particles, a proton, a neutron and an electron enter a magnetic field from the same direction and with the same velocity. Assume they entered at right angles to the field. Compare their consequent paths in the magnetic field in terms of:

(a) direction

(b) radius of curvature.

Question 5.13

How would the paths of an electron and positron compare if they both entered a magnetic field as in the previous question?

Question 5.14

A positron enters a magnetic field of 5.25×10^{-2} T at right angles to the field. Its velocity is 2.45×10^{6} m s^{-1}. Ignoring any relativistic effects, determine the radius of curvature of the positrons path in the magnetic field.

Electric and Magnetic Fields Combined

Magnetic and electrical fields can be used in combination or in sequence to separate and identify charged particles. If a charged particle moves through an area where both magnetic and electrical fields exist it will experience a force from each of them. These forces will not necessarily be equal or in the same direction.

Electric and magnetic fields act differently on charged particles. Some similarities and differences are summarised below. Importantly, the force exerted by a magnetic field depends on the particles velocity whereas it makes no difference in an electric field. This allows charged particles to be separated on the basis of thek specific velocity such as in the velocity selector used in conjunction with a mass spectrometer.

Table 5.4 The action of electric and magnetic fields on charged particles. When these fields are used in combination they can separate charged particles.

Field	Similarities	Differences
Electric Field $F = Eq$	Force depends on: • magnitude of the field • magnitude of the charge	Force is: • parallel to the field • independent of velocity
Magnetic Field $F = qvB$	Force depends on: • magnitude of the field • magnitude of the charge	Force is: • perpendicular to the field • proportional to velocity

The velocity selector

This device allows charged particles to be separated or selected on the basis of their velocity. Electric and magnetic fields are arranged perpendicular to each other so that charged particles moving through the fields experience equal and opposite forces. This will only occur for specific velocities depending on the magnitude of the two fields.

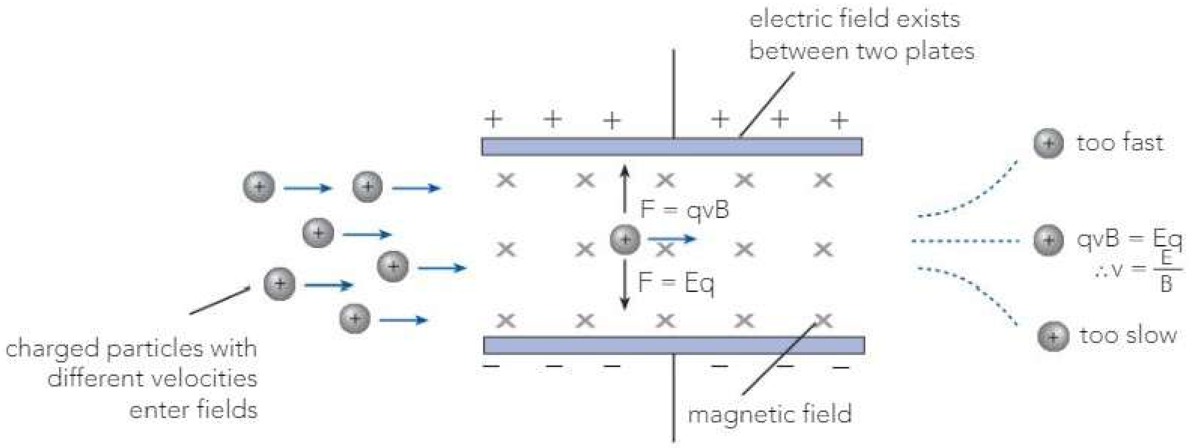


Figure 5.12 The velocity selector. Electric and magnetic fields are perpendicular to each other. Adjusting the values of E and B allows particles of specific velocities to be selected.

Question 5.15

A beam of electrons is fired into and perpendicular to a magnetic field of 5.25×10^{-4} T with a velocity of 4.45×10^{5} m s^{-1}. Determine:

(a) the force acting on each electron

____

____

(b) the radius of curvature of the subsequent path of the beam of electrons.

____

____

Question 5.16

An electric field of 5.00×10^3 V m^{-1} is set up at right angles to a magnetic field of 2.60×10^{-2} T. Alpha particles of mass 6.70×10^{-27} kg are fired at right angles to both fields.

(a) Determine the velocity of the alpha particles if they are able to pass through undeflected.

(b) Determine the change necessary to the electrical field if alpha particles of twice the velocity of those in (a) are to pass through undeflected.

Question 5.17

A proton moving at 6.85×10^4 m s^{-1} enters an area with a combined electric and magnetic field and goes through undeflected. If the electric field has an intensity of 1.45×10^3 V m^{-1} what must be the magnetic field strength? Assume the fields are perpendicular to each other.

The mass spectrometer

As we have seen, when charged particles enter a magnetic field they move in a circular path. The radius of curvature depends both on the mass and the velocity of the particle.

A very important application of this effect is the mass spectrometer which can be used to measure the masses and relative concentrations of atoms and molecules. They are also used to determine isotopic masses, assist in radioactive dating and identify small traces of contaminants or toxins.

The substance to be analysed is initially vaporised and then ionised by placing it in a strong electric field which produces positive ions. The ions are then accelerated by another electric field before they enter the mass spectrometer.

They enter the spectrometer perpendicular to a very strong magnetic field in a vacuum. The ions then follow a circular path whose radius is measured by the position of the detectors.

A velocity selector is sometimes also used prior to the ionised particles entering the mass spectrometer. This is helpful since the variation in the measured radius of curvature will only depend on the mass of the charged particle.

This is assuming all particles carry the same charge. However any difference in charge would give distinctly different results compared to small changes in masses and hence is easily accounted for.

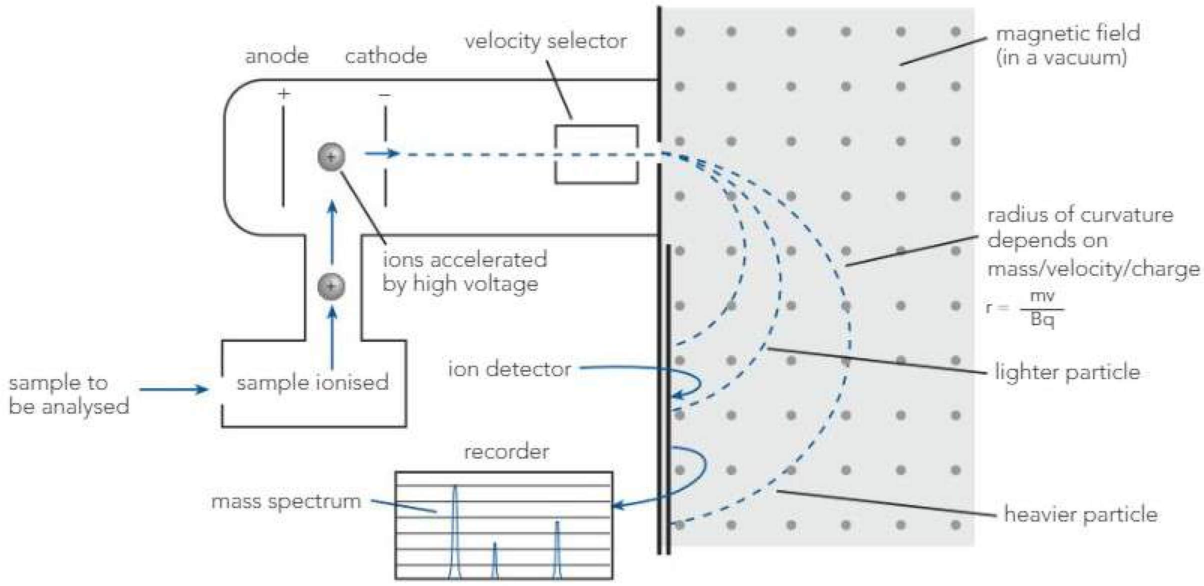


Figure 5.13 Simplified view of the mass spectrometer. The sample to be analysed is firstly ionised and then its ions are accelerated. A velocity selector is used if just identifying masses. The mass spectrometer is essentially a strong magnetic field in a vacuum with suitable detectors. The mass spectrum gives distinctive peaks for each isotope.

Question 5.18

(a) Substances to be analysed by a mass spectrometer are firstly ionised. Why is this necessary?

___

___

___

___

(b) Determine the voltage required to accelerate protons from rest to a velocity of 6.40×10^5 m s^{-1}.

___

___

(c) When a charged particle enters a mass spectrometer which of its properties influence the radius of curvature?

___

___

___

___

REVIEW QUESTIONS

Chapter 5: The Standard Model

The Universe

1. Early scientists such as Aristotle and Ptolemy proposed a geocentric model of the universe. Explain what is meant by this model and how it is different to that advanced by Copernicus some 1500 years later during the sixteenth century.

2. Light from distant galaxies exhibits what is known as a red shift when viewed through a spectrograph. Explain what is meant by the red shift and what is believed to be the cause of it.

3. In 1905 Albert Einstein announced his Special Theory of Relativity that included his concept of space-time. In what particular way did this concept alter our view of the universe?

4. In the early 1920s Alexander Friedmann developed a set of equations to describe the universe based in part on Einstein's General Theory of Relativity. Of what particular significance are these equations?

5. Edwin Hubble made many advances in our understanding of the universe during the 1920s. His detailed observation of distant galaxies and interpretation of the red shift discovered by other astronomers led to what is now referred to as Hubble's Law.
   (a) What particular feature about distant galaxies was Hubble able to predict?
   (b) What connection did he find with his results and the red shift?
   (c) State Hubble's Law.
   (d) Of what special significance is Hubble's constant?

6. The discovery of cosmic microwave radiation in 1965 was fairly significant to our understanding of the universe. Explain the reason for this.

7. Briefly explain how the distance to the stars is determined.

8. Because the distances involved in astronomy are so large a specific set of distance units are commonly used. These are the light year, the astronomical unit (AU) and the parsec.
   (a) Define each of these units.
   (b) Give the value of each unit in km.

9. The distance to the Andromeda galaxy is about 2.5 million light years away. Determine this distance in parsec and in km.

10. The speed of light is extremely fast, 3.0×10^8 m s^{-1}. Determine how long it would take a beam of light to reach you from:
   (a) a street light 20 m away,
   (b) a campfire 3.0 km away,
   (c) the Sun, 1.5×10^8 km away,
   (d) Alpha Centauri, 4.3 light years away.

11. Protons and neutrons are made up of fundamental particles called quarks. How many different type of quarks are there and how many are contained within protons and neutrons?

12. The neutrino is one of the fundamental particles of nature but proved very difficult for scientists to detect. Suggest two main reasons for this difficulty.

13. Complete the following nuclear reaction of the *Beta minus* decay of silicon-31 to form phosphorus-31, a beta minus particle and an antineutrino.

$$^{31}_{14}\mathrm{Si} \quad \rightarrow$$

14. Complete the following nuclear reaction of the *Beta plus* decay of phosphorus-30 to form silicon-30, a beta plus particle and a neutrino.

$$^{30}_{15}\mathrm{P} \quad \rightarrow$$

15. In 1931 Wolfgang Pauli suggested the existence of a then unknown particle (later termed the neutrino) as a result of his investigations of beta decay. This was despite him not been able to detect such a particle. Discuss the experimental evidence which led Pauli to make this prediction.

16. Positrons were discovered in the early 1930s during the investigation of cosmic rays. Experiments showed that positrons were similar but different to electrons. What are the similarities and differences between these two particles?

17. (a) In nature, the many different forces can all be understood in terms of four fundamental interactions. List these.
    (b) What is the general name given to the mediating particles for fundamental interactions?
    (c) What type of interaction involves Z^0 particles?

18. When two electrons approach each other they repel by way of an electromagnetic interaction.
    (a) Name the mediating particle in this case.
    (b) Illustrate the interaction by way of a Feynman diagram.

19. The Standard Model is a combination of different models put forward to explain the nature of particles and matter.
    (a) How many fundamental matter particles are there in this model?
    (b) What are their general group names?
    (c) What is the name given to force carriers in this model?

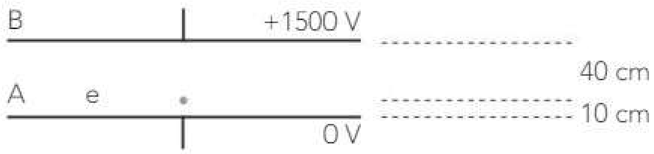
20. A neutron is made up of an up quark, u, and two down quarks, d, d.
    (a) Illustrate this combination and verify the charge and baryon number for a neutron.
    (b) Illustrate and verify the result of using anti quarks of the same type.

21. An unknown particle X is made up of an up anti quark, $\overline{u}$, and a down quark, d.
    (a) Is particle X a meson or a baryon?
    (b) Determine the charge and baryon number of X.

22. Briefly explain the difference between each of the following.
   (a) A lepton and a quark.
   (b) A lepton and a hadron.
   (c) A fermion and boson.

Particle accelerators

23. Two parallel plates are 50.0 cm apart with a potential difference of 1500 volts. An electron, initially at rest, is located 10.0 cm from plate A as shown. Determine the following:



   (a) The direction and magnitude of the electric field between the plates A and B.
   (b) The direction and magnitude of the force acting on the electron.
   (c) The direction and magnitude of the electrons acceleration.
   (d) The maximum velocity of the electron.

24. An alpha particle of mass 6.65×10^{-27} kg is located midway between two parallel plates where the electric field strength is 2.60×10^{3} V m^{-1}.
   (a) What will be the force acting on the alpha particle?
   (b) What work will be done on the alpha particle if the force moves it 3.50 mm towards the negative plate?
   (c) Calculate the subsequent velocity of the alpha particle if it was initially at rest.

25. An electron gun consists essentially of a hot cathode and an anode in an evacuated tube. Explain the purpose of each of these three components and how a fast stream of electrons is produced.

26. An electron in a cathode ray tube is accelerated through 4.25×10^{3} volts. Ignoring any relativistic effects determine the electrons final:
   (a) Kinetic energy
   (b) Velocity.

27. The Australian Synchrotron is an important device for a wide variety of important research. Answer the following.
   (a) Name the main components of the Australian Synchrotron.
   (b) Which components require very strong magnets and why.
   (c) From which component are beam lines attached.
   (d) What is produced by the Australian Synchrotron?

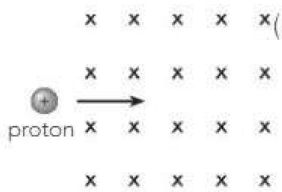
28. In the linear accelerator of the Australian Synchrotron the electrons reach a velocity of 99.99 % of the speed of light within the first metre of travel. Use the relativistic formulae to determine the total energy of the electrons at this point.

29. In the storage ring of the Australian Synchrotron the electrons have 3.0 GeV of energy. Use the relativistic formulae to determine the velocity of the electrons in the storage ring.

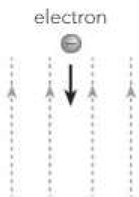
Charged particles in magnetic fields

30. Indicate the direction of the force (if any) that would be exerted on the electrons (e-) and protons which are moving as shown.

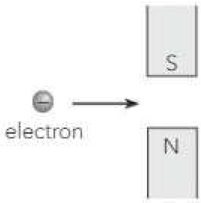
(a)



(b)



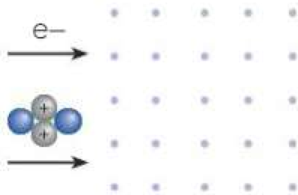
(c)



(d)

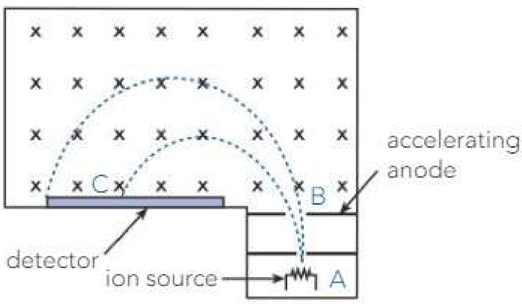
31. A positron (mass 9.11×10^{-31} kg) is fired into a magnetic field of 1.25×10^{-1} T as shown. The proton's velocity is 6.25×10^{7} m s^{-1}.
   (a) When the positron enters the field in which direction will the force act?
   (b) What is the magnitude of this force?
   (c) determine the radius of curvature of the path of the positron.
   (d) If an electron were fired into the same field with the same velocity, describe any differences to the result in (b) and (c).

32. An electron and an alpha particle moving with equal velocities both enter a magnetic field as shown.



   (a) Indicate the direction of the forces on each of these as they pass through the field.
   (b) Which particle will experience the greatest force? By what factor?
   (c) Which particle will experience the greatest acceleration? Why?

33. A mass spectrometer is used to separate and help identify small charged particles. The radius of curvature of the particle's path in the magnetic field can be used to give an accurate determination of its mass (when combined with other known data).



Charged particles from the ion source (A) are accelerated by the anode (B) and enter the magnetic field which causes them to move in a circular path to C.

(a) Show that the radius of this circular path is given by: $r = \frac{mv}{Bq}$

(b) Use this relationship for the following:

(i) Determine the radius of curvature of protons entering the magnetic field (4.50×10^{-2} T) with a velocity of 8.00×10^{4} m s^{-1}.

(ii) Determine the radius of curvature of alpha particles entering the magnetic field with the same velocity as the protons.

(iii) What is the ratio of the two radii?

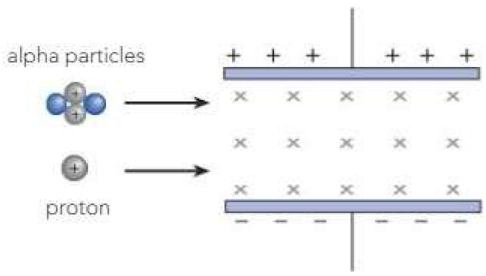
34. A mass spectrometer (as shown in question 33) is used to determine the mass of doubly ionised argon atoms. The argon ions enter the magnetic field with a velocity of 1.71×10^{4} m s^{-1} and describe a path of 9.40 cm radius. The magnetic field strength in the mass spectrometer is 5.50×10^{-2} T. Use the formulae from the previous question to determine the mass of the argon atoms.

35. A proton and an alpha particle enter a mass spectrometer with the same velocity.
    (a) Which particle will describe a circular path of greatest radius of curvature?
    (b) By what factor?

36. A velocity sector is often used in conjunction with a mass spectrometer to select charged particles of only one specific velocity.
    (a) Explain how this is possible.
    (b) Why is it preferable to know that the charged particles entering the mass spectrometer all have the same velocity?

37. A stream of protons enters a velocity selector at varying speeds. The selector contains an electric field of 6.40×10^{3} V m^{-1} at right angles to a magnetic field of 4.26×10^{-2} T. Assuming the protons enter the selector at right angles to both fields, determine the velocity of protons that pass through without any change in direction.

38. A velocity selector has an electric field of 8.25×10^{4} V m^{-1} at right angles to a magnetic field as shown. A proton with a velocity of 2.40×10^{5} m s^{-1} is able to pass through the selector undeviated.



(a) Determine the magnetic field strength of the velocity selector.

(b) If an alpha particle is to go through the selector undeflected, what would be its velocity?

TRIAL TEST 1: GRAVITY AND MOTION

Time allowed:	**60 minutes**	**Section One** – Short response	18 marks
Total marks:	**60**	**Section Two** – Problem solving	30 marks
		Section Three – Comprehension	12 marks

SECTION ONE – SHORT RESPONSE (18 MARKS)

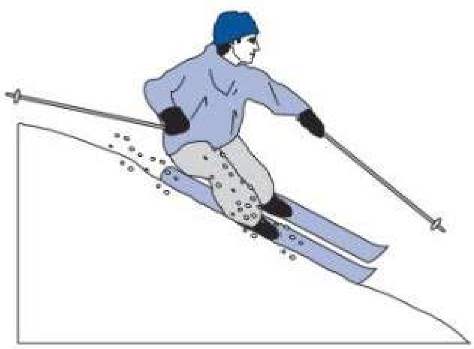
1. Rob is skiing down a 12.0° slope and achieves a constant velocity of 65.0 kmh^{-1}. His mass is 72.5 kg.

   (a) What is the weight force acting on Rob parallel to the slope?

   (b) What is the magnitude of the friction force between the skis and the slope?

   (c) Calculate Rob's kinetic energy and momentum.

[3 marks]



2. Lynette is at the "knock them down" games at an amusement park. She throws a ball horizontally and directly at a target 2.60 m away but she misses. The ball was thrown with a velocity of 22.0 m s^{-1}.

   (a) Why did Lynette miss her target? (Assume that the ball had been aimed accurately towards the target).

(b) By how much was Lynette off target?

[3 marks]

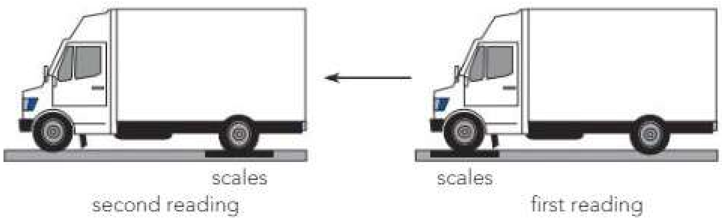
3. A thick nylon rope is erected between two walls to serve as a clothes line. It is found that no matter how tight the rope is pulled it is never exactly horizontal. Explain this observation.

[2 marks]

4. It is noticeable that during a sumo wrestling match, each of the contestants stands with their feet wide apart and their knees bent. Explain clearly how each of these actions helps them to avoid being toppled.

[2 marks]

5.



When checking the weight of a large truck, the process is usually carried out in two stages. Firstly, the front set of wheels is allowed over the weighing mechanism and a reading is taken. The truck is then moved to allow the rear wheels over the weighing mechanism and a second reading is taken. Explain clearly how and why it is possible to use these two readings to determine the weight of the truck.

[2 marks]

6. Athletes running around a circular track always lean inwards.

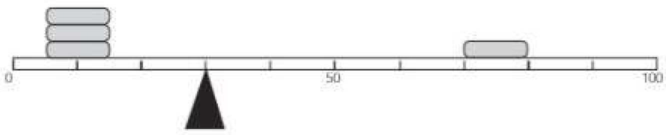
(a) Why is it necessary to lean?

(b) How does this help?

(c) Which factors would influence the angle of lean?

[3 marks]

7. Jennifer balances some masses on her metre ruler as shown in order to determine its mass. She finds that when she places three 50.0 g masses at the 10.0 cm mark and one 50.0 g mass at the 75.0 cm mark the ruler will just balance at the 30.0 cm mark.



(a) Calculate the torque due to the three 50.0 g masses at the 10.0 cm mark.

(b) If the ruler balances with the masses as shown what is its mass? Assume the ruler is of uniform shape and density.

[3 marks]

SECTION TWO – PROBLEM SOLVING (30 MARKS)

8. Planet Piccolo is a small dense planet. Planet Jumbo is a large dense planet with double the radius of Piccolo and four times its mass.

(a) If Frank weights 800 N on the surface of Piccolo how much will he weigh on the surface of Jumbo?

[2 marks]

(b) If the planet Jumbo was of the same density as Piccolo, how much would Frank weigh on its surface?

[4 marks]

9. Andrew throws a cricket ball to Paul with a velocity of 28.0 m s^{-1} at an angle of 16.0° to the horizontal. Paul catches the ball a little later at the same height as it was released. Assume no air resistance and determine the following.

(a) The vertical and horizontal components of the ball's initial velocity.

[2 marks]

(b) The height above the release point achieved by the ball.

[2 marks]

(c) The distance between Andrew and Paul.

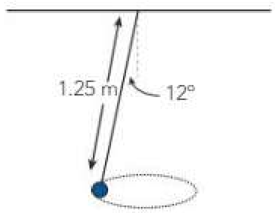
[2 marks]

(d) Maximum range is usually achieved with an initial trajectory of 45° to the horizontal. Suggest why Andrew has thrown the ball at such a low angle to Paul.

[1 mark]

10. A small metal mass of 250 g is attached to an overhead support by a thin fishing line 1.25 m and allowed to swing freely as shown. The line makes an angle of 12.0° to the vertical at all times.

(a) There are only two external forces acting on the mass. Indicate these forces on a suitable vector diagram and calculate their magnitude (HINT: the sum of forces acting on the mass in a vertical direction is zero).



[3 marks]

(b) Determine the centripetal force acting on the mass.

[2 marks]

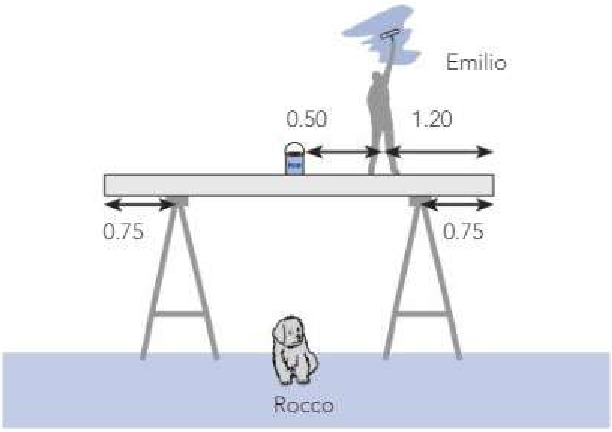
(c) Determine the speed of the mass.

[2 marks]

(d) What is the theoretical period of rotation for this mass?

[2 marks]

11. Emilio is standing on a 12.0 kg plank supported by two trestles as shown. The plank is 3.80 m long and is supported 75.0 cm from each end. Emilio has a mass of 72.0 kg and is standing 1.20 m from the right end of the plank. His 6.50 kg paint tin is located 50.0 cm to his left as shown.



(a) On the diagram above indicate and fully label all the forces acting on the plank.

[2 marks]

(b) Determine the forces exerted by each trestle on the plank.

[3 marks]

(c) In order for Emilio to finish a far corner he needs to stand as close as possible to the right end of the plank. Assuming the paint tin is not moved, determine how close to the right hand end of the plank Emilio can safely stand.

[3 marks]

SECTION THREE – COMPREHENSION (12 MARKS)

Read the article on communications satellites and then answer question 12.

COMMUNICATIONS SATELLITES

The first commercial communications satellite went into operation in 1965. Since then, many systems of satellites have gone into action across the globe. About half of all the world's international calls are carried via satellites, and increasingly, satellites are used to provide communications within a single country, as well as other services such as Pay TV.

Communications satellites are held in a geostationary orbit some 36,000 kilometres above the earth. They are placed in this orbit by rockets or a space shuttle. At this height, they take the same time to complete an orbit around the Earth as the Earth takes to complete a single rotation – almost 24 hours. This means the satellites appear to stay in the same place in relation to Earth.

Satellites' antennas have a 'footprint', or coverage area on Earth. This can be up to almost half the surface of the Earth. Satellites for international communications are usually positioned so that they can communicate with a whole continent.

To transmit telecommunications signals to and from a satellite, an antenna on the ground is needed. This can be a dish, which focuses signals on to a receiver in the centre, or it can be a rod style antenna. In the case of dishshaped antennas, the larger the diameter, the more powerful they are. Earth stations for international communications have dish antennas up to 30 metres in diameter, but dishes of as little as 30 centimetres can receive satellite signals, for example for mobile communications or Pay TV signals.

A satellite's typical lifespan is ten years. Its life is usually determined by the amount of fuel it can carry on board. This fuel is required to fire small thrusters or stabilisers on board, which keep the satellite in position, and corrects for any drift in the orbit position of the satellite that occurs over time. This drift occurs because of the gravitational attraction of the moon and sun, and because the Earth is not perfectly circular in shape.

12. (a) List two major uses for communications satellites:

(i) ______________________________

(ii) ______________________________

[2 marks]

(b) Viewed from Earth, communications satellites remain is a fixed position in the sky.

(i) Why do they appear not to move?

____

(ii) Why don't they fall down to Earth?

____

____

[2 marks]

(c) (i) Receiving antennas on Earth are usually dish shaped. Why?

____

(ii) The size of these antennas can vary greatly. What are the maximum and minimum sizes quoted in the article?

____

____

(iii) The signal energy collected by the large antenna would be greater than that of the small antenna. By what factor?

____

____

[3 marks]

(d) (i) Why do communications satellites have fuel on board?

____

____

(ii) There is no atmosphere whatsoever in the region of the satellite yet over time they drift? What are two reasons for this?

____

____

____

[2 marks]

(e) (i) It can be shown that the period of a satellite is given by: $T^2 = \frac{4\pi^2 r^3}{Gm_E}$

Assuming the satellite is 36,000 km above the Earth determine its period in hours.

____

____

[2 marks]

(ii) Comment on your result.

____

____

[1 mark]

END OF TEST (60 MARKS)

TRIAL TEST 2: ELECTROMAGNETISM

Time allowed:	**60 minutes**	**Section One** – Short response	18 marks
Total marks:	**60**	**Section Two** – Problem solving	30 marks
		Section Three – Comprehension	12 marks

SECTION ONE – SHORT RESPONSE (18 MARKS)

1. Draw a diagram showing the electric field distribution for:

    (a) two identical negatively charged spheres placed near each other,

    (b) a positively charged sphere placed near an earthed metal plate,

[2 marks]

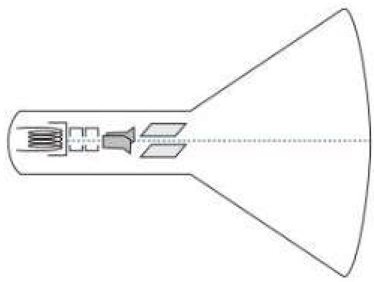
2. (a) When considering the electric field that exists between two parallel plates we are often given the voltage or potential difference between them. Define potential difference in terms of the work done on a charge moved by the field.

____

____

[1 mark]

(b) A CRO monitor has a potential difference in its picture tube of 3.00×10^3 V across which electrons (with charge of 1.60×10^{-19} C) are accelerated. Calculate the energy acquired by the electrons as they are accelerated through this potential difference.



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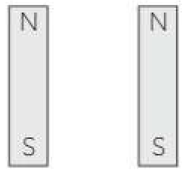
____

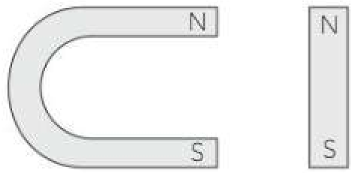
[1 mark]

3. Sketch the magnetic fields surrounding the magnets in the situations shown below. Assume all magnets are of equal strength.

(a)



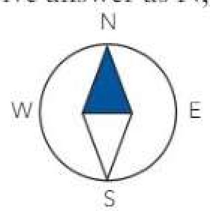
(b)



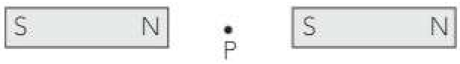
[2 marks]

4. A small compass is placed at each of the points indicated by P in the different situations below. Determine the directions of the compass in each case. Give answer as N, S, E, W, into page, out of page or directionless.

Directions on the page are as indicated at right.

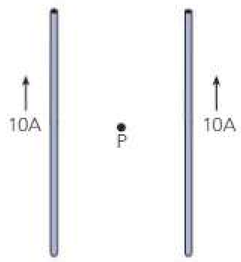


(a)



Answer: ______________________

(b)

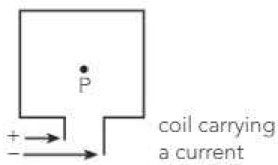


Answer: ______________________

(c)

Answer: ______________________

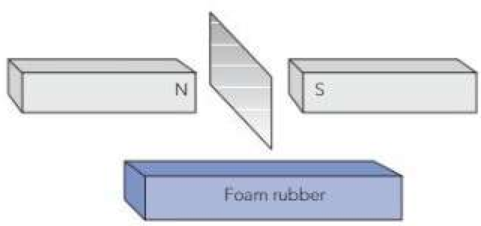
(d)



Answer: ______________________

[2 marks]

5. A flat sheet of copper metal is allowed to fall freely between and beyond two strong bar magnets. It does not touch the magnets and is allowed to fall onto soft foam rubber.



(a) After repeating this procedure several times, it is noticed that the copper metal becomes warm. Explain the cause of this heat.

____

____

[1 mark]

(b) How would the amount of heat produced in the metal sheet be affected if:

(i) the magnets are moved slightly closer together (assume all other conditions remain the same)? Why?

____

____

[1 mark]

(ii) the flat sheet was made of aluminium which has a higher resistance than copper? Why?

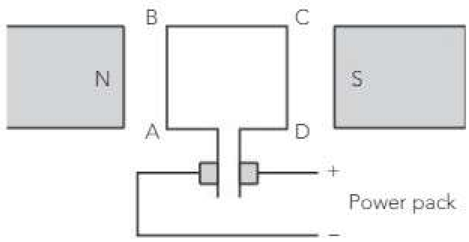
____

____

[1 mark]

6. A coil A, B, C, D is placed as shown in a strong magnetic field of 0.55 T. A current of 3.60 A passes through the coil from the power pack.

Assume AB = CD = 50 cm,
BC = AD = 40 cm.



(a) Determine the magnitude and direction of the force exerted on CD.

____

____

[1 mark]

(b) Calculate the total torque produced in this arrangement.

____

____

[1 mark]

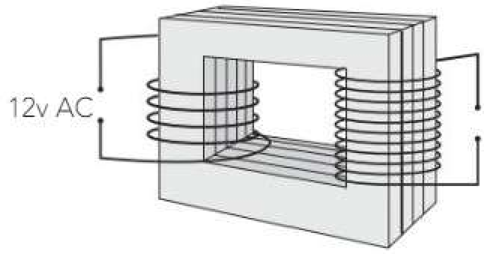
(c) State two means by which this torque could be increased.

____

____

[1 mark]

7. A typical transformer is shown. It has about twice as many turns of wire in the secondary coil than it has in the primary coil.



(a) Will the induced voltage be greater or smaller than the applied voltage? Explain.

____

____

[1 mark]

(b) Explain why the secondary coil is made of thinner wire.

____

____

[1 mark]

(c) Why is the core of the transformer laminated?

____

____

[1 mark]

(d) Will the transformer work equally well with DC current? Why/Why not?

____

____

[1 mark]

SECTION TWO – PROBLEM SOLVING (30 MARKS)

8. Two parallel plates, 15.0 mm apart, have a voltage of 275 V applied across them.

(a) Determine the electric field intensity between the plates.

[3 marks]

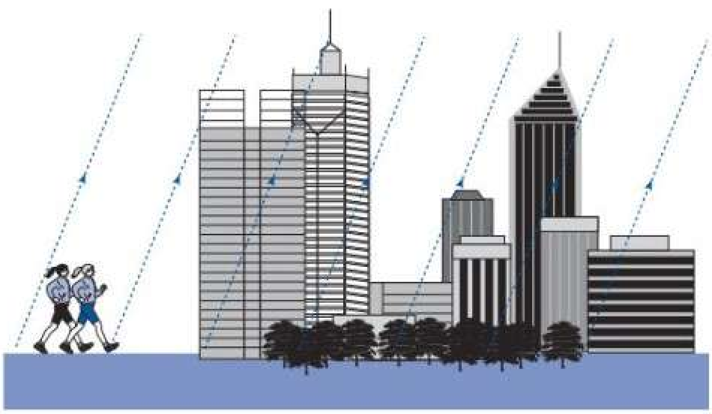
(b) Calculate the force acting on a dust particle carrying a charge of -4.00×10^{-17} C which is located midway between the plates.

[3 marks]

(c) As the dust particle moves 5.00 mm towards the positive plate are there likely to be any changes to the force being exerted on it? Explain.

[1 mark]

9. Two Perth students set out to investigate the possibility of creating a simple electric motor using a coil carrying a current in the Earth's magnetic field.



Assume the Earth's magnetic field where the students are is 5.90×10^{-5} T at 66° to the horizontal. The students construct a single copper coil 50.0 cm by 50.0 cm and arrange it so that it is freely pivoted.

(a) How should the students arrange their coil to achieve maximum torque? Include a clearly labelled sketch showing orientation of coil, current flow, forces produced and any other relevant information.

[2 marks]

(b) Determine the total torque on the coil that could be achieved in this manner with a current of 5.00 A.

[2 marks]

(c) Discuss the likely outcome or results of the students' experiment. Give reasons.

[1 mark]

(d) How could the boys improve the torque produced by their simple motor?

[1 mark]

(e) Could this experiment give better results at some other point on Earth? Explain.

[1 mark]

10. A rescue helicopter with blades that span 10.7 m across is operating in an area where the Earth's magnetic field is 5.85×10^{-5} T at an angle of 66° to the horizontal. Prior to take off the rotor blades are moving at 375 rpm in a clockwise direction when viewed from the ground.

It is found that the motion of the blades causes a potential difference between their ends.

(a) Which part of the rotor blades would be:

(i) positive? ___________________________

(ii) negative? ___________________________

[1 mark]

(b) Calculate the vertical component of the Earth's magnetic field at this point.

____

____

____

[1 mark]

(c) Calculate the total flux enclosed in the area swept out by the blades.

____

____

[1 mark]

(d) What would be the maximum EMF induced in the blades?

____

____

____

[3 marks]

(e) Between which points in the blades would this maximum EMF exist? Why?

____

[1 mark]

(f) The helicopter, which is facing south, tends to lean forward as it takes off, that is its tail lifts. How will this affect the induced EMF? Why?
(Assume blades still moving at 375 rpm).

____

____

____

[1 mark]

11. The Muja power station in the South West of W.A. provides electricity to Kalgoorlie by way of a 220 kV transmission line 650 km in length.

(a) Why are such high voltages used to transmit electricity over this distance?

[1 mark]

(b) What are some of the difficulties and possible dangers of transmitting power at such high voltages?

[1 mark]

(c) If this line is transmitting 20.0 MW of power, determine:

(i) current on the line;

(ii) power loss due to resistive heating if the total resistance of the line is 45 Ω.

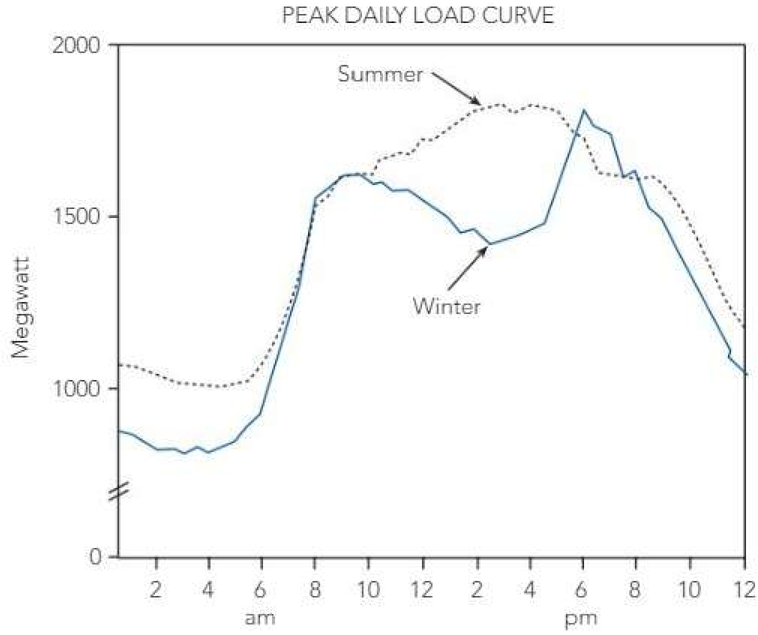
[3 marks]

(d) Determine the power loss if the power had been transmitted from Muja to Kalgoorlie with a 66 kV line. Comment on your result.

[3 marks]

SECTION THREE – COMPREHENSION (12 MARKS)

12. The graph below shows the seasonal variation in daily power consumption for a local electricity system.



Use the graph to answer the following questions.

(a) What is the highest rate of power consumption during a summer day?

____

[1 mark]

(b) At what time of the day is the greatest amount of electricity being used:

(i) in summer? ______________________

(ii) in winter? ______________________

[1 mark]

(c) Give likely reasons as to why your two answers to (b) are different.

____

____

[2 marks]

(d) Estimate the amount of electrical energy consumed on a summer day between 8.00 am and 8.00 pm. Give your answer in kWh.

____

____

____

[3 marks]

(e) What is the cost of all this energy if the average charge to the consumer is 25.0¢ per kWh unit?

[3 marks]

(f) To increase efficiency, power stations run large generators at a steady rate throughout the day even though they tend to have long start up times. These provide the base load for the system. What could be considered to be the base load for the electricity system indicated by the graph? Give reasons.

[2 marks]

END OF TEST (60 MARKS)

TRIAL TEST 3:
WAVE PARTICLE DUALITY AND THE QUANTUM THEORY

Time allowed: 60 minutes		**Section One** – Short response	18 marks
Total marks: 60		**Section Two** – Problem solving	30 marks
		Section Three – Comprehension	12 marks

SECTION ONE – SHORT RESPONSE (18 MARKS)

1. The nature of light can only be fully explained using both the wave and particle theory. (Sometimes referred to as wave-particle duality).

   (a) Describe two properties of light which support the wave theory of light.

   (i) ______________________________

   (ii) ______________________________

   (b) Describe one property of light which cannot be explained by the wave theory. Explain why not.

   ____

   ____

   (c) Describe one property of light which cannot be explained by the particle theory. Explain why not.

   ____

   ____

[3 marks]

2. A microwave transmitter is transmitting a signal of 1.52×10^{9} Hz at an average output of 1.40 W. The signal occurs in pulses of 1.25×10^{-6} s duration which are 5.00×10^{-3} s apart.

   (a) Calculate the wavelength of these microwave signals.

   ____

   (b) What are the photon energies being emitted?

   ____

   (c) How many photons leave the transmitter each second?

   ____

[3 marks]

3. A student allows the light from different sources to pass through a spectrometer so that he can view the effect. For each of the following cases describe what he would see and name the type of spectra he is viewing.

(a) Light from an incandescent globe.

___

(b) Light from the sun.

___

(c) Light from a mercury vapour lamp.

___

(d) Light from an incandescent globe which has passed through a coloured solution.

___

[2 marks]

4. The work function for the metal magnesium is given as 3.66 eV.

(a) What is meant by the work function of a metal?

___

(b) Calculate the wavelength of light required to eject an electron from a magnesium surface with a maximum kinetic energy of 1.75 eV.

___

___

___

[3 marks]

5. When the hypothesis that matter can have wave-like properties was proposed by Louis de Broglie it proved initially difficult to verify.

(a) Explain why this was so.

___

(b) Calculate the de Broglie wavelength of a cricket ball of mass 160 g as it moves in the air at 140 km h^{-1}.

___

___

___

[2 marks]

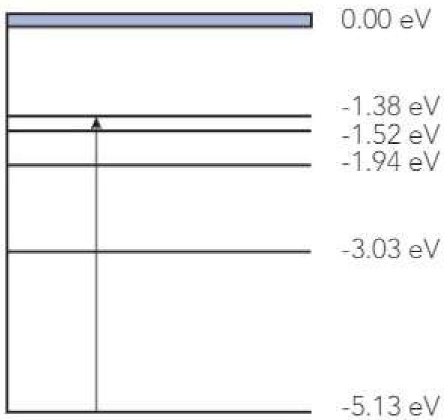
6. The band gaps for two LEDs, A and B, are listed as being 2.25 eV and 2.75 eV.

(a) Which will give light of the longest wavelength?

(b) Calculate this wavelength and suggest which colour the light might be.

[2 marks]

7. Some of the energy levels for a sodium atom are shown below. An electron from the ground state is excited to the fourth energy level as shown.



After a short time the electron returns to the ground state.

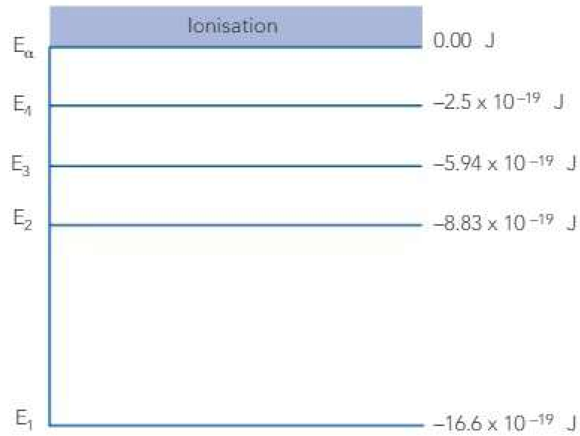
(a) Show all the possible downward transitions for this electron on the diagram.

(b) Calculate the frequency of the highest frequency photon that may be emitted.

[3 marks]

SECTION TWO – PROBLEM SOLVING (30 MARKS)

8. Fluorescent tubes contain low pressure mercury vapour whose atoms are excited by electrons travelling between the ends of the tube. Some of the energy levels of a mercury atom are shown below.



(a) Determine the possible wavelength of photons produced when ground state electrons are excited to level E_3.

____

____

____

[3 marks]

(b) To what colour (or region of the electromagnetic spectrum) do these photons belong? (Refer to table 3.1).

____

[1 mark]

(c) In view of part of your answer to (b), explain the function of the white powder on the inside of the fluorescent tube.

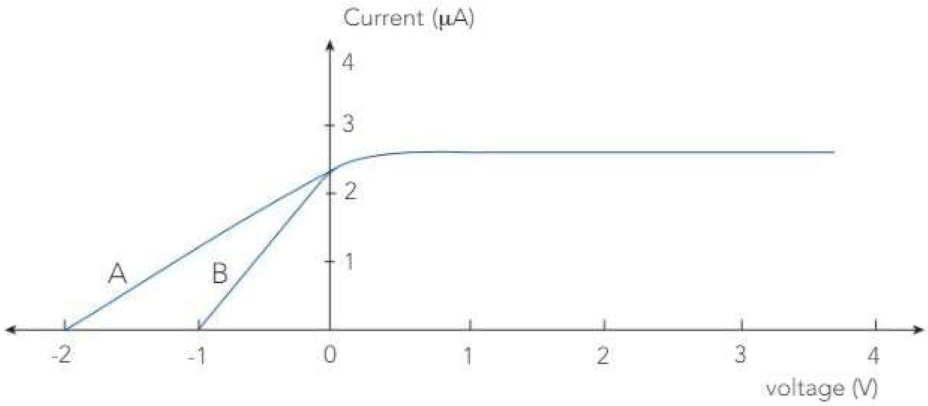
____

____

[2 marks]

9. An experiment to investigate the photoelectric effect was carried out using a photocell containing a magnesium metal cathode. Ultraviolet light of 2.20×10^{-7} m wavelength was directed onto the magnesium cathode. The light intensity was kept constant while the voltage applied to the anode was varied. The results of the variation in photocurrent that occurred with changes in voltage are graphed below.

The first set of results are indicated by the curve labelled A. By making a change to the light source, a second set of results were attained, labelled B.



(a) Why does the current remain constant for positive anode voltages?

____

____

[2 marks]

(b) What change was made to the light source to achieve the results labelled B? Explain.

____

____

[2 marks]

(c) Determine the stopping voltage for the first set of results, labelled A.
Hence determine the maximum kinetic energy of the photoelectrons produced.

____

____

____

[2 marks]

(d) Determine the work function for magnesium metal.

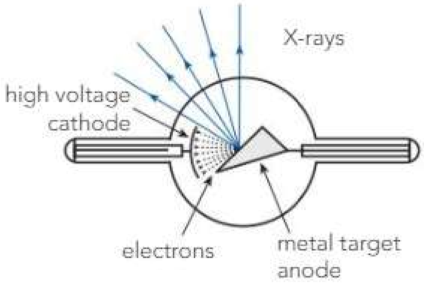
____

____

____

[2 marks]

10. The electrons in an X-ray tube are accelerated by a voltage of 95.0 kV towards a metal anode. Determine the following:



(a) The work done on the electrons by the electrical field.

[2 marks]

(b) The maximum velocity of the electrons before they hit the anode.

[2 marks]

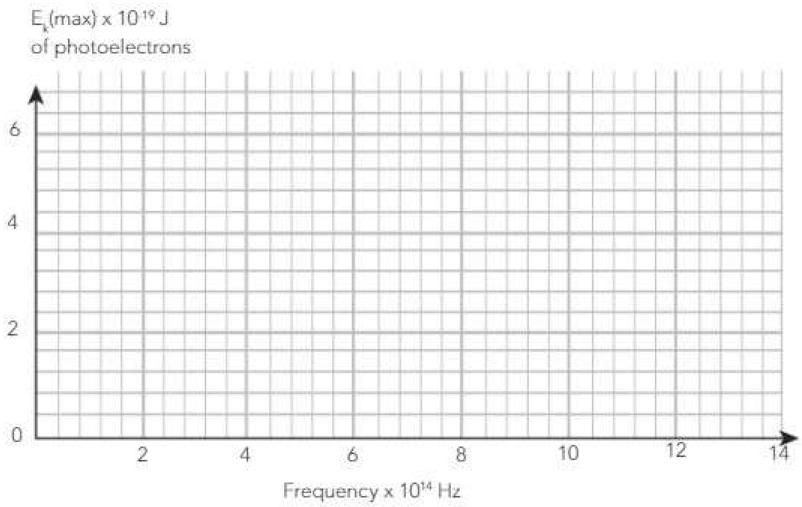
(c) The momentum and wavelength of the electrons on reaching the anode.

[2 marks]

11. An experiment was carried out to investigate the photoelectric effect over a range of frequencies. Two different photocells were used, one with a potassium cathode and the other, calcium. From the experimental data, the maximum kinetic energy of the photoelectrons ejected was calculated for each frequency. The results are tabulated below.

Frequency of incident radiation ($\times 10^{14}$ Hz)	Maximum E_k of photoelectrons $\times 10^{-19}$ J	
	Potassium	Calcium
7.50	1.31	0.380
8.90	2.24	1.31
10.3	3.17	2.24
11.8	4.16	3.23
13.4	5.22	4.29

(a) Plot the data given, frequency versus maximum kinetic energy, on the graph grid below and determine the line of best fit for each metal. The axes have already been indicated for simplicity.



[3 marks]

(b) From the graph determine the threshold frequency for each metal.

[1 mark]

(c) Use your results from (b) to calculate the work function in each case.

[2 marks]

(d) Determine the gradient for the line of best fit for each of the two metals. Include units.

[2 marks]

(e) Explain the significance of the values you calculated.

[2 marks]

SECTION THREE – COMPREHENSION (12 MARKS)

12.

MEASURING THE SPEED OF LIGHT

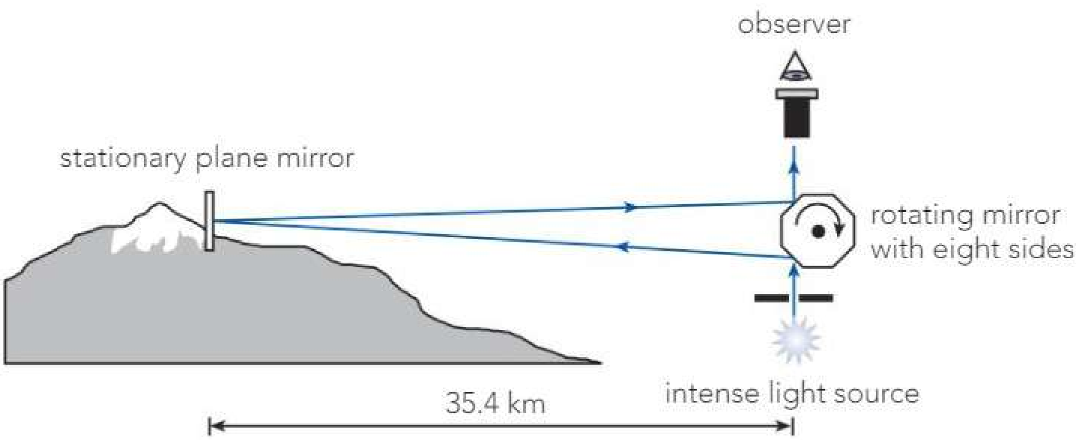
As we know the speed of light is extremely fast. Early attempts to measure it proved difficult due to the very small time intervals involved and lack of precise timing equipment.

Galileo attempted to measure the time delay between uncovering a bright lantern on one hilltop and seeing a lantern on an opposing hilltop uncovered by an assistant in response. The time delay was not measurable.

In 1676, the Danish astronomer Olaus Roemer provided the first real estimate of the speed of light when he made careful observations of the time between eclipses of Jupiter's moon Io. The times were measurably shorter when Jupiter was closest to Earth. He argued that this time difference was due to the lesser distance light had to travel when Jupiter was closer.

Based on these observations Roemer explained that light took 22 minutes to cross the diameter of Earth's orbit around the Sun (actually it is closer to 17 minutes). Using estimates of the Earth's orbit, as then known, and the observed time difference of the eclipses a value for the speed of light of 2.26×10^8 m s^{-1} was obtained. Importantly, although a little inaccurate, this showed for the first time that the speed of light is not infinite and was measurable.

Much more accurate measurements of the speed of light were made during the 19th century by Fizeau, Foucault and other scientists with values close to 3.0×10^8 m s^{-1}. Albert Michelson achieved very precise measurements using an intense light source and a rapidly rotating octagonal mirror as shown below.



A light beam was deflected by the rotating mirror to a stationary mirror on a mountainside 35.4 km away. The reflected beam returned to the rotating mirror and was visible to an observer for particular rotation frequencies. The rotation frequency and distances involved were used to calculate the speed of light.

His experiments were carried out with improving accuracy over many years, 1877 to 1927, with a final result of 2.99796×10^8 m s^{-1}. The accepted value today is 2.997925×10^8 m s^{-1}.

(a) To determine the speed of light which two quantities need to be measured as accurately as possible?

[1 mark]

(b) Suggest the main reason that Galileo found it impossible to measure the speed of light.

[1 mark]

(c) Roemer was able to get a good estimate of the speed of light even though time measurement techniques had changed very little since Galileo's attempt to measure the speed of light. Suggest the main differences in Roemer's method for determining the speed of light which made it successful.

[1 mark]

(d) Roemer's estimate for the speed of light was too low, due mainly to his assumed time of 22 minutes for light to travel the diameter of the Earth's orbit. Had he used the more correct time of 17 minutes in his calculations, what would have been his result?

[1 mark]

(e) Albert Michelson used a rotating octagonal mirror to bounce light from to and from a stationary mirror on a mountain side 35.4 km away. In some ways Michelson's experiment is similar to that attempted by Galileo using shuttered lanterns some 8.0 km apart. Compare the two experiments by discussing or calculating the following.

(i) Similarities in technique

[1 mark]

(ii) The advantage of a fixed mirror on the mountain rather than an assistant with a shuttered lantern.

[1 mark]

(iii) Time intervals being measured in each case

[2 marks]

(iv) The minimum frequency that the rotating octagonal mirror used by Michelson would need to achieve in measuring the speed of light.

[4 marks]

END OF TEST (60 MARKS)

TRIAL TEST 4: SPECIAL RELATIVITY AND THE STANDARD MODEL

Time allowed: **60 minutes**		**Section One** – Short response	18 marks
Total marks: **60**		**Section Two** – Problem solving	30 marks
		Section Three – Comprehension	12 marks

SECTION ONE – SHORT RESPONSE (18 MARKS)

1. Jason drops a ball from the window of his bus which is travelling at 15.0 m s^{-1} due East. As the ball falls the 1.85 m to the ground it is also observed by his friend Shane who is standing by the side of the road. In answering the following assume no effect from air resistance.

   (a) Determine the vertical velocity of the ball as it hits the ground.

   ___

   ___

   [1 mark]

   (b) Describe the trajectory of the ball as seen by:

   (i) Jason ___

   (ii) Shane ___

   [1 mark]

2. Muon particles in our atmosphere are due to cosmic radiation interacting with atoms in the upper atmosphere. They have a very short half life, some 2.2 μs, and few would be expected to reach the Earth's surface. However this is not the case.

   An experiment carried out by Rossi and Hall in 1940 showed that a much larger number of muons than would be expected did penetrate the atmosphere. They made their observations at two different points of a hillside at elevations of 3240 m and 1616 m.

   (a) Assuming no relativistic effects determine the time it would take the muons to traverse the vertical distance between the two observation points if their measured velocity was 0.99c.

   ___

   ___

   (b) Based on the much greater number of muons reaching the lower observation point it was calculated that the muons had decayed at a much slower rate than their half life would indicate. Give a possible explanation for this.

   ___

   ___

(c) From the data given determine the vertical distance between the two observation points in:

(i) The Earth's reference frame

(ii) The muon's reference frame

[3 marks]

3. You are viewing an approaching spaceship moving at 0.80c toward your space station. A light is flashing from the spaceship for 4.00 s every minute. Determine from your viewpoint at the space station:

(a) The time duration of the flashes.

(b) The time between flashes.

[2 marks]

4. An unknown particle X is made up of an up quark, u, and two down quarks, d, d.

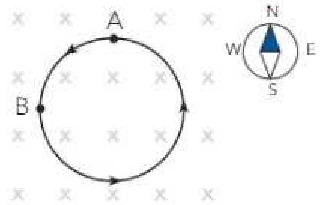
(a) Is particle X a meson or a baryon? Why?

(b) Determine the charge and baryon number of X.

(c) What is particle X likely to be?

[3 marks]

5. The diagram at right shows a charged particle moving in a circular motion in a magnetic field. The field is into the page.



(a) Is the particle likely to be a proton or an electron?

____

[1 mark]

(b) What is the direction of the force on the particle at points *A* and *B*? (N, S, W, or W)

(i) At *A* _____________ (ii) At *B* _____________

[1 mark]

(c) How would the path change if the particle had double the charge (assume all other conditions unchanged)? Why?

____

____

[1 mark]

6. Edwin Hubble investigated the red shift of distant galaxies and graphed its extent versus the estimated distances to those galaxies.

(a) Explain what is meant by red shift and what is believed to be the cause of it.

____

____

(b) What was the relationship that Hubble discovered from graphing his known data?

____

____

(c) How is this relationship indicated mathematically?

____

____

(d) How does this relationship support the Big Bang theory?

____

____

[2 marks]

7. An electron is accelerated in an electric field to a velocity of 0.85 c. Determine relativistic values for each the following at this velocity.

(a) The electron's momentum

____

____

(b) Its total energy

____

____

(c) Its kinetic energy

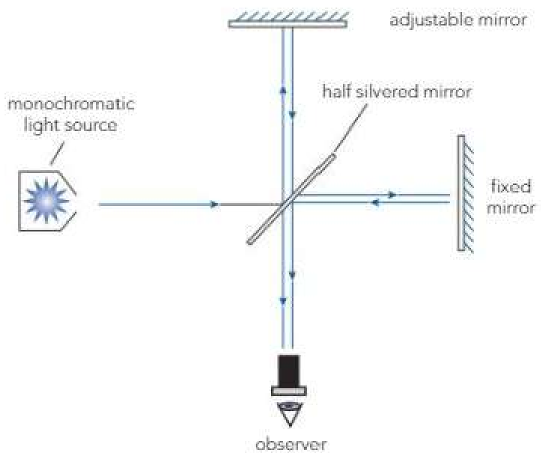
____

____

[3 marks]

SECTION TWO – PROBLEM SOLVING (30 MARKS)

8. A simplified diagram of the apparatus used in the Michelson-Morley experiment of 1887 is shown below. A monochromatic beam of light was split into two with the resulting beams travelling in different directions as shown. An interference pattern could be seen by the observer.



(a) What was the aim of the Michelson-Morley experiment?

____

____

(b) What was the purpose of the half silvered mirror?

____

(c) Why were the two light beams made to travel at right angles to each other?

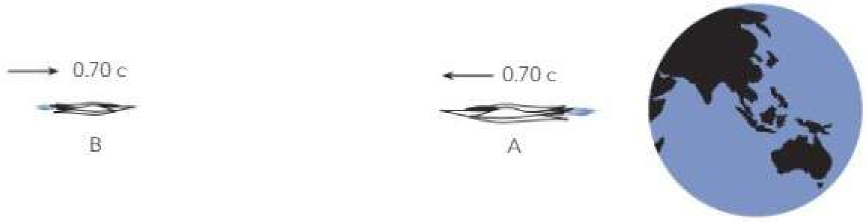
____

____

(d) What indications from the interference pattern were Michelson and Morley looking for?

[8 marks]

9. Chelsea is located on Earth and monitoring the movements of two spaceships. As seen from Earth both spaceships are travelling at 0.70 c. Space ship A is travelling directly away from Earth while space ship B, which is further away, is travelling towards Earth.



(a) Determine the velocity of spaceship B as seen from spaceship A.

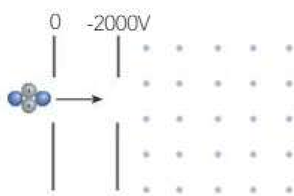
(b) Space ship A is 225 m long in its own frame of reference. What length will it appear to be to:

(i) An observer on spaceship B

(ii) Chelsea on Earth

[8 marks]

10. Alpha particles are accelerated from rest through 2.00×10^3 volts then enter a magnetic field at right angles to their motion as shown. Alpha particles have a mass of 6.65×10^{-27} kg and a charge of $2 \times 1.6 \times 10^{-19}$ C. The magnetic field strength is 3.25×10^{-2} T.



(a) Determine the velocity of the alpha particles as they reach the magnetic field.

[2 marks]

(b) Calculate the magnitude and direction of the force on the alpha particles when they enter the magnetic field.

[2 marks]

(c) Describe the motion of the alpha particles in the magnetic field.

[2 marks]

(d) Explain fully how an electrical field could be used to allow the alpha particles to pass through the magnetic field without any deviation to their motion. Determine the strength of such a field.

[2 marks]

11. An important first component of some synchrotrons is the electron gun.

(a) What is the purpose of the electron gun?

(b) Briefly describe how the electron gun works.

(c) If the electron gun is operated at 85.0kV determine the following assuming no relativistic effects.

(i) The maximum kinetic energy of the electrons.

(ii) The maximum velocity of the electrons.

[6 marks]

SECTION THREE – COMPREHENSION (12 MARKS)

12.

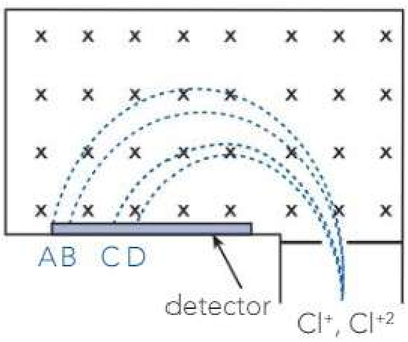
An important application of the mass spectrometer is to help identify different isotopic masses. The sample to be analysed is firstly ionised. The resulting ions are then accelerated by an electric field and allowed to enter the magnetic field of the mass spectrometer.

The ions begin to move in a circular path once in the magnetic field of the mass spectrometer. This is due to the force of the magnetic field on the moving particle. This force, $F = qvB$, provides the centripetal force necessary for circular motion to occur.

(a) The radius of curvature of this path depends on the ion's mass, charge and velocity as well as the magnetic field strength of the mass spectrometer. By considering the force due to the magnetic field and your understanding of circular motion develop an expression for the radius of curvature of the ions moving in a magnetic field.

[2 marks]

(b) The isotopes of chlorine Cl^{35} and Cl^{37} were being investigated with a mass spectrometer. The ion source produced both single and double ionised atoms of these isotopes. The ions were then accelerated and allowed to enter the magnetic field. Four distinct positions were recorded on the photographic film as shown (A, B, C, D).



Which positions on the film would correspond to:

(i) the Cl^{+2} ions? ______________

(ii) the ions of the Cl^{37} isotope? ______________ [2 marks]

(c) Using the expression you developed in (a) determine the following ratios:

(i) $\dfrac{\text{radius of curvature to A}}{\text{radius of curvature to C}}$

[2 marks]

(ii) $\dfrac{\text{radius of curvature to A}}{\text{radius of curvature to B}}$

[2 marks]

(d) Assuming that the velocity of the ions entering the mass spectrometer is 1.45×10^3 m s^{-1} and the magnetic field strength is 1.80×10^{-3} T calculate the mass of the singly charged Cl^{35} isotope if it describes a path of 29.2 cm radius.

[4 marks]

END OF TEST (60 MARKS)

ANSWERS TO CHAPTER AND REVIEW QUESTIONS

CHP 1: GRAVITY AND MOTION

1. Chapter Questions

1.1

The force between you and the Earth is mutual but since the Earth's mass is very large its acceleration towards you is very small ($a = F/m$).

1.2

Yes, you weight will be slightly less because you are further from the centre of the Earth.

1.3

(a) *Yes. A good example is the boomerang. It spins about its centre of mass. Also high jumper doing the Fosbury flop.*

(b) *Its centre of gravity would be near its centre but closer to the earth.*

1.4

(a) $g = \dfrac{Gm_E}{r_2} = \dfrac{(6.67 \times 10^{-11})(5.97 \times 10^{24})}{(6.38 \times 10^{6} + 1.0 \times 10^{6})^2}$

$= 7.31\ m\ s^{-2}$

(b) $g \propto \dfrac{1}{r_2} \therefore g\ (r = 30) = 9.80\ (\dfrac{1}{30})^2$

$= 0.0109\ m\ s^{-2}$

1.5

(a) *At point A*

$E_p = mgh$

$= (0.200)(9.80)(1.50) = 2.94\ J$

$E_k = 1/2mv^2$

$= (0.5)(0.200)(4.00)^2 = 1.60\ J$

Total energy at point A = 4.54 J

(b) *When the car reaches point B all its potential energy is lost.*

Total energy (E_T) will all be kinetic energy.

E_p *lost* $= E_k$ *gained* $= 2.94\ J$

Total $E_k = 1.60 + 2.94 = 4.54\ J$

(c) E_T *at point C* $= 4.54\ J$

E_p *at point C* $= mgh = (0.200)(9.80)(0.50)$

$= 0.980\ J$

E_k *at point C* $= E_T - E_p$

$= 4.54 - 0.980$

$= 3.56\ J$

Hence $1/2mv^2 = 3.56$

$v^2 = (3.56)(2)/(0.200)$

$v = 5.97\ m\ s^{-1}$ *at point C*

1.6

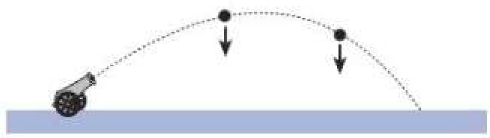
(a) *By increasing the release angle to 45°. This optimises flight time and horizontal velocity.*

(b) *45°*

(c) *By firing arrow vertically upwards.*

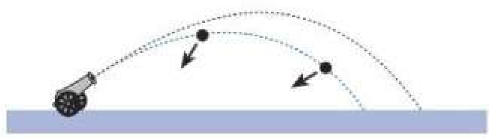
1.7

(a)



Only force acting is force due to gravity – directly downwards.

(b)



Force is resultant of the downward force of gravity and force of air resistance. Air resistance at top of flight would be horizontal and to the left (i.e. opposite in direction of the projectile at that point).

1.8

(a) *Air resistance reduced horizontal velocity such that the downward velocity due to gravity becomes more significant.*

(b) *It will take longer to return to earth. Consider the forces acting on the object.*

going up ↑ *coming down ↓*

The net force is less on the way down. The smaller acceleration means a greater time taken to cover the same distance.

1.9

(a) $\dfrac{a}{g} = \dfrac{26.5}{9.80} = 2.70$

(b) $a = \dfrac{v^2}{r}$ *and* $v = \dfrac{2\pi r}{r}$

$\therefore a = \dfrac{4\pi^2 r}{T^2}$ *or* $a \propto r$

$\therefore \dfrac{r\ edge}{r\ point\ near\ centre} = \dfrac{2}{1}$

1.10

(a) Friction between the tyres and the road.

(b) The reaction force provides a component force towards the centre.

(c) Large reaction forces occur between the seat and the pilot.

1.11

(a) Net force must be upwards towards the centre.
Hence $T > mg$.

(b) If $T = 0$ you would experience apparent weightlessness.
This will occur if $\frac{mv^2}{r} = mg$.

(c) The reaction force, R, is your 'apparent weight' – that is, the weight you feel. Since $R > mg$ at the bottom, you feel heavier than your usual weight mg.

(d) (i) Your 'apparent weight' is the reaction force R.
(ii) If $R = 0$ (i.e. $mg = \frac{mv^2}{r}$) then your 'apparent weight' is zero.

(e) If $R = 0$, apparent weight $= 0$.

(f) If $R = mg$ then apparent weight is your normal weight

1.12

At speeds lower than 143 m s^{-1}, R is negative, that is, circular motion would not be achieved.

1.13

$\tan\theta = \frac{v^2}{rg}$ $\therefore v^2 = rg\tan\theta$

$\therefore v = 26.3\ m\,s^{-1}$ This would seem reasonable.

1.14

(a) (i) $R\sin\phi$ ($= F_c =$ centripetal force)
(ii) $R\sin\phi$ (frictional force provides the F_c)

(b) (i) $R\sin\phi$ ($= F_c$)
(ii) $R\cos\phi$ ($= -m\,g$)

(c) (i) $T\sin\phi$ ($= F_c =$ centripetal force)
(ii) $T\cos\phi$ (frictional force provides the F_c)

1.15

A velocity of 29000 km h^{-1} will allow satellite motion near the Earth's surface except that air resistance would quickly reduce this velocity.

1.16

$$v^2 = \frac{GM}{r}$$

$$\left(\frac{2\pi}{T}\right)^2 = \frac{GM}{r}$$

$$\frac{4\pi^2 r^2}{T^2} = \frac{GM}{r}$$

$$\frac{T^2}{r^3} = \frac{4\pi^2}{GM}$$

1.17

The force of attraction is at right angles to its movement.

1.18

(a) T = 24 h to match the Earth's period of rotation.

(b) Equatorial to match the Earth's spin.

(c) $r^3 = \frac{Gm_E}{4\pi^2}.T^2$

$$= \frac{(6.67\times10^{-11})(5.97\times10^{24})(24\times60\times60)^2}{4\pi^2}$$

$r = 4.22\times10^7 m$

1.19

$$\frac{T^2}{r^3} = \frac{4\pi^2}{GM}$$

For any given central mass M such as that of the sun, the value of T^2 / r^3 is a constant. Hence

$(T_E)^2 / (r_E)^3 = (T_J)^2 / (r_J)^3$

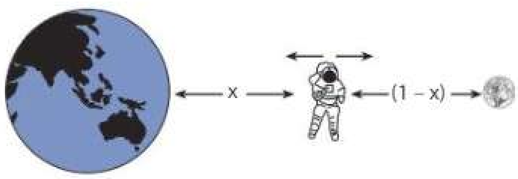
$(3.156\times10^7)^2 / (1.50\times10^{11})^3$

$= (T_J)^2 / (7.78\times10^{11})^3$

$(T_J)^2 = (3.156\times10^7)^2 (7.78\times10^{11})^3 / (1.50\times10^{11})^3$

$T_J = 3.73\times10^8$ s (approx 11.8 Earth years)

1.20



Since the force of gravity from the Earth and Moon are equal we have:

$$\frac{Gm_E}{x^2} = \frac{Gm_M}{(1-x)^2}$$

$$\frac{81}{x^2} = \frac{1}{(1-x)^2}$$

$$\frac{9}{x} = \frac{1}{1-x}$$

$$x = \frac{9}{10}$$

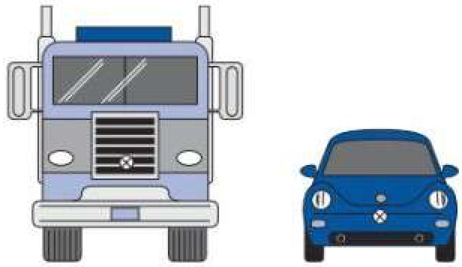
i.e. weightlessness occurs 9/10 of the way to the moon.

1.21

By leaning to his right, Rob is maintaining the overall centre of mass above his support base (feet).

1.22

(a)



(b) *The sport car is much more stable since its centre of gravity is much lower.*

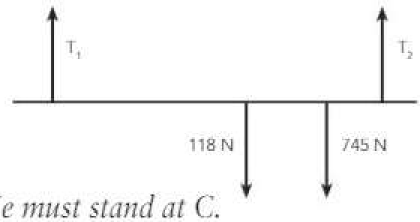
1.23

(i) Σ *c.w.m.* = Σ *a.c.w.m., about point B*
$(R_A)(16) = (9.31 \times 10^3)(3.6) + (350 \times 10^3)(8) + (34.3 \times 10^3)(11.8)$
$R_A = 202.4$ kN

(ii) *The total weight of the bridge and vehicles will be equally shared by the two ends.*
$\therefore 2R = 350{,}000 + 9310 + 34{,}300$
$R = 197$ kN

1.24

(a)



(b) *He must stand at C.*
$2T = 745 + 118$
$T = 431$ N

(c) *As far left as he can without toppling the plank. The plank will pivot about B and reduce the tension in cable at D.* $\therefore$ *Tension in cable at B increases.*

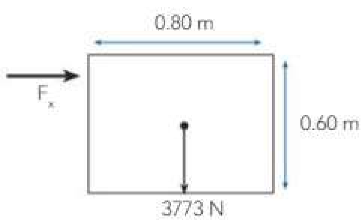
1.25

(a) T_1 *would increase since the rope is more vertical (T_2 would decrease).*

(b) T_2 *would decrease since the total vertical component of $T_1 + T_2$ remains the same.*

(c) *Both cables vertical.*
$2T = 441$
$\therefore T = 220$ N

1.26



$\Sigma cwm = \Sigma acwm$ *about bottom right hand corner*
$\therefore (F_x)(0.60) = (3773)(0.40)$
$F_x = 2.52 \times 10^3$ N

1.27

(a) *The tension will decrease. The cable will be more vertical thereby increasing the turning effect.*

(b) *Reaction force will become more vertical as it is supporting the load to a greater extent.*

1.28

(a) (i) R_W *will increase since a.c.w. moment increases.*
(ii) R_X *will increase to equalise* R_W.
(iii) R_Y *- no change - vertical forces have not changed.*

(b) *Good friction surfaces are necessary to prevent slipping.*

(c) *Using a rough surface with grip.*

1. Review Questions

Gravitation

1.

(a) $F = \dfrac{Gm_1m_2}{r^2}$

$= \dfrac{(6.67 \times 10^{-11})(5.97 \times 10^{24})(7.35 \times 10^{22})}{(3.84 \times 10^8)^2}$

$= 1.98 \times 10^{20}$ N

(b) *F also* $= 1.98 \times 10^{20}$ N

(c) *The Earth's tides are due to the pull of the moon's gravity.*

2.

(a) $F = \dfrac{Gm_1m_2}{r^2} = \dfrac{(6.67 \times 10^{-11})(0.300)(0.300)}{(0.15)^2}$

$= 2.67 \times 10^{-10}$ N

(b) *This force is far too small to overcome friction.*

3.

(a) *mass* = 3.50 kg *(unchanged)*

(b) $F = \dfrac{Gm_1m_2}{r^2}$

$= \dfrac{(6.67 \times 10^{-11})(7.35 \times 10^{22})(3.50)}{(1.74 \times 10^6)^2}$

$= 5.66$ N

4.

(a) *g is less since distance to the Earth's centre is greater.*

(b) *g is greater – closer to Earth's centre.*

(c) *g slightly less – further from Earth's centre.*

(d) *g slightly less – although closer to Earth's centre the mass of Earth above you attracts you upwards.*

5.

(a) $g \propto \dfrac{1}{r^2}$ $\quad g = 9.80$ *at* r_E

$$\frac{1}{r_x^{\ 2}} = \frac{1}{4} \quad \therefore r_x = 2r_E$$

Hence g = ¼ of g on Earth at a height of 1 Earth radii (i.e. ht of 6.38 × 10⁶ m).

(b) $$\frac{1}{r_x^{\ 2}} = \frac{1}{100} \quad \therefore r_x = 10r_E$$

$\therefore$ *must be* $9r_E$ *above Earth's surface*

$(9 \times 6.38 \times 10^6\ m)$.

6.

(a) $g = \dfrac{Gm_p}{r_p}$ *i.e.* $g \propto \dfrac{m_{planet}}{(r_{planet})^2}$

$$g_{jumbo} = \frac{(g_{Earth})(21)}{(3)^2} = 22.9\ m\ s^{-2}$$

(b) *Volume of a sphere* $= \dfrac{4}{3}\pi r^3$

i.e. $V \propto r^3$

$\therefore V_{jumbo} = (3)^3(V_{Earth})$

= 27 Earth volumes

Also Density $= \dfrac{Mass}{Volume}$

Given Mass (Jumbo) = 21 Mass (Earth)

$\therefore$ *ratio* $\dfrac{density\ (Jumbo)}{density\ (Earth)} = \dfrac{21}{27} = 0.778$

7.

(a)

$$g = \frac{Gm}{r^2}$$

$$\therefore\ g(Earth) = \frac{(6.67 \times 10^{-11})\ (5.97 \times 10^{24})}{(0.75 \times 3.84 \times 10^8)^2}$$

$= 4.80 \times 10^{-3}\ m\ s^{-2}$

$$g(Moon) = \frac{(6.67 \times 10^{-11})\ (7.35 \times 10^{22})}{(0.25 \times 3.84 \times 10^8)^2}$$

$= 5.32 \times 10^{-4}\ m\ s^{-2}$

therefore will begin to fall towards the Earth.

(b) *Net g experienced by the astronaut* $= 4.27 \times 10^{-3}\ m\ s^{-2}$ *towards the Earth.*

(c) $s = ut + \dfrac{1}{2}at^2$

$2.88 \times 10^8 = 0 + (4.27 \times 10^{-3})(t^2)$

$t = 2.60 \times 10^5\ s = 72\ h$

(d) *It would take much less time since the acceleration will keep on increasing as it gets closer to Earth.*

8.

(a) *Practical difficulties include*

- *extreme high temps internally*
- *molten lava would erupt*
- *suitable materials to withstand temperatures and pressures not available.*

(b) (i) *velocity is maximum at the centre of the Earth.*

(ii) *acceleration is a maximum at the surface.*

(iii) *force will equal zero at the centre of the Earth.*

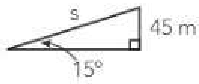
(c) *Yes – tunnels between, say Melbourne and Perth would work except that a means of reducing friction with the ground would need to be found. This is because the tunnels would not be vertical.*

9.

(a) *F(down slope) = mg sin θ*

$= (67)(9.8)(\sin 15°)$

$= 170\ N$



(b) *Friction force = 170 N*

(c) *slope distance (s)*

$= 45/\sin 15° = 174\ m$

$$v = \frac{s}{t} \quad \therefore t = \frac{s}{v} = \frac{174}{75} \times 3.6 = 8.35\ s$$

10. *At point A*

(a) $E_p = mgh = (0.050)(9.80)(0.600)$

$= 0.294\ J$

$E_k = 1/2mv^2 = ½(0.050)(4.00)^2$

$= 0.400\ J$

(b) E_k *at point B* $= E_k$ *(initial)* $+ E_p$ *lost*

$= 0.694\ J$

Hence $1/2mv^2 = 0.694\ J$

$v^2 = (0.694)(2)/(0.050)$

$v = 5.27\ m\ s^{-1}$ *at point B*

(c) *For the marble to reach point C its kinetic energy at B must be greater than the potential energy at point C.*

At point C

$E_p = mgh = (0.050)(9.80)(0.800)$

$= 0.392\ J$

Hence marble will reach point C

11.

(a) $v_x = 8.25 \cos 12.5° = 8.05\ m\ s^{-1}$

(b) $v_y = 8.25 \sin 12.5° = 1.79\ m\ s^{-1}$

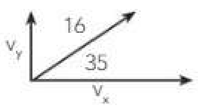
12. (a) *A*

(b) $9.80\ m\ s^{-2}$, *downwards*

(c) *E (when it stops in the target)*

(d) *speed, acceleration, kinetic energy*

13.



$v_y = (16)(\sin 35^\circ) = 9.18\ m\ s^{-1}$
$v_x = (16)(\cos 35^\circ) = 13.1\ m\ s^{-1}$

$u = 9.18\ m\ s^{-1}$ (up is +ve)
$v = 0$
$a = 9.8\ m\ s^{-2}$
$s = ?$

$v^2 = u^2 + 2as$

$\therefore s = \dfrac{0 - (9.18)^2}{2(-9.8)}$

Max ht = 4.30 m

(b) first find t to reach max height
$v = u + at$
$0 = 9.18 + (-9.8)(t)$
$\therefore t = 0.936\ s$
$\therefore$ total flight time = 1.87 s
Consider horizontal flight
$s = vt = (13.1)(1.87)$
Range = 24.5 m
$\therefore$ John is 24.5 m from Aaron.

14.
(a) Firstly find time of flight

$s = ut + \frac{1}{2}at^2$

$0.15 = 0 + \frac{1}{2}(9.8)t^2$

$\therefore t = 0.175\ s$

$\therefore$ velocity of bullet (v)

$v = \dfrac{s}{t} = \dfrac{450}{0.175} = 2572\ m\ s^{-1}$

(b) The sight is adjusted so that the bullet is actually aimed 15 cm above its target.

15.
(a) Since they are vertically above their target the downward velocity due to gravity becomes very significant and causes the objects to fall too steeply if projected at 45°.
(b) (i) Consider vertical motion only

$v_y = (24)(\sin 30^\circ) = 12\ m\ s^{-1}$

also $s = ut + \frac{1}{2}at^2$

$s = (12)(3.60) + 0.5(-9.8)(3.60)^2$
$= -20.3\ m$ (i.e. below throwers)

(ii) Consider horizontal velocity
$s = vt = (24)(\cos 30)(3.60)$
$= 74.8\ m$

16.
(a) Consider vertical motion only

$v_y = (7.00)(\sin 51^\circ) = 5.44\ m\ s^{-1}$

(i) $s = ut + \frac{1}{2}at^2$

$(3.05-2.30) = (5.44)(t) + (0.5)(-9.8)t^2$
$4.9t^2 - 5.44t + 0.75 = 0$
$\therefore t = 0.161\ s$ or $0.949\ s$
Hence $t = 0.949\ s$ (coming down)
(ii) To find horizontal distance
$s = vt$
$= (7.00 \cos 51^\circ)(0.949)$
$= 4.18\ m$

(b) Higher angles allow a steeper fall of flight. This allows for move margin of error for the ball to fit through the hoop.

17.


For maximum height

$v^2 = u^2 + 2as$

$0 = u^2 + 2(-9.8)(15)$

$v_x = 17.1\ m\ s^{-1}$

Since $v_x = v \sin 20^\circ$

$v = 17.1/\sin 20^\circ$

$= 50.1\ m\ s^{-1}$

18.
(a) $v_y = \dfrac{(90)(\sin 15^\circ)}{3.6} = 6.47\ m\ s^{-1}$

(b) $v = u + at$

$t = \dfrac{0 - 6.47}{9.8} = 0.66\ s$ (to top)

$\therefore$ total flight time = 1.32 s

(c) $s = vt = (\frac{90}{3.6})(\cos 15^\circ)(1.32) = 31.9\ m$

Circular Motion

19.
(a) $T = \dfrac{12.5}{10} = 1.25\ s$

$v = \dfrac{2\pi r}{T} = (2\pi)(1.90)/1.25 = 9.55\ m\ s^{-1}$

(b) Tension $F_c = \dfrac{mv^2}{r}$

$= \dfrac{(0.325)(9.55)^2}{1.90} = 15.6\ N$

20.
(a) For water not to fall

$\dfrac{mv^2}{r} \geq mg \therefore v^2 \geq rg$

$\geq (0.95)(9.80)$

$v \geq 3.05\ m\ s^{-1}$

$velocity\ of\ water = \dfrac{2\pi r}{T}$

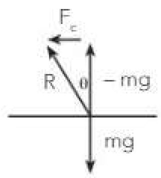
$= (2\pi)(0.95)/1 = 5.97\ m\ s^{-1}$

hence water will not fall.

(b) *No. The force of gravity is still acting and is actually providing some of the centripetal force at the top of the circle.*

21.

(a) *Bending allows the force of gravity to provide, through a reaction with the ground, a centripetal force into the corner.*



(b) *Since* $\tan\theta = \dfrac{v^2}{rg}$

the angle of lean would depend on velocity (v), radius of curvature (r) and gravitational field strength (g).

22.

(a) $f = 150\ rpm = \dfrac{150}{60}\ Hz$

$= 2.50\ Hz$

$\therefore T = \dfrac{1}{f} = 0.40\ s$

$v = \dfrac{2\pi r}{T} = \dfrac{(2\pi)(0.24)}{0.40} = 3.77\ m\ s^{-1}$

(b) $\dfrac{a_c}{g} = \dfrac{59.2}{9.80} = 6.04$

(c) *The sides of the spin drier provide a reaction force for the clothes to remain in circular motion. The holes in the side of the bowl cannot provide a similar reaction force for water. The water therefore flies off at a tangent.*

23. *For clothes to tumble*

$\dfrac{mv^2}{r} \leq mg$

$\therefore v^2 \leq gr \leq (9.80)(0.25)$

$v \leq 1.57\ m\ s^{-1}$

$Now\ v = \dfrac{2\pi r}{T}\ \therefore T = \dfrac{2\pi r}{v}$

$\therefore T = \dfrac{(2\pi r)}{1.57} = 1.00\ s$

$\therefore f = 1.00\ Hz = 60\ rpm$

The speed of the tumble drier must not exceed 60 rpm.

24.

(a) $F_c = \dfrac{mv^2}{r} = \dfrac{(1240)(6013.6)^2}{450} = 765\ N$

(b) *This force is applied through the friction force between the road and the tyres.*

25.

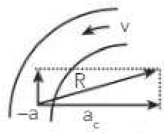
(a) $\dfrac{mv^2}{r} \leq 1600$

$\therefore v^2 \leq \dfrac{(1600)(120)}{850}$

$v \leq 15.0\ m\ s^{-1}$

(b) $a_c = \dfrac{v^2}{r} = \dfrac{(15.0)^2}{120} = 1.88\ m\ s^{-2}$

(c)



$v\ =\ 15.0\ m\ s^{-1}$
$a_c\ =\ 1.88\ m\ s^{-2}$
$-a$ = *car's linear deceleration*
R = *total acceleration*

When the car brakes, the initial overall acceleration of the car will be greater. Since there is insufficient friction with the road the car will skid or slip.

(d) $\tan\theta = \dfrac{v^2}{rg} = \dfrac{(15)^2}{(120)(9.8)}$

$\theta = 10.8^{o}$

26.

(a) *At the bottom of the swing*

$Tension = T = \dfrac{mv^2}{r} + mg$

$= \dfrac{(53.0)(5.0)^2}{1.85} + (53.0)(9.8)$

$= 1235$ N *(total for 2 ropes)*

$\therefore T = 618$ N *in each rope*

(b) *At the bottom of the swing.*

27.

(a) $a_c = \dfrac{v^2}{r} = \dfrac{(350/3.6)^2}{8.50 \times 10^3}$

$= 1.11\ m\ s^{-2}$

(b) $\tan\theta = \dfrac{v^2}{rg} = \dfrac{(97.2)^2}{(8500)(9.8)}$

$\theta = 6.47^{o}$

28.

(a) $v = \dfrac{2\pi r}{T} = \dfrac{(2\pi)(3500)}{85.0} = 259\ m\ s^{-1}$

(b) Pilot will feel heaviest at the bottom of his flight. His apparent weight is the reaction force from his seat.

$R = \dfrac{mv^2}{r} + mg$

$= \dfrac{(84.5)(259)^2}{3500} + (84.5)(9.80)$

$= 2444\ N$

(c) $\dfrac{\text{Apparent wt}}{\text{Normal wt}} = \dfrac{2444}{828}$

i.e. the flight creates 2.95 g and hence is within the pilot's safety limits.

29.

(a) The nett force in both cases is the centripetal force. force $(\dfrac{mv^2}{r})$ $\therefore$ ratio = 1

(b) Ratio is 1 since speed is constant.

(c) $T_{bottom} = \dfrac{mv^2}{r} + mg$

$T_{top} = \dfrac{mv^2}{r} - mg$

$\therefore$ ratio $= \dfrac{86.5 + 9.8}{86.5 - 9.8} = 1.26$

30.

(a) (i) $\dfrac{1}{2}mv^2 = mgh$

$v^2 = (2)(9.8)(0.40)$

$v = 2.80\ m\ s^{-1}$

(ii) $v = 4.43\ m\ s^{-1}$

(b) At point D we need

$\dfrac{mv^2}{r} \geq mg$

$v^2 \geq (9.80)(0.30)$

$v = 1.71\ m\ s^{-1}$ (minimum speed to remain in contact)

Since track is frictionless

v at D $= 2.80\ m\ s^{-1}$ (same as B)

$\therefore$ Car remains in contact with track.

31.

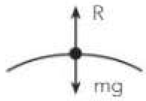
(a) Effect is caused by circular motion. The water bunches up against the solid wall which is able to provide a reaction force.

(b) At the edge velocity is greater. Hence a_c and F_c are greater. The steeper angle creates a reaction force with a greater horizontal component.

(c) The water would rise further since gravity is weaker.

32.

(a)



$F_c = mg - R$

Since cars are undergoing circular motion there is a nett force towards the centre. Hence $R = mg - \dfrac{mv^2}{r}$ and $R = 0$ if velocity is too great.

(b) (i) $\dfrac{mv^2}{r} = mg$

$\therefore v^2 = gr\ (9.80)(8.50)$

$v = 9.13\ m\ s^{-1}$

(ii) Consider vertical motion separately

$s = ut + \dfrac{1}{2}at^2$

$8.50 = 0 + (0.5)(9.80)t^2$

$t = 1.32$ s (time to fall)

$\therefore$ Horizontal distance travelled

$s = vt = (9.13)(1.32)$

$= 12.0\ m$

33. They will move off at a tangent to their circular motion. This means that they move off in opposite directions.

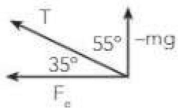
34.

(a) $v = \dfrac{2\pi r}{T} = \dfrac{(2\pi)(1.70)}{2.20} = 4.86\ m\ s^{-1}$

(b) The nett force acting on the hammer is the centripetal force.

$F_c = \dfrac{mv^2}{r} = \dfrac{(7.26)(4.86)^2}{1.70} = 101\ N$

(c)



The tension in the thrower's arms provides both F_c and a component force against gravity.

$\therefore T\cos 35^\circ = 101\ N$

$T = 123\ N$

Satellite Motion

35.

(a) $W = mg = (55.0)(9.80)$

$= 539\ N$

(b) $F = \dfrac{Gm_1m_2}{r^2}$

$$= \frac{(6.67 \times 10^{-11})(5.97 \times 10^{24})(55.0)}{(6.38 \times 10^6 + 7.0 \times 10^5)^2}$$

$= 437$ N

(c) Apparent weight will be zero since he is essentially in free fall. There is no reaction force between him and any surface and so he is experiencing weightlessness.

36.

(a) At the equator since he is moving faster.

(b) Apparent $wt = R = mg - \frac{mv^2}{r}$

Now $v = \frac{2\pi r}{T} = \frac{(2\pi)(6.38 \times 10^6)}{(24)(3600)}$

$= 464\ m\ s^{-1}$ (at the equator)

$\therefore a_c = \frac{v^2}{r} = \frac{(464)^2}{6.38 \times 10^6} = 0.0337$

$\therefore \% = \frac{a_c}{g} = \frac{0.0336}{9.80} \times 100 = 0.0344$

$= 0.344\%$

There will be an apparent loss of weight of 0.344%.

(c) To be weightless $R = 0$

$\frac{mv^2}{r} = mg$

$v^2 = (9.80)(6.38 \times 10^6)$

$v = 7907\ m\ s^{-1}$

$\therefore T = \frac{2\pi r}{v} = \frac{(2\pi)(6.38 \times 10^6)}{7907}$

$= 5070\ s$

$= 1.41\ h$

37.

(a) for orbit $\frac{mv^2}{r} = \frac{Gm_1m_2}{r^2}$

$\therefore v^2 = \frac{Gm}{r}$ also $v = \frac{2\pi r}{T}$

hence by substitution we can show

$r^3 = \frac{Gm}{4\pi^2} . T^2$

$$\therefore r^3 = \frac{(6.67 \times 10^{-11})(7.35 \times 10^{22})(2.36 \times 10^6)^2}{4\pi^2}$$

$\therefore r = 8.84 \times 10^7\ m$

(b) $v^2 = \frac{Gm}{r}$

$$= \frac{(6.67 \times 10^{-11})\ (7.35 \times 10^{22})}{(1.74 \times 10^6 + 1.0 \times 10^5)}$$

$v = 1.63 \times 10^3\ m\ s^{-1}$

38. The period of a geostationary satellite orbiting the Earth is 24.0 h
Hence we have for:

Geostationary satellite
$T = 24.0\ h = 8.64 \times 10^4 s$
$R = 4.22 \times 10^7\ m$

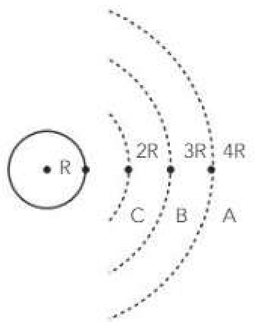
Hubble space telescope
$T = ?$
$R = r_E + 593\ km = 6.38 \times 10^6\ m + 5.93 \times 10^5\ m$
$= 6.97 \times 10^6\ m$

For any given central mass M such as that of the Earth:

$r^3 / T^2 =$ a constant
$(6.97 \times 10^6)^3/T^2 = (4.22 \times 10^7)^3/(8.64 \times 10^4)^2$
$T^2 = (6.97 \times 10^6)^3 \times (8.64 \times 10^4)^2/(4.22 \times 10^7)^3$
$T = 5.80 \times 10^3\ s$ (approx 96.7 minutes)

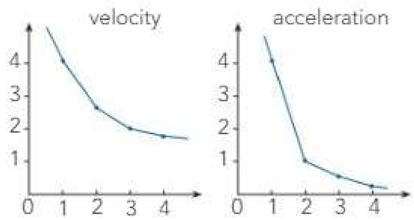
39.

(a)



(i) greatest velocity at orbit C
(ii) greatest acceleration at orbit C

(b)



$v^2 = \frac{Gm}{r}$ $\quad g\ \alpha\ \frac{1}{r^2}$

$v\ \alpha\ \frac{1}{\sqrt{r}}$

(c) $v^2 = \frac{Gm_p}{r}$ $\quad \therefore m_p = \frac{v^2 r}{G}$

$$m_p = \frac{(8.66 \times 10^3)^2(2 \times 10^7)}{6.67 \times 10^{-11}}$$

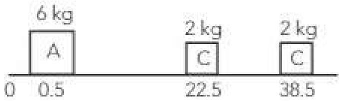
$= 2.25 \times 10^{25}\ kg$

40.

(a) will simply go into a lower orbit.
(b) backwards, so that it would cancel its orbiting velocity.

Torque

41.



$$X = \frac{\Sigma mx}{\Sigma m}$$

$$= \frac{(6 \times 5) + (2)(22.5) + (2)(38.5)}{10}$$

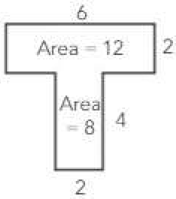
$= 15.2$ *cm*

42. *If he bends over without being able to shift some of his weight behind him his centre of mass will not be over his support base (feet) and hence he would fall.*

43. *The walking stick increases the support base greatly and hence they can lean without fear of falling, i.e. their c.m. falls through a larger area resulting in greater stability.*

44. *The outstretched hand helps to counterbalance the heavy load by maintaining the centre of mass over the painter's feet (support base).*

45. *Centre of mass is along the vertical grid line 4.To find how high:*



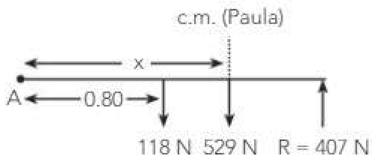
$$X = \frac{\Sigma mx}{\Sigma m}$$

$$\frac{(3)(8)+(6)(12)}{20}$$

∴C.G. is at (4, 4.8)

Note we have considered area to be proportional to mass.

46. *(a)*



Take moments about A

Σ c.w.m. = Σ a.c.w.m.

$(118)(0.80) + (529)(x) = (407)(1.60)$

$x = 1.05$ *m*

Paula's centre of mass is 1.05 m from her feet.

(b) Use fulcrum supports that are as thin as possible for accuracy in length measurement. Align feet accurately with support point.

Equilibrium

47. *You must lean forward to ensure that your centre of mass is above your support base.*

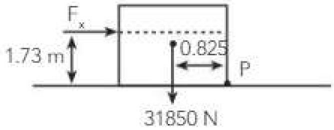
48.

(a) The stability of a vehicle depends upon

(i) the width of its support base;

(ii) the height of its centre of mass.

(b)



Assume van will just begin to tip about point P.

Σcwm = Σacwm

about P

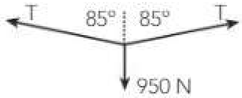
$\therefore F_x(1.73) = 31850 \times 0.825$

$\therefore F_x = 1.52 \times 10^4$ N

49.

(a) By moving the pole sideways he is able to more easily maintain his centre of mass directly over the wire.

(b)



$\Sigma F_y = 0$ *(Vertical forces = Sum to zero)*

$2T \cos 85^o = 950$

$T = 5450$ N

$= 5.45 \times 10^3$ N

50. $\Sigma F_y = 0$

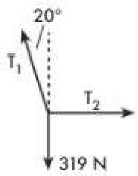
$T_1 \cos 20^o = 318.5$

$T_1 = 339$ N

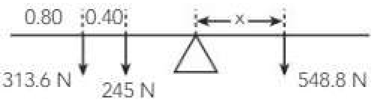
$\Sigma F_x = 0$

$T_2 = T_1 \sin 20^o$

$T_2 = 116$ N



51.



Σ c.w.m. = Σ a.c.w.m. (about pivot point)

$(548.8)(x) = (245)(0.70)+(313.6)(1.10)$

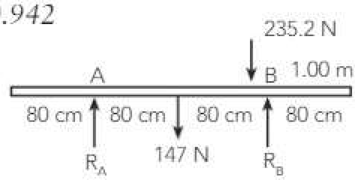
= 0.941 m from fulcrum.

Vanessa must place herself 94.1 cm from the fulcrum.

52. *Σ c.w.m. = Σ a.c.w.m. (about pivot point)*

$(549)(x)=(245)(0.70)+(314)(1.10)$

$x = 0.942$



(a) Take moments about A

Σ c.w.m. = Σ a.c.w.m.

$(147)(0.80)+(235.2)(1.40)=(R_B)(1.60)$

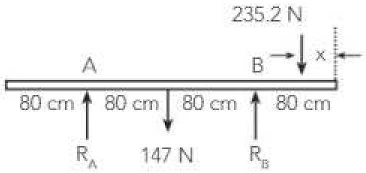
$R_B = 279$ N

Also $\Sigma F_y = 0$

$R_A + R_B = 147 + 235.2$

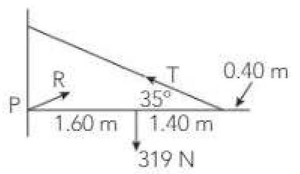
$\therefore\ R_A = 103\ N$

(b)



The bench will tip about point B if the box is moved too close to end B. In this situation
$R_A = 0$
Σ *c.w.m.* = Σ *a.c.w.m. (about B)*
$(235.2)(0.80-x)=(147)(0.80)$
$x = 0.30\ m$
i.e. box cannot be placed any closer than 30 cm from the end if stability is to be maintained.

53.
(a)



(b) *Take moments about P*

$\Sigma\tau_{CW} = \Sigma\tau_{ACW}$

$(319)(1.60) = (T \sin 35)(2.80)$

$T = 318\ N$

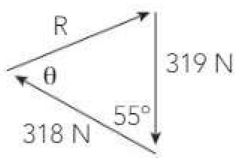
Also

$R^2 = (318)^2 + (319)^2 - 2(318)(319)(\cos 35)$

$R = 294\ N$

and

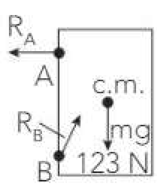
$\frac{\sin \theta}{319} = \frac{\sin 55}{294}$



$\theta = 62.7°$

$\therefore$ *Reaction force is 294 N 27.7° above the horizontal.*

54.
(a)



(b) *Take moments about B*

$\Sigma\tau_{CW} = \Sigma\tau_{ACW}$
$(122.5)(0.41) = (R_A)(1.60)$
$\therefore R_A = 31.4$

To find $R_B = \Sigma F = 0$

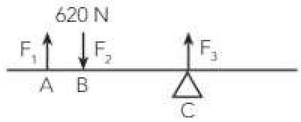
$R_B^2 = (31.4)^2 + (122.5)^2$

$R_B = 126\ N$ *14.4° to the vertical*

55.

Σ *c.w.m.* = Σ *a.c.w.m. about pivot point*
$(16.17)(0.15)+(35.28)(0.362)=(F_x)(0.042)$
$F_x = 362\ N$

56.
(a)



$AB = 3.80\ cm$
$BC = 12.0\ cm$

Take moments about C
Σ *c.w.m.* = Σ *a.c.w.m.*
$(F_1)(0.158)=(620)(0.12)$
$F_1 = 471\ N$

(b) F_3 *is the reaction to the person's weight.*
$\therefore F_3 = 620\ N$

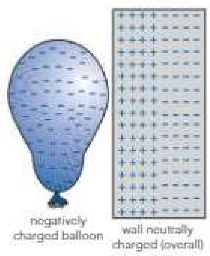
(c) $\Sigma F_2 + F_3 = 0$
F_1 *is the tension in the muscle and is equalised by an equal and opposite force acting downwards on the body.*

CHP 2: ELECTROMAGNETISM

2. Chapter Questions

2.1 *Protons are located in the nucleus of atoms and are not free to move.*

2.2 *The charged balloon (say negatively charged) induces an opposite charge on the surface of the wall it is near. Attraction between opposite charges results.*



2.3
(a) *Force between electron and A*

$$F = \frac{1}{4\pi\varepsilon_0}\frac{q_1q_2}{r^2}$$

$$= \frac{9.00 \times 10^9 \times 3.00 \times 10^{-9} \times 1.60 \times 10^{-19}}{(2.50 \times 10^{-2})^2}$$

$= 6.92 \times 10^{-15}\ N$
The force is attraction towards A

Similarly the force between electron and B

$$F = \frac{9.00 \times 10^9 \times 9.00 \times 10^{-8} \times 1.60 \times 10^{-19}}{(2.50 \times 10^{-2})^2}$$

$= 2.08 \times 10^{-13}$ N.

The force is repulsion away from B

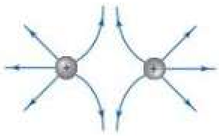
Net Force $F = 2.14 \times 10^{-13}$ N *towards A*

(b) *The electron will move towards A.*
Initial acceleration is given by

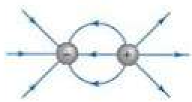
$$a = \frac{F}{m} = \frac{2.14 \times 10^{-13}}{9.11 \times 10^{-31}} = 2.35 \times 10^{17}\ m\ s^{-2}$$ *(wow!)*

2.4

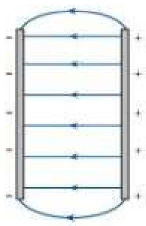
(a)



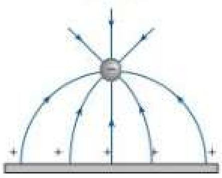
(b)



(c)



(d)



2.5

$$E = \frac{F}{q} = \frac{2.65 \times 10^{-20}}{1.6 \times 10^{-19}} = 0.166\ N\ C^{-1}$$

2.6

(a) $E = \frac{V}{d} = \frac{9.00}{20 \times 10^{-3}}$

$= 4.50 \times 10^2\ V\ m^{-1}$

(b) $F = Eq = (4.50 \times 10^2)(1.6 \times 10^{-19})$
$= 7.20 \times 10^{-17}$ N

(c) (i) *No change*
(ii) *If plates are closer E will change*

$$E = \frac{V}{d} = \frac{9.00}{10 \times 10^{-3}} = 9.00 \times 10^2\ V\ m^{-1}$$

$\therefore$ $F = Eq = 1.44 \times 10^{-16}$ N

2.7

(a) $E = \frac{V}{d} = \frac{200}{6.00 \times 10^{-3}}$

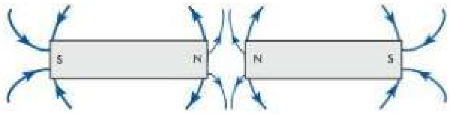
$= 3.33 \times 10^4\ Vm^{-1}$

(b) $F = Eq = (3.33 \times 10^4)(8 \times 10^{-18})$
$= 2.66 \times 10^{-13}$ N

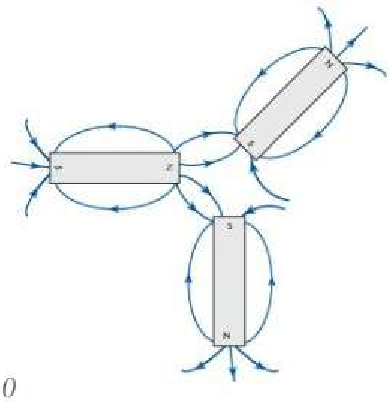
(c) $W = Fs = (2.66 \times 10^{-13})(2.00 \times 10^{-3})$
$= 5.33 \times 10^{-16}\ J$

2.8

(a)



(b)



2.9

(a) ≈ 0

(b) 90°

(c) 66°

(d) *just less than 90°*

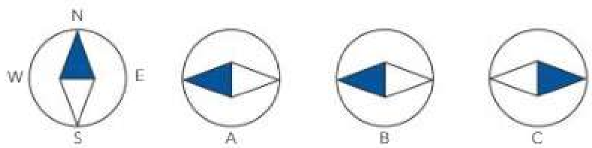
2.10

(a) *The compass is trying to line up with the Earth's magnetic field lines which may not be horizontal at that point.*

(b) *South seeking end would point down.*

(c) *At the equator.*

2.11



2.12

(a) (i) *Increase the current.*
(ii) *Increase number of turns of the coil.*
(iii) *Use a soft iron core.*

(b)

(i) *Shape of magnetic field around a solenoid is the same as that around a permanent magnet.*

(ii) *Field within a solenoid is fairly uniform and parallel. Outside it is not very strong and reduces rapidly with distance unlike that of a permanent magnet. The field of a solenoid can also be switched off by removing the current.*

2.13

(a) $B = \frac{\mu_0}{2\pi} \frac{I}{r}$

$= 4\pi \times 10^{-7} \times 10.0 / 2\pi \times 1.50$

$= 1.33 \times 10^{-6}\ Wb\ m^{-2}$

(b) *Compass would point directly east.*

2.14

(a) $B = 6.2 \times 10^{-6}$ T $\theta = 70°$

$A = ?$ $\phi = 1$ Wb

$\phi = BA$

$$A = \frac{1}{6.2 \times 10^{-6}} = 1.61 \times 10^{5}\ m^2$$

(b) *The coil should be at right angles to the field. Hence the plane of the coil should be East West at an angle of 20° to the horizontal.*

(c) *The coil would take the space of a very large oval and would be difficult to be held up at 20°.*

2.15

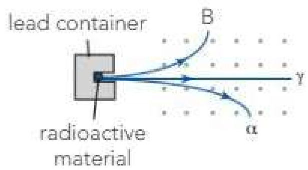
(a) *up, out of page*   (b) *upwards*
(c) *into page*   (d) *upwards*
(e) *zero force*   (f) *upwards*

2.16

(a) *out of page*   (b) *downwards*
(c) *into page*   (d) *into page*
(e) *zero force*   (f) *into page*

2.17

(a)



(b)

(i) $F = qvB \therefore F_\alpha = (2)(10)(1) = 20$ *units*

$F_\beta = (1)(10^8) = 10^8$ *units*

Force greater on β *by* 5.00×10^6 *times*

(ii) $a_\alpha = \frac{F}{m} = \frac{20}{7300} = 2.74 \times 10^{-3}$ *units*

$a_\beta = \frac{F}{m} = \frac{5 \times 10^6}{1} = 5 \times 10^6$ *units*

$\therefore \beta$ *most deflected.*

2.18

(a) *They move off in different directions.*

(b) *The electron goes into a much smaller circle due to its far smaller mass.*

2.19

(a) *ACW*

(b) (i) *None* (ii) *None* (iii) *Decrease*

(c) *Temporarily there is no current and no torque. The momentum of the coil keeps it moving, the current in the coil reverses and the torque will once again act to keep it rotating.*

(d) *Parallel*

(e) (i) *Use stronger magnets*
(ii) *Increase the number of coils*
(iii) *Increase the size (area) of coils*
(iv) *Use a soft iron core (armature).*

2.20

(a) *Greatest emf when AB almost past the magnets (greatest velocity while still in strong field).*

(b) (i) *random motion*
(ii) e^- *move towards A*
(iii) *back again then random motion*

2.21

(a) (i) *ACW* (ii) *none* (iii) *CW*

(b) (i) *Magnetic damping. Induced current creates an opposing magnetic field.*
(ii) *Heat produced in the copper coil.*

(c) *Magnetic damping, meters.*

2.22

(a) *B*

(b) *A (only during time from when switch is off to just on, thereafter zero induced current).*

2.23

$$EMF = -N\frac{\Delta \phi}{\Delta t} \qquad \phi = BA$$

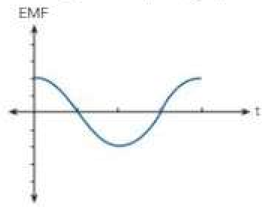
$\therefore$ *increase no. of turns of coil*
$\therefore$ *increase field strength (B)*
$\therefore$ *increase area*
$\therefore$ *reduce time (go faster).*

2.24

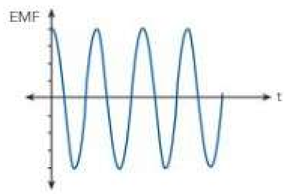
$f = 50$ *Hz* $= 50$ *r.p.s.*
$\therefore = (50)(60)$ *rpm*
$= 3000$ *rpm*

2.25

Original output graph

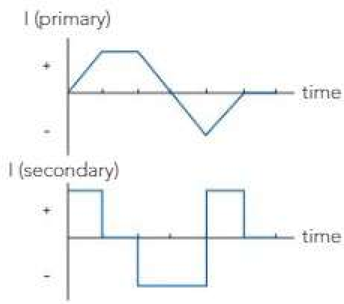


Both emf and frequency have doubled.



2.26

Original graph



2.27 $\frac{V_s}{V_p} = \frac{N_s}{N_p} \therefore N_s = (1000)(\frac{12}{240}) = 50$ *turns*

2.28

A changing magnetic field is needed to induce an EMF. This requires a changing voltage (AC).

2.29

(a) $P = 10^4$ W $V = 66 \times 10^3$ V

$I = ?$ $R = 1.5\ \Omega$

$P = VI \therefore I = \frac{P}{V}$

$= \frac{10^4}{6.6 \times 10^4} = 0.152$ A

Power lost along the line

$P = I^2R = (0.152)^2(1.5) = 0.0344$ W

(b) $\therefore$ *Voltage at end of line*

$V_{(end)} = 240 - IR$

$= 240 - (0.152)(1.5)$

≈ 240 V

Almost no loss in voltage.

2. Review Questions

Electromagnetism

1. *No. Some electrons from the surface atoms of the woollen cloth are transferred to the rod leaving the cloth with an equal amount of positive charge. The negative charge is not created and a conservation of charge occurs between the rod and the woollen cloth.*
2. *A metal rod is a good conductor and any charge on the rod will quickly flow along the rod and through the body to the Earth. An insulator does not have 'free' charge carriers (electrons) to enable the charge to flow throughout the insulator.*

3. $F = \frac{1}{4\pi\varepsilon_0} \frac{q_1q_2}{r^2}$

$= \frac{9.00 \times 10^9 \times 3.00 \times 10^{-6} \times 6.00 \times 10^{-6}}{(4.00 \times 10^{-2})^2}$

$= 1.01 \times 10^2$ N. *The force is attractive*

4.

(a) *Force between the charges* $\alpha \ \frac{1}{r^2}$

Hence at twice the distance

$F = (\frac{1}{4})(1.01 \times 10^2)$

$= 25.25$ N *(attraction)*

(b) *If the metal spheres touch, the total charge on the two spheres will be equally distributed between them. Hence we have:*

Total charge $= (+3.00\ \mu C) + (-6.00\ \mu C)$

$= -3.00\ \mu C$

Charge on each sphere will now be

$= -1.50\ \mu C$

Force between the charged spheres now given by

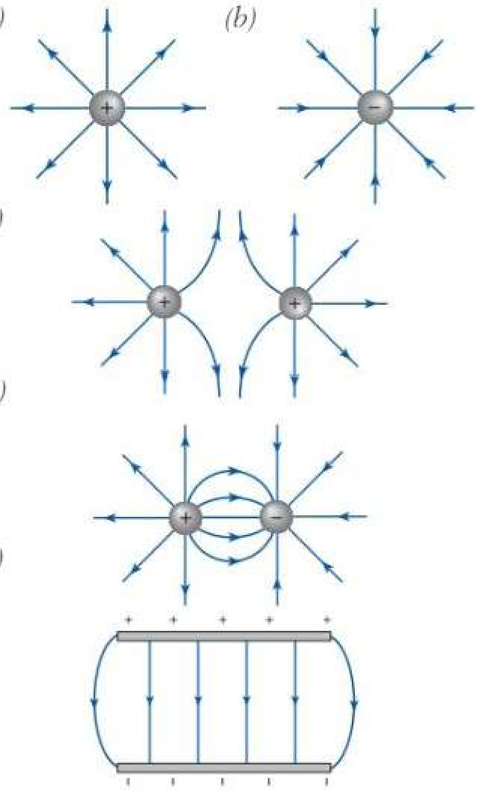
$F = \frac{1}{4\pi\varepsilon_0} \frac{q_1q_2}{r^2}$

$= \frac{9.00 \times 10^9 \times 1.50 \times 10^{-6} \times 1.50 \times 10^{-6}}{(8.00 \times 10^{-2})^2}$

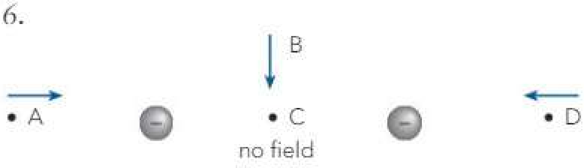
$= 3.16$ N.

The force is repulsive (like charges)

5. (a) (c) (d) (e)



6.



7. $E = \frac{F}{q} = \frac{7.50 \times 10^{-16}}{1.6 \times 10^{-19}}$

$= 4.69 \times 10^3$ N C^{-1}

8.

(a) $E = \frac{V}{d} = \frac{12.0}{5.40 \times 10^{-3}}$

$= 2.22 \times 10^3$ V m^{-1}

(b) $F = Eq = (2.22 \times 10^3)(1.6 \times 10^{-19})$

$= 3.56 \times 10^{-16}$ N

(c) The force is the same at any point between the plates.

9.

(a) $F = Eq = (1.45 \times 10^3)(2 \times 1.6 \times 10^{-19})$
$= 4.64 \times 10^{-16}$ N

(b) $W = Fs = (4.64 \times 10^{-16})(2.65 \times 10^{-3})$
$= 1.23 \times 10^{-18}$ J

(c) $W = E_K$ gained

$$\frac{1}{2} m v^2 = 1.23 \times 10^{-18}$$

$$v^2 = \frac{1.23 \times 10^{-18}}{6.65 \times 10^{-27}} \times 2$$

$$v = 1.92 \times 10^4 \text{ m s}^{-1}$$

10. $q = I\,t$

$200 = I\,(3.00 \times 60)$

$$I = \frac{200}{3.00 \times 60} = 1.11 \text{ A}$$

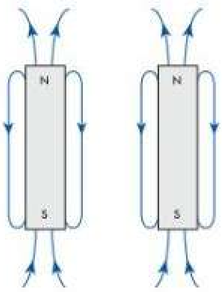
$\therefore$ Current in the lamp = 1.11 A

11.

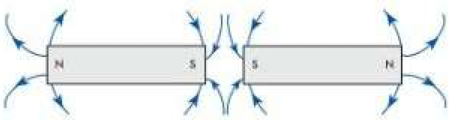
(a) Potential difference is equal to the work done per unit charge (by an external force) to move an electric charge from one point to another in an electric field.

(b) $W = Vq$
$= 3.00 \times 10^3 \times 1.60 \times 10^{-19}$
$= 4.80 \times 10^{-16}$ J

12. (a)



(b)

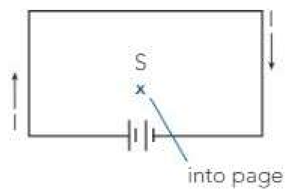


13. (a)

(b)

(c)

(d)

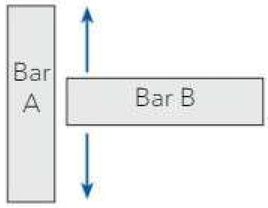


14.

(a) (i) C (ii) A only (iii) A only

(b) Westerly

15.



(a) Move one of the bars (say B) along the length of the other (A). If attraction is uniform all along A then A is just iron and B the magnet.

(b) Suspend the bar magnet. The North seeking pole will point approximately towards geographic North, toward the North magnetic pole.

16.

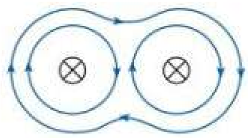
(a) P into page
Q no field
R out of page

(b) Out of page

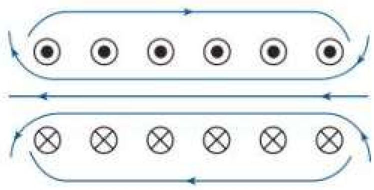
(c) Yes, towards wire AB

17.

(a)



(b)



18.

(a) $\phi = BA = (6.25 \times 10^{-2})(0.25 \times 0.35)$
$= 5.47 \times 10^{-3}$ Wb

(b) The coil can be turned 90°, hence no flux through the coil. Alternatively the coil can be removed from the field.

19.

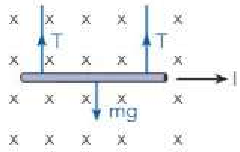
(a) $$B = \frac{\mu_0}{2\pi} \frac{I}{r}$$

$$= \frac{4\pi \times 10^{-7} \times 2.75}{2\pi \times 0.125}$$

$$= 4.4 \times 10^{-6} \text{ Wb m}^{-2}$$

(b) *Use the right hand grip rule to determine direction. West of the vertical wire the compass will point south.*

20.



$F = IlB = (12)(1)(2.5 \times 10^{-6})$
$= 3 \times 10^{-5}$ N
$\therefore$ *each Tension force (T) will change by* 1.5×10^{-5} N.

21.

(a) $N = 200$ $r = 1.2 \times 10^{-2}$ m
$I = 0.500$ A $B = 3.5 \times 10^{-1}$ T
Length of coil $= (N)(2\pi r)$
$= (200)(2\pi)(1.2 \times 10^{-2})$
$= 15.1$ m
$F = IlB$
$= (0.50)(15.1)(3.5 \times 10^{-1})$
$= 2.64$ N

(b) (i) *If N doubles, F will double*
(ii) *If B doubles, F will double*
(iii) *If diameter doubles* $\rightarrow l$ *doubles*
$\rightarrow F$ *doubles*

22.

(a) $B = \dfrac{\mu_0}{2\pi}\ \dfrac{1}{r}$

$= \dfrac{4\pi \times 10^{-7} \times 2.50}{2\pi \times 3.00 \times 10^{-2}}$

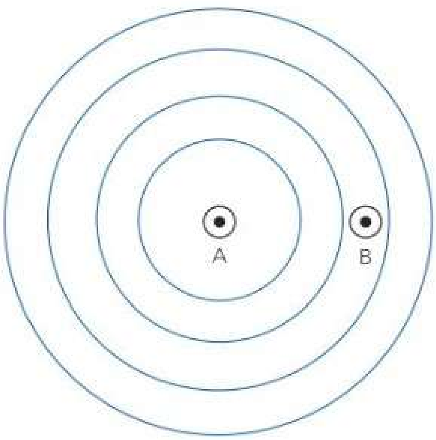
$= 1.67 \times 10^{-5}$ Wb m^{-2}

$F = I\,l\,B = (3.00 \times 10^{-2})(1.00)(1.67 \times 10^{-5})$

$= 5.00 \times 10^{-7}$ N

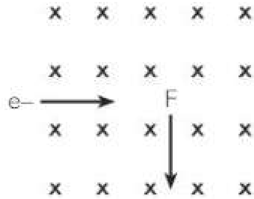
(b) *The following shows wire A and B carrying upwards currents (out of the page). Using the right hand palm rule we can see that wire B will feel a force to the left.*

(c) *Hence the force is a force of attraction.*

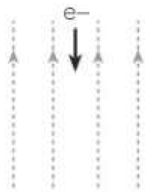


23.

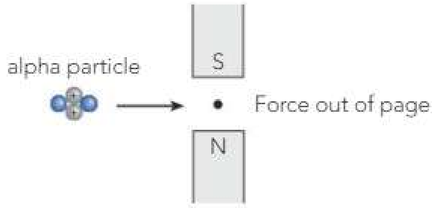
(a)



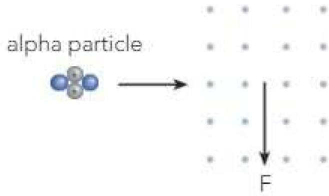
(b) *No force.*



(c)



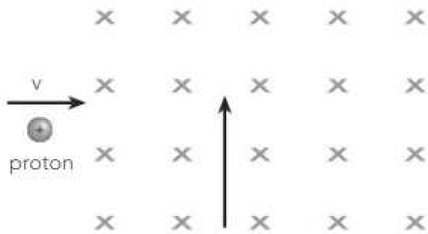
(d)



24. *Electrons will go into a circular path above either of the Earth's poles. They will move in an anticlockwise direction as viewed from the ground at the Earth's North magnetic pole. The opposite will be the appearance from the ground at the Earth's S.M.P. These 'trapped' charges will eventually discharge to ground creating the aurora effects.*

25.

(a) *The force will be upwards.*



(b) $F = qvB = (1.6 \times 10^{-19})(4.2 \times 10^{5})(0.15)$
$= 1.01 \times 10^{-14}$ N

(c) *Force would be the same magnitude (since charge is the same magnitude) but opposite in direction.*

26.

(a) *Right of screen (into page).*

(b) *An AC current would cause the beam to deflect back and forth across the screen.*

27.

(a) *The electromagnets must be rotated 90° from their present position so that the magnetic field between them is at right angles to the page.*

(b) $T = \frac{1}{f} = 0.001\ s$

Hence for the beam to move between P and R (½ cycle) it will take 5.00×10^{-4} s.

28.

(a) $v = \frac{s}{t}\ \therefore t = \frac{s}{v}$

$\therefore t = \frac{2.50 \times 10^{-2}}{1.50 \times 10^{7}} = 1.67 \times 10^{-9} s$

(b) $F = qvB$

$= (1.6 \times 10^{-19})(1.50 \times 10^{7})(2.25 \times 10^{-4})$

$= 5.40 \times 10^{-16}$ N

(c) $a = \frac{F}{m} = \frac{5.4 \times 10^{-16}}{9.11 \times 10^{-31}}$

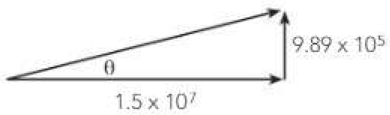
$= 5.93 \times 10^{14}\ m\ s^{-2}$

(d) $v = u + at$

$= 0 + (5.93 \times 10^{14})(1.67 \times 10^{-9})$

$= 9.89 \times 10^{5}\ m\ s^{-2}$

(e) *Use vectors.*



$\tan\theta = \frac{9.89 \times 10^{5}}{1.5 \times 10^{7}}$

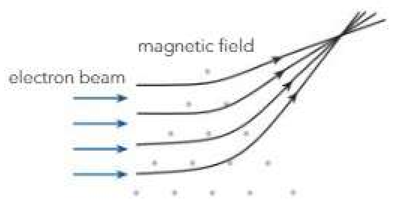
$\therefore \theta = 3.78^{o}$

(f) *Electrons would describe a circular path and hence the direction of the force acting on them is continually changing.*

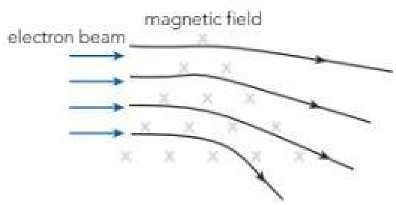
29. (a) *upwards.*

(b) *the bottom part.*

(c) *the beam will tend to focus to a point.*



(d)



The beam will tend to diverge.

30.

(a) *upwards*

(b) *for no nett force*

$qvB = mg$

$\therefore v = \frac{mg}{qB}$

$= \frac{(9.11 \times 10^{-31})(9.80)}{(1.6 \times 10^{-19})(2.38 \times 10^{-5})}$

$= 2.34 \times 10^{-6}\ m\ s^{-1}$

(c) *Since most electrons are moving with far greater speeds than $2.34 \times 10^{-6}\ m\ s^{-1}$ the effect of the magnetic field would be the greatest.*

31.

(a) *AB out of page*   *BC out of page*

CD no force

(b) *The loop will rotate clockwise as viewed from the front.*

32.

(a) $B = 4.25 \times 10^{-2}$ T

$I = 2.25$ A

$F = IlB$

$l = 0.250\ m$

$F = (2.25)(0.250)(4.25 \times 10^{-2})$

$= 2.39 \times 10^{-2}$ N *downwards.*

(Right hand palm rule)

(b) $F = 2.39 \times 10^{-2}$ N

$\tau = r F$

$R = 7.5 \times 10^{-2}\ m$

$= (7.5 \times 10^{-2})(2.39 \times 10^{-2})$

$= 1.79 \times 10^{-3}$ N m

(c) $\tau_{total} = 2\ (r\ F)$

$= 3.59 \times 10^{-3}$ N m

33.

(a) $F = IlB = (4.2)(0.160)(0.64)$

$= 0.43$ N

Hence force acting on

(i) AB is 0.43 N out of page

(ii) BC - no force

(iii) CD is 0.43 N into page

(b) *Zero (forces cancel)*

(c) *Torque = Fr*

on AB $= (0.43)(0.080) = 3.44 \times 10^{-2}$ N m

on BC $= 0$

on CD $= 3.44 \times 10^{-2}$ N m

(d) *Total torque* $= 6.88 \times 10^{-2}$ N m

(e) *Coil will move clockwise.*

34.

(a) *A multicoil armature provides a more constant overall torque since each loop is in a different part of its cycle. This averages out the effect of a single coil which provides a varying torque between zero and a maximum each 90°.*

(b) *A segmented commutator is necessary to provide contact for the ends of the different sets of coils.*

(c) Field coils can take the place of permanent magnets in a motor and are much more powerful.

(d) Laminations are necessary to reduce eddy current effects which cause heat and loss of efficiency.

Power Generation

35.

(a) A potential difference (voltage) exists because the metallic aerial is cutting the Earth's magnetic field.

(b) Top is positive.

(c) $emf = 0.125\ mV \quad B = 3.6 \times 10^{-5}\ T$

$l = 1.6\ m \qquad v = ?$

$emf = lvB$

$$v = \frac{0.125 \times 10^{-3}}{(1.6)(3.6 \times 10^{-5})} = 2.17\ m\ s^{-1}$$

(d) (i) North - zero volts

(ii) South - zero volts

(iii) West - 0.125 mV

36.

(a) $emf = ?$

$B = 5.95 \times 10^{-5}\ T$

$\therefore B_{vertical} = (5.95 \times 10^{-5})(\cos 23^{o})$

$l = 41.5\ m$

$v = 920\ kmh^{-1} = 256\ m\ s^{-1}$

Hence

$emf = lvB$

$= (41.5)(256)(5.48 \times 10^{-5})$

$= 0.581$ Volt

(b) Right wing is positive always for southern hemisphere.

(c) emf will increase since the wings will be moving perpendicularly to the earth's field.

37.

(a) emf is generated. B is positive.

(b) No resistive force since there is no current flowing.

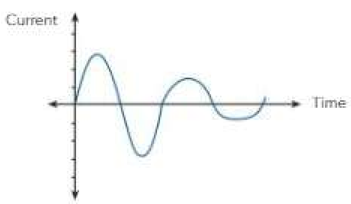
38.

(a) The pendulum will slow down rapidly each time it passes between the magnet's poles, and will stop altogether fairly quickly.

(b) There would be no difference.

(c) The pendulum would swing freely and eventually stop due to friction forces.

(d)



39.

(a) $emf = lvB = (0.048)(12)(2.56 \times 10^{-2})$

$= 1.47 \times 10^{-2}$ V

(b) $I = \frac{V}{R} = \frac{1.47 \times 10^{-2}}{8.00} = 1.84 \times 10^{-3}$ A

(c) Q to R through 8 Ω

(d) $F = IlB = (1.84 \times 10^{-3})(0.048)(2.56 \times 10^{-2})$

$= 2.26 \times 10^{-6}$ N

This force must be applied in the direction of movement to overcome the force resisting motion through the field.

(e) If 4 Ω used, a greater current would flow and more work would need to be done to cut the magnetic field (i.e. greater force needed).

40.

(a) An electric current is induced in a conductor if there is a changing magnetic field in the region of the conductor.

(b) Producing electricity, electromagnetic damping, transformers.

(c) No. If there is no complete circuit only an emf exists.

41.

(a) A to B

(b) B to A

(c) No current

(d) A to B then B to A

42. $A = 4.2 \times 10^{-2}\ m^2 \quad f = 3000$ rpm

$N = 600 \qquad = 50$ Hz

$B = 1.5\ T \qquad T = \frac{1}{f}$

$R = 100\ \Omega \qquad = 0.02$ s

(a) Consider ($t = \frac{T}{4}$) (i.e. ¼ of a turn).

$$emf = \frac{-N(\phi_2 - \phi_1)}{\Delta t}$$

$$= \frac{-600\ (0 - 6.3 \times 10^{-2})}{0.005}$$

$= 7560$ V

(b) $I = \frac{V}{R} = \frac{7560}{100}$

$= 75.6$ A

(c) $P = VI$

$= 572$ kW

43.

(a) $A = (0.25)(0.25) = 0.0625\ m^2$

$B = 0.25\ T$

$\phi = BA = 1.56 \times 10^{-2}$ Wb

Since

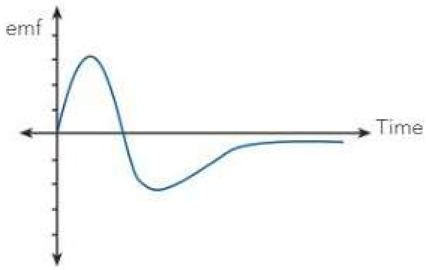
$$emf = \frac{-N(\phi_2 - \phi_1)}{\Delta t}$$

$$= \frac{-1\ (0 - 1.56 \times 10^{-2})}{0.25}$$

$$= 6.25 \times 10^{-2}\ V$$

(b) *A is positive*
(c) *emf is the same , A is positive*
(d) *(i) Situation (a) (ii) Situation (c)*

44.
(a)



(b) *Since current would flow, work is done, magnet is slowed.*
(c) *Smaller emf since magnet is slowed.*

45.
(a) $N = 20 \qquad emf_{max} = -2\pi\ NBA\ f$

$A = (0.250)(0.150)$

$= 3.75 \times 10^{-2}\ m^2$

$= -2\pi\ (20)(1.45)(3.75 \times 10^{-2})(50.0)$

$= -3.42 \times 10^2\ V$

$B = 1.45\ T$ *maximum emf*

$$f = \frac{3000}{60}$$

$= 50.0\ Hz$

(b) $$emf_{rms} = \frac{emf_{max}}{\sqrt{2}}$$

$$= \frac{342}{\sqrt{2}}$$

$= 242\ V$

(c) *Since* $emf_{max} = -2\pi\ NBA\ f$

We can double the induced emf produced by doubling any of the following: the number of turns of coil; the magnetic field strength; the area of the coil or the frequency.
Interestingly if all of these changes were made the maximum emf would be 16 times as much, that is, 5472 V.

46. $V_p = 240\ V \qquad V_x = 12\ V$
$N_p = 1500 N_s \qquad N_s = ?$
$I_p = 25\ mA \qquad I_s = ?$

(a) $$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

$$N_s = 1500 \times \frac{12}{240} = 75$$

(b) $$I_s = 2.5 \times 10^{-2} \times \frac{240}{12} = 0.50\ A$$

(c) $P = VI = (240)(25 \times 10^{-3}) = 6.0\ W$

47.
(a) *The transformer steps up the voltage.*
(b) *The AC voltage in the primary coil creates a fluctuating magnetic field. This induces a fluctuating voltage in the secondary coil.*

(c) $$V_s = 12 \times \frac{1200}{600}$$

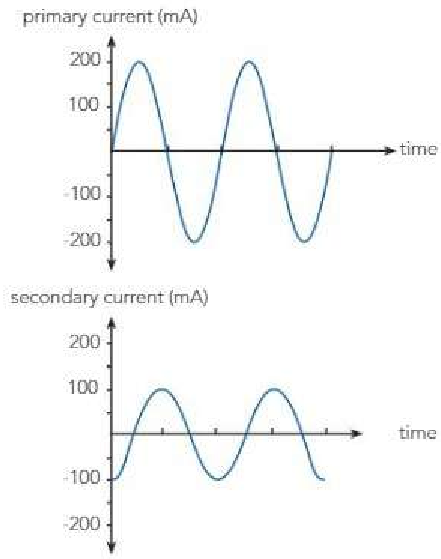
$= 24$ *Volt*

$$I_s = (0.2)\ \frac{600}{1200}$$

$= 0.10\ A$

(d) *The primary wires should be thicker as they carry more current.*

(e)



Note 90° phase difference

48.
(a) *Total power consumed is*
$(4 \times 75) + 195 + (1.85 \times 240) + (8.0 \times 240)$
$= 2859\ W$

(b) $$I = \frac{P}{V} = \frac{2859}{240} = 11.9\ A$$

(c) *Voltage loss* $= I\ R$
$= (11.9)(0.45) = 5.36\ V$

49.
(a) (i) $P = 1.20 \times 10^4\ W \qquad$ *Since* $P = V\ I$

$V = 240\ V \qquad I_{line} = \frac{P}{V} = \frac{12000}{240}$

$I_{line} = ? \qquad = 50.0\ A$

$R_{line} = 0.550\ \Omega$

$\therefore$ *Power lost* $\qquad P = I_2R = I_{line}^{\ 2}\ R_{line}$

$= (50.0)2\ (0.550)$

$= 1.375 \times 10^3\ W$

This represents over 11.5 % of the power being lost down the 2.0 km line.

(ii) V_{loss} = ? Voltage loss along the line

$I_{line} = 50\ A \qquad V_{loss} = I_{line} R_{line}$

$R_{line} = 0.550\ \Omega \qquad = (50)(0.550)$

$= 27.5\ V$

Voltage which reaches the end of the line will be

$V_{end} = 240 - 27.5$

$= 212.5\ V$

(b) Two ways to achieve a near 240 V output at the end of the line are:

- Transmitting power at a higher voltage by using a step up transformer prior to the line and a step down transformer at the end of the line.
- Using a generator that produces a slightly higher voltage initially and better quality (lower resistance) line.

50.

(a) Highest demand is around 6.00 pm. Cooking/heating as people get home from work.

(b) $E = P\ t = (1770 \times 10^6)\ (2) = 3.4 \times 10^6$ kWh

(c) Approx. $\approx 1450 \times 10^6$ W

Find total daily load by breaking up graph. Say $(6h \times 1000) + (2 \times 1300) + (8 \times 1700) + (4 \times 1800) + (4 \times 1400) = 35000 \times 10^3$ kWh

$\therefore \approx 35 \times 10^6$ kWh

CHP 3: WAVE PARTICLE DUALITY AND THE QUANTUM THEORY

3. Chapter Questions

3.1

(a) Using a distant point source will provide a parallel beam of light. A small slit can provide this.

(b) (i) crests

(ii) compression (or area of high pressure).

(c) The particle model would have predicted two bright lines only.

3.2

(a) They are called short waves as they are small in comparison to other radio waves (see Fig 3.19).

(b) No. Radio waves are the longest waves of the electromagnetic spectrum.

3.3 The wave theory could not explain why low frequency light, no matter how bright, failed to cause photoelectric effect.

3.4

(a) Blue light has the most energetic photons since it has the shortest λ and greatest f.

$$E_{ph} = hf = \frac{hc}{\lambda}$$

$$= \frac{(6.63 \times 10^{-34})(3.00 \times 10^8)}{(4.70 \times 10^{-7})}$$

$$= 4.23 \times 10^{-19}\ J$$

(b) The red lamp will emit the most photons per second. Photons of red light have the least energy and so a greater number will be required per second to deliver the same energy.

$$\text{Energy of red photons} = E_{ph} = hf = \frac{hc}{\lambda}$$

$$= \frac{(6.63 \times 10^{-34})(3.00 \times 10^8)}{(6.70 \times 10^{-7})}$$

$$= 2.97 \times 10^{-19}\ J$$

$$\text{Power} = \frac{\text{Energy}}{\text{Time}} = 5.00 \times 10^2\ J\ s^{-1}$$

This means that 500 J of energy are emitted every second.

Hence, number of photons emitted per second

$$= \frac{5.00 \times 10^2}{2.97 \times 10^{-19}}$$

$$= 1.68 \times 10^{21}\ \text{photons.}$$

3.5

(a)
$$E_{ph} = hf = \frac{hc}{\lambda}$$

$$= \frac{(6.63 \times 10^{-34})(3.00 \times 10^8)}{(4.29 \times 10^{-7})}$$

$$= 4.64 \times 10^{-19}\ J$$

(b) $W = 4.64 \times 10^{-19}\ J$ or $(2.90\ eV)$

= minimum energy for electrons to be released from the metal

(c)
$$E_{k(max)} = hf - W = \frac{hc}{\lambda} - W$$

$$= \frac{(6.63 \times 10^{-34})(3.00 \times 10^8)}{(3.50 \times 10^{-7})} - 4.64 \times 10^{-19}$$

$$= 1.04 \times 10^{-19}\ J$$

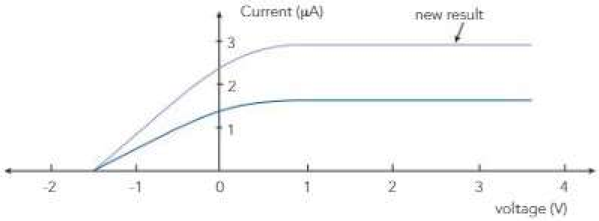
3.6

(a) The stopping voltage is approximately – 1.50 V

(b) (i) An increase in light intensity will not affect stopping voltage. Stopping voltage depends on the energy of the incident photons and the work function of the metal.

(ii) An increase in light wavelength will reduce the energy of the incident photons *and the stopping voltage will be less negative.*

(c) *The increased light intensity will result in a proportional increase in photocurrent. Each photon of light releases one electron from the metal surface. Hence photocurrent is proportional to light intensity as shown on graph. The stopping voltage is not affected as the energy of the individual photons has not changed.*



(d)

(i) $E_{ph} = hf = \dfrac{hc}{\lambda}$

$= \dfrac{(6.63 \times 10^{-34})(3.00 \times 10^{8})}{(2.42 \times 10^{-7})}$

$= 8.22 \times 10^{-19}\ J$

(ii) *The stopping voltage allows us to calculate the maximum energy (kinetic) of the ejected photoelectrons.*

The work done by the negative voltage in stopping the electrons is given by:

$W = qV$

$E_{k(max)} = qV = (1.6 \times 10^{-19})(1.50)\ J$

$= 2.40 \times 10^{-19}\ J$ or $(1.50\ eV)$

(iii) $E_{k(max)} = hf - W$

$W = 8.22 \times 10^{-19} - 2.40 \times 10^{-19}$

Work function $= 5.82 \times 10^{-19}\ J = 3.64\ eV$

3.7

(a) *Bullet*

$\lambda = \dfrac{h}{p} = \dfrac{h}{mv}$

$m = 0.145\ kg \quad v = 3.50 \times 10^{2}\ m\ s^{-1}$

$= \dfrac{(6.63 \times 10^{-34})}{(0.145)(3.50 \times 10^{2})}$

$= 1.31 \times 10^{-35}\ m$ *(bullet wavelength)*

Alpha particle

$= \dfrac{h}{p} = \dfrac{h}{mv}$

$m = 6.64 \times 10^{-27}\ kg \quad v = 8.25 \times 10^{5}\ m\ s^{-1}$

$= \dfrac{(6.63 \times 10^{-34})}{(6.64 \times 10^{-27})(8.25 \times 10^{5})}$

$= 1.21 \times 10^{-13}\ m$
(α particle wavelength)

The α particle has by far the greater wavelength!

(b) *The electron has been accelerated to a + 25.0 V potential.*

$W = qV = \Delta E_k$

$\Delta E_k = (1.6 \times 10^{-19})(25.0) = 4.0 \times 10^{-18}\ J$

$\Delta E_k = \frac{1}{2} mv^2 = 4.0 \times 10^{-18}\ J$

$v^2 = \dfrac{(4.0 \times 10^{-18})(2)}{(9.11 \times 10^{-31})}$

$v = 2.96 \times 10^{6}\ m\ s^{-1}$

Hence electron wavelength given by:

$= \dfrac{h}{p} = \dfrac{h}{mv}$

$= \dfrac{(6.63 \times 10^{-34})}{(9.11 \times 10^{-31})(2.96 \times 10^{6})}$

$= 2.46 \times 10^{-10}\ m$

Also neutron wavelength given by:

$= \dfrac{h}{p} = \dfrac{h}{mv}$

$= \dfrac{(6.63 \times 10^{-34})}{(1.67 \times 10^{-27})(0.150 \times 3.0 \times 10^{8})}$

$= 8.82 \times 10^{-15}\ m$

The electron has the much greater wavelength!

3.8

(a) 10 lines

(b) $E_5 \rightarrow E_1$

(c) $E_4 \rightarrow E_2 = 4.08 \times 10^{-19}\ J$

$E = hf = \dfrac{hc}{\lambda}$

$\therefore \lambda = \dfrac{(6.63 \times 10^{-34})(3 \times 10^{8})}{4.08 \times 10^{-19}}$

$= 4.88 \times 10^{-7}\ m$

(d) Blue.

3.9

(a) The line due to E_2 to E_1 transition.

(b) $E_2 \rightarrow E_1 = 16.26 \times 10^{-19}$ J

$$\lambda = \frac{hc}{E}$$

$$\lambda = \frac{(6.63 \times 10^{-34})(3 \times 10^8)}{16.26 \times 10^{-19}}$$

$$= 1.22 \times 10^{-7}\,m$$

(c) longest λ for $E_4 - E_3$

$$\lambda = \frac{(6.63 \times 10^{-34})(3 \times 10^8)}{1.06 \times 10^{-19}}$$

$$= 1.88 \times 10^{-6}\,m$$

3.10

(a) Scattered electron energies	8.00×10^{-19} J
	0.03×10^{-19} J
(b) Photon energy	7.77×10^{-19} J

3.11

(a) No interaction.

(b) Photon absorbed then photons of 3 possible energies emitted.

(c) Photon absorbed, atom is ionised, photons of many different energies may be emitted.

3.12

Unlike electrons, only specific photon energies will interact to create spectra. Electrons may also create a variety of upward electron transitions.

3.13

Our eyes cannot distinguish the light as separate colours and instead sees them as a blend. A prism can separate these colours.

3.14

The absorption lines are distinctive of the gases through which the light has passed. Careful analysis of these lines can tell us the composition of the atmospheres it has passed through.

3.15

Ultraviolet light (high energy photons) is absorbed, leaving the atom in an excited state. The electrons return to the ground state by a series of small energy jumps which correspond to the visible spectrum.

3.16

The peaks are due to photons emitted when electrons fall to lower energy levels. Energy levels are unique to each atom and hence so are the peaks in the spectrum.

3.17

(a) $\lambda = \frac{c}{f} = \frac{3 \times 10^8}{1.21 \times 10^{19}} = 2.48 \times 10^{-11}\,m$

(b) $\frac{\lambda\ light}{\lambda\ x\text{-}rays} \approx \frac{5 \times 10^{-7}}{2.48 \times 10^{-11}} \approx 20{,}000$

i.e. light waves are about 20,000 times larger than x-rays.

3. Review Questions

The Nature of Light

1. Supports the wave theory. Particle theory cannot explain diffraction effects.

2. U.V. radiation has higher energy photons which can more easily ionise the atoms in our skin tissue. This can lead to undesirable health effects.

3.

(a) $f = \frac{c}{\lambda} = \frac{3 \times 10^8}{0.1225} = 2.45 \times 10^9$ Hz

(b) $E_{ph} = hf$
$= (6.63 \times 10^{-34})(2.45 \times 10^9)$
$= 1.62 \times 10^{-24}$ J

(c) $P = \frac{E}{t} = 850\ Js^{-1}$

$\therefore$ No. of photons $= \frac{850}{1.62 \times 10^{-24}}$

$= 5.23 \times 10^{26}$ photons

4.

(a) Yellow light

(b) (i) $\frac{E_{ph}(blue)}{E_{ph}(yellow)} = \frac{5.9 \times 10^{-7}}{4.8 \times 10^{-7}} = 1.23$

(ii) $\frac{No_{ph}(blue)}{No_{ph}(yellow)} = \frac{1}{1.23} = 0.813$

5.

(a) Vision signal

$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{2.09 \times 10^8} = 1.43\,m$

Audio signal

$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{2.147 \times 10^8} = 1.40\,m$

(b) Audio signal photons have higher energies.

$E = hf = (6.63 \times 10^{-34})(2.147 \times 10^8)$
$= 1.42 \times 10^{-25}$ J

(c) $\therefore$ No. of photons $= \frac{1000}{1.42 \times 10^{-25}}$

$= 7.02 \times 10^{27}$ photons per second

6. *Microwave oven (A)*

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{2450 \times 10^6} = 0.122\ m$$

Air traffic radar (B)

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{2800 \times 10^6} = 0.107\ m$$

$$\frac{\lambda_A}{\lambda_B} = \frac{0.122}{0.107} = 1.14$$

$$\frac{E_{ph}(A)}{E_{ph}(B)} = \frac{2450}{2800} = 0.875$$

7.

(a) (i) $\lambda = \frac{c}{f} = \frac{3 \times 10^8}{2.80 \times 10^9} = 0.107\ m$

(ii) $E_{ph} = hf$

$= (6.63 \times 10^{-34})(2.80 \times 10^9)$

$= 1.86 \times 10^{-24}\ J$

(b) $E = P \times t = (600 \times 10^3)(1 \times 10^{-6}) = 0.600\ J$

$\therefore$ No. of photons $= \frac{0.60}{1.86 \times 10^{-24}}$

$= 3.23 \times 10^{23}$ *photons per second*

8.

(a) $f = \frac{c}{\lambda} = \frac{3 \times 10^8}{6.33 \times 10^{-7}} = 4.74 \times 10^{14}\ Hz$

Colour is red.

(b) $E_{ph} = hf = (6.63 \times 10^{-34})(4.74 \times 10^{14})$

$= 3.14 \times 10^{-19}\ J$

(c) $P = \frac{E}{t} = \frac{(3.14 \times 10^{-19})(5 \times 10^{18})}{1}$

$= 1.57\ W$

9.

(a) *Electrode X contains the test metal. It is the cathode.*

(b) *The filter allows the selection of particular colours of light to be used. Hence changes in light wavelengths can be tested.*

(c) (i) *Current will double. Increased light intensity means more photons are incident on the target metal and hence more electrons will be ejected (one photon ejects one electron).*

(ii) No change. Photons from the blue light will be more energetic but the same number of electrons will be ejected (photocurrent).

(iii) No change. The anode voltage was already positive and all available photoelectrons were been collected at the anode. Increasing the voltage will not provide any more photoelectrons.

10. *Photocurrent would occur with blue light but not with red. Blue light has a shorter wavelength than green light and hence the photons have more energy. Since green causes a photocurrent so will blue. The wavelength of red light is longer than yellow light (which did not cause a current) and so no photocurrent results.*

11.

(a) $E_{ph} = hf = \frac{hc}{\lambda}$

$$= \frac{(6.63 \times 10^{-34})(3.00 \times 10^8)}{(2.60 \times 10^{-7})}$$

$= 7.65 \times 10^{-19}\ J$

$$E_{ph} = \frac{7.23 \times 10^{-19}}{1.6 \times 10^{-19}} = 4.78\ eV$$

(b) *We can use the stopping voltage to calculate the $E_{k(max)}$ of the ejected electrons.*

$W = qV = E_{k(max)}$

$E_{k(max)} = qV = (1.6 \times 10^{-19})(0.550)\ J$

$= 8.80 \times 10^{-20}\ J = 0.550\ eV$

(c) *To find the work function (W) we have:*

$W = hf - E_{k(max)} = 4.78 - 0.550$

$= 4.23\ eV$

(d) *At the threshold frequency the electrons are able to reach the surface of the metal but have zero kinetic energy. At this point the incident photon energy is exactly equal to the work function.*

$E_{k(max)} = hf - W$

$hf_0 = W$

Since $E_{k(max)} = 0$

$hf_0 = 4.23\ eV = (4.23)(1.6 \times 10^{-19})$

$= 6.77 \times 10^{-19}\ J$

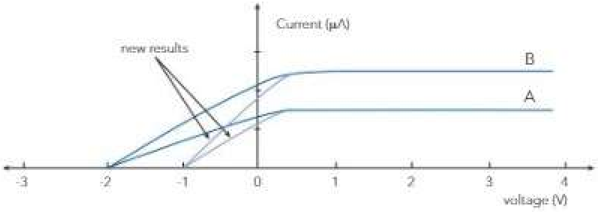
$f_0 = 6.77 \times 10^{-19} / 6.63 \times 10^{-34}$

Threshold frequency $= 1.02 \times 10^{15}\ Hz$

12.

(a) *Curve B is for the higher light intensity. More photons from the brighter light mean more photoelectrons produced.*

(b) *See graph below. The longer wavelength means less energetic photons. Ejected electrons will have less kinetic energy and hence a lower stopping voltage is needed. Since the light intensities are the same the maximum photocurrent will not change in either case.*



(c) *The stopping voltage is approximately – 2.00 V*

(i) The work done by the negative voltage in stopping the electrons is given by:

$$W = qV = E_{k(max)}$$

$$E_{k(max)} = qV = (1.6 \times 10^{-19})(2.00)\ J$$

$$= 3.20 \times 10^{-19}\ J \quad or \quad = 2.00\ eV$$

(ii) Energy of the incident photons

$$E_{ph} = hf = \frac{hc}{\lambda}$$

$$= \frac{(6.63 \times 10^{-34})(3.00 \times 10^{8})}{(2.90 \times 10^{-7})}$$

$$= 6.86 \times 10^{-19}\ J = 4.29\ eV$$

We can now find the work function using:

$$E_{k(max)} = hf - W$$

$$W = hf - E_{k(max)}$$

$$= 6.86 \times 10^{-19} - 3.2 \times 10^{-19}$$

$$= 3.66 \times 10^{-19}\ J = 2.29\ eV$$

(iii) At the threshold frequency the electrons are able to just reach the surface of the metal but have zero kinetic energy. In this case the incident photon energy is exactly equal to the work function.

$$hence\ hf_0 = W$$

$$hf_0 = 3.66 \times 10^{-19}\ J$$

$$f_0 = \frac{3.66 \times 10^{-19}}{6.63 \times 10^{-34}}$$

Threshold frequency $= 5.52 \times 10^{14}\ Hz$

13.

(a) *The wavelengths predicted by the de Broglie theory are extremely small for large objects moving slowly. Matter waves were first detected by the diffraction of fast moving electrons.*

(b) (i) $\lambda = \frac{h}{p} = \frac{h}{mv}$

$$= \frac{(6.63 \times 10^{-34})}{(71.0)(12.0)}$$

$$= 7.78 \times 10^{-37}\ m$$

This is an extremely small wavelength and difficult to detect.

(ii) $\lambda = \frac{h}{p} = \frac{h}{mv}$

$$= \frac{(6.63 \times 10^{-34})}{(1.25 \times 10^{3})(\frac{60.0}{3.6})}$$

$$= 3.18 \times 10^{-38}\ m$$

This is an even smaller wavelength mainly due to the large mass.

(iii) The electron has been accelerated to a + 150 V potential.

$$W = qV = \Delta E_k$$

$$\Delta E_k = (1.6 \times 10^{-19})(150) = 2.40 \times 10^{-17}\ J$$

$$\Delta E_k = \tfrac{1}{2} mv^2 = 2.40 \times 10^{-17}\ J$$

$$v^2 = \frac{(2.40 \times 10^{-17})(2)}{(9.11 \times 10^{-31})}$$

$$v = 7.26 \times 10^{6}\ m\ s^{-1}$$

$$\lambda = \frac{h}{p} = \frac{h}{mv}$$

$$= \frac{(6.63 \times 10^{-34})}{(9.11 \times 10^{-31})(7.26 \times 10^{6})}$$

$$= 1.00 \times 10^{-10}\ m$$

The wave nature of electrons of this wavelength can be detected by diffraction

14.

(a) *A band gap, or energy gap, is the energy difference between the valence and conduction bands of a semiconductor such as an LED chip.*

(b) $\lambda = \frac{hc}{E_g}$

$$= \frac{(6.63 \times 10^{-34})\ (3.00 \times 10^{8})}{(2.25 \times 1.6 \times 10^{-19})}$$

$$= 5.52 \times 10^{-7}\ m \quad or \quad 552\ nm$$

(c) This wavelength corresponds to green light. If red light is required, then a smaller band gap is necessary as red light has a longer wavelength ($\approx$ 700 nm). A band gap of $\approx$ 1.8 eV would achieve this.

Spectra

15.

(a) Atoms can be excited
   (i) thermally
   (ii) by bombarding electrons
   (iii) by absorbing photons.

(b) Excited electrons give up energy by emitting photons and returning to ground state.

16.

(a) $E_5 = \dfrac{-13.6}{(5)^2} = 0.544$ eV

$E_6 = \dfrac{-13.6}{(6)^2} = 0.378$ eV

(b) $E_6 - E_5 = 0.166$ eV

$\therefore \lambda = \dfrac{hc}{E}$

$= \dfrac{(6.63 \times 10^{-34})(3 \times 10^8)}{0.166 \times 1.6 \times 10^{-19}}$

$= 7.48 \times 10^{-6}$ m

(c) Infra-red.

17.

(a) The energies are negative as it indicates the loss of potential energy. A free electron has zero potential energy.

(b) (i) 7.96×10^{-19} J ($E_1 \rightarrow E_2$)
   (ii) 13.4×10^{-19} J ($E_1 \rightarrow$ ionisation)

(c) $E_3 \rightarrow E_1 = 10.04 \times 10^{-19}$ J
   $E_3 \rightarrow E_2 = 2.08 \times 10^{-19}$ J
   $E_2 \rightarrow E_1 = 7.96 \times 10^{-19}$ J

Max. frequency: $f = \dfrac{E}{h} = \dfrac{10.04 \times 10^{-19}}{6.63 \times 10^{-34}}$

$= 1.51 \times 10^{15}$ Hz

18.

(a) $E_2 \rightarrow E_1 = \dfrac{hc}{\lambda}$

$= \dfrac{(6.63 \times 10^{-34})(3 \times 10^8)}{5.89 \times 10^{-7}}$

$= 3.38 \times 10^{-19}$ J

Also $E_3 - E_1 = 5.13 \times 10^{-19}$ J
$\therefore E_3 - E_2 = 1.75 \times 10^{-19}$ J

$\therefore \lambda_{ph} = \dfrac{hc}{1.75 \times 10^{-19}}$

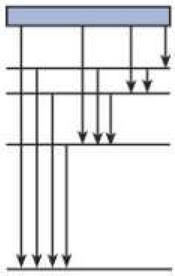
$= 1.14 \times 10^{-6}$ m

(b) Infra-red.

19.

(a) $f = \dfrac{E}{h} = \dfrac{8.21 \times 10^{-19}}{6.63 \times 10^{-34}} = 1.24 \times 10^{15}$ Hz

(b)



10 different frequency photons are possible.

(c) largest λ = minimum energy

$\therefore \lambda = \dfrac{hc}{E} = \dfrac{hc}{0.89 \times 10^{-19}} = 2.23 \times 10^{-6}$ m

20.

(a) Only photons of 10.2 eV will be absorbed. (−13.6 eV $\rightarrow$ −3.4 eV)

(b) The atom would interact with all electron energies between 10.2 eV and 12.0 eV.

(c) highest f = highest ΔE

$\therefore f = \dfrac{E}{h} = \dfrac{(12.1 \times 1.6 \times 10^{-19})}{6.63 \times 10^{-34}}$

$= 2.92 \times 10^{15}$ Hz

21.

(a) Scattered electron energies
   7.5 eV, 2.6 eV, 0.8 eV.

(b) possible photon energies
   6.7 eV, 4.9 eV, 1.8 eV.

(c) 10.4 eV needed for ionisation.

22.

(a) No interaction.

(b) 4.9 eV, 6.7 eV, 8.8 eV

(c) 6 possible photon energies
   8.8 eV, 6.7 eV, 4.9 eV, 3.9 eV, 2.1 eV, 1.8 eV

23.

(a) E_{ph} (absorbed) $= h f$
   $= (6.63 \times 10^{-34})(1.15 \times 10^{15})$
   $= 7.62 \times 10^{-19}$ J
   $= 4.77$ eV

$\therefore$ E of 2[nd] photon emitted
   (4.77 − 2.07)
   = 2.70 eV

(b) λ (photon 1) $= \dfrac{hc}{E} = \dfrac{hc}{2.07 \times 1.6 \times 10^{-19}}$

$= 6.00 \times 10^{-7}$ m

λ (photon 2) $= \dfrac{hc}{2.70 \times 1.6 \times 10^{-19}}$

$= 4.61 \times 10^{-7}$ m

(c) *photon 1 ≈ orange spectrum*
photon 2 ≈ blue/indigo spectrum

24.

(a) $W = qV = E_K$ *of electrons*

$\therefore E_K = (1.6 \times 10^{-19})(120000)$

$= 1.92 \times 10^{-14} J$

(b) $E = hf$

$$\therefore f = \frac{E}{h} = \frac{1.92 \times 10^{-14}}{6.63 \times 10^{-34}} = 2.90 \times 10^{19} Hz$$

(c) $E = Pt = VIt$

$=(1.20 \times 10^5)(0.1)(0.04)$

$= 480 J$

E *(photons)* $= 9.6 \times 10^{-15} J$

$$\therefore \text{No. (photons)} = \frac{480}{9.6 \times 10^{-15}}$$

$= 5 \times 10^{16}$

CHP 4: SPECIAL RELATIVITY

4. Chapter Questions

4.1

(a) $v = 2.0\ kmh^{-1}$ *West*

(b) $v = 50 + 2.0$

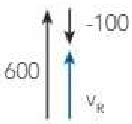
$= 52\ kmh^{-1}$ *West*

(c) $v = 50 + 2.0 + 70$

$= 122\ kmh^{-1}$ *West*

4.2

(a)



$v_R = 650 - 100$

$= 550\ kmh^{-1}$ *North*

(b)

$v_R = 650 + 100$

$= 750\ kmh^{-1}$ *North*

(c)

Use Pythagoras.

$v_R = 658\ kmh^{-1}$,

8.75^o *East of North*

4.3

(a) $v = \frac{s}{t}$

$$\therefore t = \frac{s}{v} = \frac{10{,}000}{3.00 \times 10^8}$$

$= 3.33 \times 10^{-5} s$

(b) *Reaction time of the observers is much greater than the time interval involved. Lack of timing devices for such small time intervals.*

4.4

(a) *From the diagram Figure 4.7 we have, using Pythagoras:*

$$(ct)^2 = L^2 + (vt)^2$$

$$c^2t^2 = c^2t_o^2 + v^2t^2$$

$$t^2 = t_o^2 + (\frac{v^2}{c^2})\, t^2$$

$$t^2 - (\frac{v^2}{c^2})\, t^2 = t_o^2$$

$$1 - (\frac{v^2}{c^2}) = \frac{t_o^2}{t^2}$$

$$t^2 = \frac{t_o^2}{1 - (\frac{v^2}{c^2})}$$

$$t = \frac{t_o}{\sqrt{1 - \frac{v^2}{c^2}}}$$

(b) *The time between Hannah's waves (in her spaceship) is given by:*

$$T = \frac{60}{40} = 1.5 s$$

Viewed from Chelsea's spaceship the time would be:

$$t = \frac{t_o}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$t = \frac{1.5}{\sqrt{1 - (\frac{0.25 c^2}{c^2})}}$$

$$t = \frac{1.5}{\sqrt{0.9375}} = 1.55 s$$

Chelsea will see fewer waves per minute as they each take a longer time.
The frequency will be $= \frac{60}{1.55} = 39$ *waves per minute.*

4.5

(a) *From Fig 4.8 we have*

For the driver:

$$t_o = \frac{2L_o}{c}$$

For the stationary observer:

$$t = \frac{2L}{\sqrt{(c)\,(1 - \frac{v^2}{c^2})}}$$

Using $t = \frac{t_o}{\sqrt{1 - \frac{v^2}{c^2}}}$

$$= \frac{2L}{(c)(1 - \frac{v^2}{c^2})} = \frac{t_o}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$= \frac{2L}{(c)(1 - \frac{v^2}{c^2})} = \frac{(\frac{2L_o}{c})}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$L = L_o\sqrt{1 - \frac{v^2}{c^2}}$$

(b) $l = l_o\sqrt{1 - \frac{v^2}{c^2}}$

$$l = (0.350)\sqrt{1 - \frac{(7.5 \times 10^7)^2}{(3.0 \times 10^8)^2}}$$

$l = (0.350)\ 1 - 0.0625$
$l = 0.339\ m$

(c) $v = 7.50\ m\ s^{-1}$ $\quad t = \frac{s}{v}$

$s = 0.339\ m$ $\quad = \frac{0.339}{7.50 \times 10^7}$

$t = ?$ $\quad = 4.52 \times 10^{-9}\ s$

4.6

u = the velocity of car B relative to Max
= ?
v = the velocity of car A relative to Max
= $70.0\ m\ s^{-1}$
u' = the velocity of car B relative to car A.
= $60.0\ m\ s^{-1}$

$$u = \frac{(v + u')}{1 + (\frac{vu'}{c^2})}$$

$$u = \frac{(70.0 + 60.0)}{1 + (\frac{(70.0 \times 60.0)}{(3.0 \times 10^8)^2})}$$

$$u = \frac{(130.0)}{1 + 4.67 \times 10^{-14}}$$

$u = 130\ m\ s^{-1}$

As we can see the relativistic effect is extremely small at these velocities and our usual classical equations are appropriate to use.

4.7

Consider Max on Earth to be in one reference frame, S, and the two spaceships in reference frame S′ as shown below. Reference frame S′ is moving at a velocity of 0.70c away from frame S. As we know the velocity of spaceship B as viewed from Earth (u = - 0.50c) we need to use the inverse velocity transformation equation to find u'.

u = the velocity of B relative to S

= - 0.50c

u' = the velocity of B relative to S′

= ?

v = the velocity of S′ relative to S

= 0.70c

$$u' = \frac{(u - v)}{1 - (\frac{(uv)}{c^2})}$$

$$u = \frac{(-0.50c - (0.70c))}{1 - (\frac{(-0.50c)(-0.70c)}{c^2})}$$

$$u = \frac{-1.20c}{1 + 0.35}$$

$u = -0.89c$

The velocity of spaceship B will be – 0.89c relative to spaceship A. The negative sign indicates it is moving in the opposite direction to spaceship A, towards it and the Earth.

4.8(a)

$$p = \frac{mv}{\sqrt{1 - (\frac{v^2}{c^2})}}$$

$$p = \frac{(6.64 \times 10^{-27})(8.50 \times 10^7)}{\sqrt{1 - \frac{(8.50 \times 10^7)^2}{(3 \times 10^8)^2}}}$$

$$p = \frac{5.64 \times 10^{-19}}{\sqrt{1 - 0.0803}}$$

$p = 5.88 \times 10^{-19}\ kg\ m\ s^{-1}$

(b) Total energy of alpha particle given by

$$E = \frac{mc^2}{\sqrt{1 - (\frac{v^2}{c^2})}}$$

$$= \frac{(6.64 \times 10^{-27})(3.0 \times 10^8)^2}{\sqrt{1 - \frac{(8.50 \times 10^7)^2}{(3 \times 10^8)^2}}}$$

$$= \frac{5.98 \times 10^{-10}}{\sqrt{1 - 0.0803}}$$

$= 6.23 \times 10^{-10}\ J$

(c) E_k = total energy - rest energy
$= 6.23 \times 10^{-10} - m c^2$
$= 6.23 \times 10^{-10} - (6.64 \times 10^{-27})(3.0 \times 10^8)^2$
$= 2.55 \times 10^{-11}\ J$

(d) Not possible. For the particle to reach light *velocity infinite energy would be required.*

4.9

(a) *The rest energy for Vesta is given by*

$$E_o = mc^2$$

$$= (2.60 \times 10^{18})(3.0 \times 10^8)^2$$

$$= 2.34 \times 10^{35}\ J$$

(b) *Velocity of Vesta, v, is*

$$v = 19.3\ km\ s^{-1}$$

$$= 1.93 \times 10^4\ m\ s^{-1}$$

Total energy is given by

$$E = \frac{mv}{\sqrt{1 - (\frac{v^2}{c^2})}}$$

$$= \frac{2.34 \times 10^{35}}{\sqrt{1 - \frac{(1.93 \times 10^4)^2}{(3 \times 10^8)^2}}}$$

$$= \frac{2.34 \times 10^{35}}{\sqrt{1 - 4.14 \times 10^{-8}}}$$

$$= 2.34 \times 10^{35}\ J$$

Vesta's kinetic energy is insignificant compared to its rest energy.

4. Review Questions

Relative Motion – Frames of Reference

1.

(a) *An inertial reference frame is one that is not accelerating. A reference frame can be your classroom (not moving or accelerating relative to the ground) or it could be the inside of your bus if travelling at a constant velocity. In both cases all the laws of physics apply relative to that frame of reference.*

(b) *No, since the Earth travels in a circular path hence it is accelerating.*

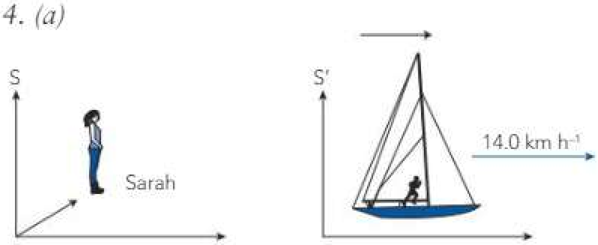
2.

(a) *You cannot tell if you are moving as it is not possible to do so within your own frame of reference. If you could look outside the train you would be able to do so.*

(b) *Yes, if you were accelerating you would feel a force between yourself and your seat. If standing you would lurch in the opposite direction to any acceleration.*

3. *There is no frame of reference that has zero velocity. Hence all motion is relative and there is no point in the universe that is at absolute rest.*

4. (a)



We consider Sarah to be in one reference frame, S, and the boat and Max in S′ as shown above.

u = *the velocity of Max relative to Sarah.*

= ?

v = *the velocity of frame S′ relative to frame S.*

= $12.0\ km\ h^{-1}$

u' = *the velocity of Max relative to frame S′*

= $14.0\ km\ h^{-1}$

$$u = v + u'$$

Velocity of Max relative to Sarah

= $12.0 + 14.0 = 26.0\ km\ h^{-1}$ *away from Sarah*

(b) *We need to use the inverse equation as we are looking for Sarah's velocity as seen from S′. Max is now moving towards the back of the boat so his velocity in frame S′ is given by* $u = -14.0\ km\ h^{-1}$.

$$u' = u - v$$

Sarah's velocity relative to Max

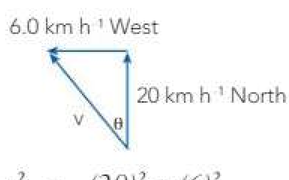
$$u = -14.0 - (-12)$$

= $-2.0\ km\ h^{-1}$ *(moving towards Sarah)*

5. *Note: vector diagrams not to scale.*

(a) *v (relative to bank)* = $(20.0 - 6.0)\ km\ h^{-1}$ *East* = $14.0\ km\ h^{-1}$ *East*

(b)



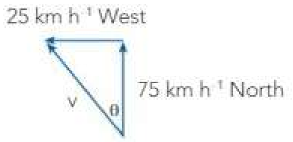
Also $\tan\theta = \frac{6}{20}$

$\theta = 16.7^o$

$$v^2 = (20)^2 + (6)^2$$

$v = 20.9\ km\ h^{-1}\ 16.7^o$ *West of North*

6.
(a)



$\tan\theta = \dfrac{25}{75}$

$\theta = 18.4^o$

$v^2 = (75)^2 + (25)^2$

$v = 79.1\ km\ h^{-1}\ 18.4^o$ *West of North*

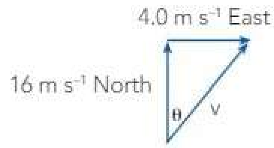
(b) *Use the Westerly velocity to determine how far West the glider moves in 10 minutes.*

$s = vt$

$= (25.0\ kmh^{-1})(10/60\ h)$

$= 4.17\ km$

7.
(a)



$\tan\theta = \dfrac{4}{16}$

$\theta = 14.0^o$

$v^2 = (16)^2 + (4)^2$

$v = 16.5\ km\ h^{-1}\ 14.0^o$ *East of North*

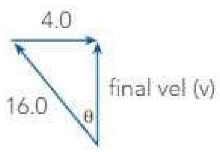
(b) *Use velocity in the direction of the 625 m to find time to cross.*

$t = \dfrac{s}{v} = \dfrac{625}{16.0} = 39.1\ s$

(c) *Use water velocity to find out how far the boat has drifted.*

$s = v.t = (4.00)(39.1) = 156\ m$

8.
(a)



$\sin\theta = \dfrac{4.0}{16.0}$

$\theta = 14.5^o$ *West*

Boat must head 14.5^o *West of North*

(b) $v^2 = (16.0)^2 - (4)^2$

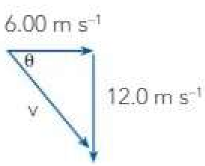
$v = 15.5\ m\ s^{-1}$

$\therefore$ *time to cross* $= \dfrac{625}{15.5} = 40.3\ s$

9.
(a) $v = u + at$

$= 0 + (9.8)(1.22) = 12.0\ m\ s^{-1}$

(b)



$\tan\theta = \dfrac{12.0}{6.00}$

$\theta = 63.4^o$

$v^2 = (6.00)^2 + (12)^2$

$= 13.4\ m\ s^{-1}\ 63.4^o$ *from the horizontal.*

(c) (i) *The ball moves vertically downwards.*

(ii) *The ball moves vertically downwards.*

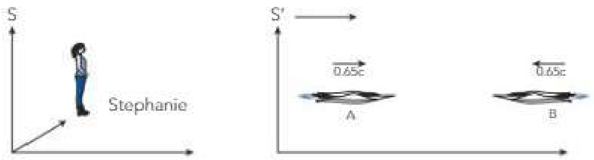
(iii) *The ball moves in a parabolic path downwards and in an Easterly direction.*

10.
(a) *Light beam was split using a half silvered mirror.*

(b) *To detect the luminiferous aether.*

(c) *The beams were at right angles so that if one was travelling parallel to the presumed aether 'flow' then the other would not be affected by this 'flow'. Hence if the aether existed there would be a time delay for the beam going back and forth in line with the aether and this would be detected by the interference pattern created when the two beams recombined.*

11.
(a) *Consider Stephanie on Earth to be in one reference frame, S, and the two spaceships in reference frame S′ as shown below. Reference frame S′ is moving at a velocity of 0.65c away from frame S. As we know the velocity of spaceship B as viewed from Earth (u = - 0.65c) we need to use the inverse velocity transformation equation to find u′.*



u = *the velocity of B relative to S*

$= -0.65c$

u' = *the velocity of B relative to S′.*

$= ?$

v = *the velocity of S′ relative to S*

$= 0.65c$

$$u' = \frac{(u - v)}{1 - (\frac{(uv)}{c^2})}$$

$$u' = \frac{(-0.65c - (0.65c)}{1 - (\frac{(-0.65c)(-0.65c)}{c^2})}$$

$$u' = \frac{-1.30c}{1 + 0.4225}$$

$u- = -0.91c$

The velocity of spaceship B will be – 0.91c relative to spaceship A. The negative sign indicates it is moving in the opposite direction to spaceship A, towards it and the Earth.

(b)

(i) The velocity of spaceship A is 0.91c relative to spaceship B and 0.65c relative to Stephanie on Earth.

Hence

$$l = l_o\sqrt{1 - \frac{v^2}{c^2}}$$

$$l = 145\sqrt{1 - \frac{(0.91c)^2}{c^2}}$$

$$l = 145\sqrt{1 - 0.828}$$

l = 60.1 m (length relative to spaceship B)

(ii) Similarly

$$l = l_o\sqrt{1 - \frac{v^2}{c^2}}$$

$$l = 145\sqrt{1 - \frac{(0.65c)^2}{c^2}}$$

l = 110 m (length relative to Earth)

12.

(a) No change to the speed of light. It is constant in all reference frames.

(b) The light flashes will appear closer together than when they left.

(c) The frequency of the light will be greater (Doppler effect)

13.

(a) The duration of the flashes as measured on the spaceship, to, is 2.00 s. To the observer at the space station their clock will appear slow. The time duration, t, as measured at the space station is given by:

$$t = \frac{t_o}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$= \frac{2.00}{\sqrt{1 - \frac{(0.82c)^2}{c^2}}}$$

$$= \frac{2.00}{\sqrt{1 - 0.672}}$$

= 3.49 s (flash duration)

(b) The time between flashes at the space station will also appear to be longer. The time would be longer by the same factor as above.

Time between flashes on Earth

$$= \frac{5.00}{\sqrt{1 - 0.672}} = 8.74 \text{ minutes}$$

14.

(a) Hannah's spaceship will appear to be moving at 0.4 c relative to Chelsea.

(b) Hannah's clock will appear to be slower to Chelsea(although normal to Hannah)

(c) Hannah's space ship will appear to shorter to Chelsea.

(d) The speed of light will be c. The speed of light is the same in all reference frames.

15.

(a) The duration of Chelsea's sleep, as measured on her spaceship, to, is 30 minutes. To Hannah, Chelsea's clock will appear slow. The time duration, t, as measured by Hannah is given by:

$$t = \frac{t_o}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$= \frac{30}{\sqrt{1 - \frac{(0.20c)^2}{c^2}}}$$

$$= \frac{30}{\sqrt{1 - 0.04}}$$

= 30.6 minutes

(b) Similarly, the length of Chelsea's bed will appear shorter from Hannah's spaceship.

$$l = l_o\sqrt{1 - \frac{v^2}{c^2}}$$

$$l = 1.80\sqrt{1 - \frac{(0.20c)^2}{c^2}}$$

l = 1.76 m

16.

(a) As seen from the moving spaceship the Earth will contract in the direction of relative motion. This will create an 'egg shape' or ellipsoid. At a velocity of 0.90c this contraction would be to less than half.

(b) When the spaceship was approaching from afar the contraction effect would still occur. However since the contraction would be in the direction of relative motion (towards the Earth) it would not be noticeable. The Earth would be more of a 'flatter' disc but circular in appearance.

17.

(a) $$p = \frac{mv}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$p = \frac{(9.11 \times 10^{-31})(0.45 \times 3.0 \times 10^{8})}{\sqrt{1 - \frac{(0.45c)^2}{c^2}}}$$

$$p = \frac{1.23 \times 10^{-22}}{\sqrt{1 - 0.2025}}$$

$$p = 1.38 \times 10^{-22} \ kg\ m\ s^{-1}$$

(b) $$p = \frac{(9.11 \times 10^{-31})(0.90 \times 3.0 \times 10^{8})}{\sqrt{1 - \frac{(0.91c)^2}{c^2}}}$$

$$p = \frac{2.46 \times 10^{-22}}{\sqrt{1 - 0.81}}$$

$$p = 5.93 \times 10^{-22} \ kg\ m\ s^{-1}$$

(c) *Although the velocity was only doubled, the momentum has increased by more than four times. The relativistic effect at velocities closer to the speed of light increases the mass of the particle. Eventually the mass would approach infinity as it is not possible to reach the speed of light.*

18.

(a) *Protons rest energy is its rest mass in energy terms*

$$\begin{aligned} E_o &= mc^2 \\ &= (1.67 \times 10^{-27})(3.0 \times 10^{8})^2 \\ &= 1.50 \times 10^{-10}\ J \end{aligned}$$

(b) (i) *The total energy of the proton is given by*

$$E = \frac{mv}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$= \frac{(1.67 \times 10^{-27})(3.0 \times 10^{8})^2}{\sqrt{1 - \frac{(0.80c)^2}{c^2}}}$$

$$= \frac{1.50 \times 10^{-11}}{\sqrt{1 - 0.64}}$$

$$= 2.50 \times 10^{-11}\ J$$

(ii) *The protons kinetic energy is given by*

$$E_k = \text{total energy - rest energy}$$

$$= 2.50 \times 10^{-11} - mc^2$$

$$= 2.50 \times 10^{-11} - 1.50 \times 10^{-11}$$

$$= 1.00 \times 10^{-11}\ J$$

19.

(a) $$l = l_o \sqrt{1 - \frac{v^2}{c^2}}$$

$$l = (2.0 \times 10^{3})\left(\sqrt{1 - \frac{(0.95c)^2}{c^2}}\right)$$

$$l = (2.0 \times 10^{3})\left(\sqrt{1.0 - 0.9025}\right)$$

$$l = 620\ m$$

The particle accelerator will appear 620 m in length.

(b) *Time to traverse the accelerator*

(i) *For laboratory observer*

$$t = \frac{s}{v} = \frac{2.0 \times 10^{3}}{0.95 \times 3 \times 10^{8}}$$

$$= 7.0 \times 10^{-6}\ s$$

(ii) *In the particles reference frame*

$$t = \frac{s}{v} = \frac{620}{0.95 \times 3 \times 10^{8}}$$

$$= 2.2 \times 10^{-6}\ s$$

20.

(a) ***Time dilation.*** *The clock in a moving inertial reference frame will appear to be slower compared to a stationary reference frame.*

(b) ***Length contraction.*** *Length in a moving inertial reference frame will appear to be shorter in the direction of the motion when viewed from a stationary reference frame.*

(c) ***Proper time.*** *This is the time measured in your own inertial reference frame.*

(d) ***Proper length.*** *This is the length measured in your own inertial reference frame.*

(e) ***Mass-energy equivalence.*** *Einstein concluded that mass and energy are equivalent. Mass can be converted to energy and energy is required to create mass. The equation* $E = mc^2$ *relates the two quantities.*

5. Chapter Questions

The Standard Model

5.1

(a) 1 light year $= 9.46 \times 10^{12}$ km

250 light years $= (250)(9.46 \times 10^{12}$ km$)$

$= 2.365 \times 10^{15}$ km

(b) 1 pc $= 3.26$ light years

$\therefore$ distance $= \dfrac{250}{3.26}$

$= 76.7$ pc to Antares

5.2

	Distance (km)	Distance (Au)	Distance Light years	Distance Parsec (pc)
Earth–Moon distance	3.84×10^{5}	2.57×10^{-3}	4.06×10^{-8}	1.24×10^{-8}
Earth–Sun distance	1.50×10^{8}	1.00	1.59×10^{-5}	4.86×10^{-6}
Pluto–orbit Sun distance	5.89×10^{9}	39.4	6.23×10^{-4}	1.91×10^{-4}
Distance to Proxima centauri	3.99×10^{13}	2.67×10^{5}	4.22	1.30
Expanse of Milky Way	1.42×10^{18}	9.49×10^{9}	1.50×10^{5}	4.60×10^{4}
Edge of observable Universe	1.23×10^{23}	8.22×10^{14}	1.30×10^{10}	3.99×10^{9}

5.3

(a) The neutrino is an extremely small particle. The fact that it is neutrally charged means that it is not affected by magnetic or electrical fields or by charged particles.

(b) $^{14}_{6}\mathrm{C} \rightarrow {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}e + {}^{0}_{0}\overline{v}$

(c) $^{23}_{12}\mathrm{Mg} \rightarrow {}^{23}_{11}\mathrm{Na} + {}^{0}_{+1}e + {}^{0}_{0}v$

5.4

(a) Gravitational
(b) Strong nuclear
(c) Electromagnetic
(d) Weak nuclear

5.5

(a) A fermion is a matter particle whereas a boson is a force carrier.

(b) Baryons and mesons are both hadrons and interact through the strong nuclear force. However baryons are made up of three quarks and mesons by two, a quark and anti-quark pair.

5.6

$\overline{u}, \overline{u}, \overline{d}$ will give $\longrightarrow$

$$charge = \frac{-2}{3} + \frac{-2}{3} + \frac{1}{3}$$

$$baryon\ number = \frac{-1}{3} + \frac{-1}{3} + \frac{-1}{3} = -1$$

These are correct as they are the opposite of the proton.

5.7

The particle is a baryon as it is made up of three quarks.

u, u, s will give

$$charge = \frac{2}{3} + \frac{2}{3} + \frac{-1}{3} = 1$$

$$baryon\ number = \frac{1}{3} + \frac{1}{3} + \frac{1}{3} = 1$$

5.8

(a) The electrons from a hot tungsten cathode are accelerated by a large positive voltage on the anode.

(b) The linear accelerator of the Australian synchrotron uses a series of radio frequency cavities to accelerate the electrons.

(c) Powerful magnets are able to bend the path of fast moving electrons.

(d) Synchrotron light is produced in the storage ring of the synchrotron. When the electrons are forced to move in a circular path they emit radiation.

5.9

(a) $W = qV = (1.6 \times 10^{-19})(9.00 \times 10^{4})$

$= 1.44 \times 10^{-14}$ J

or

(b) $W = qV = (1\ e)(90.0\ \mathrm{kV}) = 90.0$ keV

$$W = qV = \frac{1}{2}mv^2$$

$$\frac{1}{2}mv^2 = 1.44 \times 10^{-14}\ \mathrm{J}$$

$$v^2 = \frac{(1.44 \times 10^{-14})(2)}{9.11 \times 10^{-31}}$$

$$v = 1.78 \times 10^{8}\ \mathrm{m\ s^{-1}}$$

5.10

The total relativistic energy of the electrons is given by

$$E = \sqrt{\frac{mc^2}{1 - \frac{v^2}{c^2}}}$$

$$= \sqrt{\frac{(9.11 \times 10^{-31})(3.0 \times 10^{8})^2}{1 - \frac{(0.999987c)^2}{c^2}}}$$

$$= \sqrt{\frac{8.199 \times 10^{-14}}{1 - 0.999974}}$$

$$= \sqrt{\frac{8.199 \times 10^{-14}}{0.000026}}$$

$$= 1.608 \times 10^{-11}$$

$$= 1.61 \times 10^{-11}\ J$$

$$\text{or in ev} = \frac{1.608 \times 10^{-11}}{1.6 \times 10^{-19}}$$

$$= 1.005 \times 10^{8}\ eV$$

$$= 100\ MeV$$

5.11

(a) out of page *(b) upwards*

(c) zero force *(d) out of page*

5.12

(a) Proton and electron move in opposite directions. Neutron undeflected.

(b) Proton radius of curvature ≈ 2000 times greater than electrons.

5.13

They move off in different directions. However, their radius of curvature would be the same.

5.14

$$r = \frac{mv}{Bq}$$

$$= \frac{(9.11 \times 10^{-31})(2.45 \times 10^{6})}{(5.25 \times 10^{-2})(1.6 \times 10^{-19})}$$

$$= 2.66 \times 10^{-4}\ m$$

5.15

(a) $F = Bqv$

$$= (5.25 \times 10^{-4})(1.6 \times 10^{-19})(4.45 \times 10^{5})$$

$$= 3.74 \times 10^{-17}\ N$$

(b) $r = \frac{mv}{Bq}$

$$= \frac{(9.11 \times 10^{-31})(4.45 \times 10^{5})}{(5.25 \times 10^{-4})(1.6 \times 10^{-19})}$$

$$= 4.83 \times 10^{-3}\ m$$

5.16

(a) $Eq = Bqv$

$$\therefore v = \frac{E}{B} = \frac{5.00 \times 10^{3}}{2.60 \times 10^{-2}}$$

$$= 1.92 \times 10^{5}\ m\ s^{-1}$$

(b) *$v = E/B$ for an undeviated path.*

Hence if the velocity of the alpha particle is doubled E must also double. (Assuming no change in B).

5.17

$$v = \frac{E}{B}$$

$$\therefore B = \frac{E}{v} = \frac{1.45 \times 10^{3}}{6.85 \times 10^{4}}$$

$$= 2.12 \times 10^{-2}\ T$$

5.18

(a) The ions can be accelerated by the electrical field and interact with the magnetic field.

(b) $W = Vq = \frac{1}{2} mv^2$

$$V = \frac{(\frac{1}{2})(1.67 \times 10^{-27})(6.40 \times 10^{5})^2}{1.60 \times 10^{-19}}$$

$$= 2.14 \times 10^{3}\ V$$

(c) Mass, velocity and change.

5. Review Questions

The Universe

1. *The geocentric model considered the Earth to be the centre of the universe. Copernicus proposed a heliocentric model, in which the sun is the centre of the universe.*

2. *Red shift is caused by a change in the apparent frequency of light coming from receding stars (Doppler effect). The lower frequency observed, as compared to that of a close star such as the sun, results in spectral lines being closer to the red end of the spectrum.*

3. *Space and time are considered to be in the universe. Previously it was considered that the universe existed in an infinite space.*

4. *The Friedmann equations described the universe in a mathematical way and predicted its expansion. The equations also have various solutions for the future of the universe depending on the value of some constants which are not accurately measurable.*

5.

(a) He more accurately measured the distance to far nebulae (galaxies).

(b) The more distant galaxies had a greater red shift.

(c) The speed at which galaxies are receding is proportional to their distance from the Earth.

(d) The inverse of Hubble's constant can be interpreted as the age of the universe.

6. *One of the predictions of the proposed Big Bang Theory was that microwave radiation would have resulted from the early formation of the universe. Its discovery gave the Big Bang Theory greater acceptance.*

7. *Distance to stars is measured by viewing them from different positions and determining the parallax angle. For example if stars are viewed 6 months apart the baseline for determining the angle is the distance the Earth has shifted during that time(orbital diameter around the Sun). The stars are measured against a relatively fixed background of much more distant galaxies.*

8.
(a) *Light year – distance travelled by light in one year. 1 light year = 9.46×10^{12} km.*
(b) *Astronomical unit (AU) – the average distance from the Earth to the Sun. 1 AU = 1.496×10^{8} km.*
(c) *The distance to a star that would have a parallax of one second of arc using 1 AU as the baseline. 1 parsec = 3.26 light years = 3.086×10^{13} km.*

9. $s = 2.5 \times 10^{8}$ *light years*

$= (2.5 \times 10^{8}) / 3.26$

$= 7.67 \times 10^{7}$ *parsec*

also

$s = (2.5 \times 10^{8}) \times 9.46 \times 10^{12}$ km

$= 2.37 \times 10^{21}$ km

10.
(a) $t = \frac{s}{v} = \frac{20}{3.0 \times 10^{8}}$

$= 6.67 \times 10^{-8}$ s

(b) $t = \frac{3.0 \times 10^{3}}{3.0 \times 10^{8}} = 1.0 \times 10^{-5}$ s

(c) $t = \frac{1.5 \times 10^{11}}{3.0 \times 10^{8}} = 500$ s

≈ 8.33 min

(d) $t = 4.3$ *years.*

11. *There are 6 different types of quarks. Protons and neutrons each contain 3 different quarks.*

12. *The neutrino is a very small neutral particle of almost zero mass. It can travel huge distances through matter without interacting. Since it has no charge it cannot be detected by either electric or magnetic fields.*

13. $^{31}_{14}Si \rightarrow {}^{31}_{15}P + {}^{0}_{-1}e + {}^{0}_{0}v$

14. $^{30}_{15}P \rightarrow {}^{30}_{14}Si + {}^{0}_{+1}e + {}^{0}_{0}v$

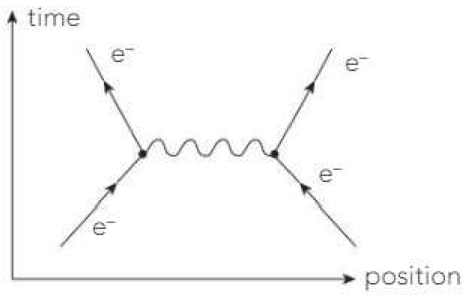
15. *Careful measurements of all the masses and energies involved in Beta decay resulted in an unaccountable loss of energy. An undetected neutral particle was suspected.*

16. *Positrons have the same mass as electrons but a positive charge instead of a negative one.*

17.
(a) *Strong, electromagnetic, weak and gravitational interactions.*
(b) *Mediating particles are bosons.*
(c) *Z^{o} particles are involved in the weak nuclear force interactions.*

18.

(a) *photon*
(b) *Feynman diagram*

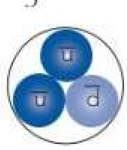


19.
(a) *There are 12 fundamental matter particles.*
(b) *Leptons and quarks.*
(c) *Force carriers are bosons.*

20.
(a)
$u + d + d \longrightarrow$ 

Charge $(\frac{+2}{3}) + (\frac{-1}{3}) + (\frac{-1}{3}) = 0$

Baryon No $(\frac{1}{3}) + (\frac{1}{3}) + (\frac{1}{3}) = 1$

(b)
$\overline{u} + \overline{d} + \overline{d} \longrightarrow$ 

Charge $(\frac{-2}{3}) + (\frac{+1}{3}) + (\frac{+1}{3}) = 0$

Baryon No $(\frac{-1}{3}) + (\frac{-1}{3}) + (\frac{-1}{3}) = -1$

This particle will be an anti neutron.

21.
(a) Particle is a meson since there are only 2 quarks.
(b) $\overline{u}$ + d $\rightarrow$ meson particle

Charge $(\frac{-2}{3}) + (\frac{-1}{3}) = -1$

Baryon No $(\frac{-1}{3}) + (\frac{+1}{3}) = 0$

22.
(a) Both fundamental particles. However leptons can exist as individual point particles whereas quarks are part of hadrons and cannot be isolated individually.
(b) A lepton is a fundamental particle whereas a hadron is made up of quarks.
(c) A fermion is the group name given to fundamental matter particles whereas bosons are force carriers.

Particle accelerators

23.
(a) $E = \frac{V}{d} = \frac{1500}{0.500}$

$= 3.00 \times 10^3\ V\ m^{-1}$ from plate B towards plate A

(b) $F = Eq = (3.00 \times 10^3)(1.6 \times 10^{-19})$
$= 4.80 \times 10^{-16}\ N$ towards plate B

(c) $a = \frac{F}{m} = \frac{4.80 \times 10^{-16}}{9.11 \times 10^{-31}}$

$= 5.27 \times 10^{14}\ m\ s^{-2}$ towards B

(d) $v^2 = u^2 + 2as$

$= 0 + (2)(5.27 \times 10^{14})(0.40)$

$v = 2.05 \times 10^7\ m\ s^{-1\ o}$ towards B

Alternatively could determine velocity by:

$W = Fs = Eqd = \frac{1}{2}mv^2$

$\frac{1}{2}mv^2 = (4.80 \times 10^{-16})(0.400)$

$v = 2.05 \times 10^7\ m\ s^{-1}$ towards B

24.
(a) $F = Eq = (2.60 \times 10^3)(2 \times 1.6 \times 10^{-19})$
$= 8.32 \times 10^{-16}\ N$
(b) $W = Fs = (8.32 \times 10^{-16})(3.50 \times 10^{-3})$
$= 2.91 \times 10^{-18}\ J$
(c) $W = E_K$ gained

$\frac{1}{2}mv^2 = 2.91 \times 10^{-18}$

$v^2 = \frac{2.91 \times 10^{-18}}{6.65 \times 10^{-27}} \times 2$

$v = 2.95 \times 10^4\ m\ s^{-1}$

25. The hot cathode provides electrons on its surface by thermionic emission. The positively charged anode attracts and accelerates the electrons towards it. The evacuated tube allows for a vacuum so that the processes are unhindered by air particles.

26.
(a) $W = qV = (1.6 \times 10^{-19})(4.25 \times 10^3)$
$= 6.80 \times 10^{-16}\ J$

(b) $W = qV = \frac{1}{2}mv^2$

$\frac{1}{2}mv^2 = 6.80 \times 10^{-16}\ J$

$v^2 = \frac{(6.80 \times 10^{-16})(2)}{9.11 \times 10^{-31}}$

$v = 3.86 \times 10^7\ m\ s^{-1}$

27.
(a) The main components are:
- Electron gun
- Linear accelerator (Linac)
- Booster ring
- Storage ring
- Beam lines.

(b) Strong magnets are used in the booster and storage rings. These are required to so that the electrons are forced to move in a circular path.
(c) Beam lines come from different parts of the storage ring.
(d) The cyclotron produces intensely bright beams of synchrotron light (radiation).

28.
The total relativistic energy of the electrons is given by

$$E = \frac{mc^2}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$= \frac{(9.11 \times 10^{-31})(3.0 \times 10^8)^2}{\sqrt{1 - \frac{(0.9999c)^2}{c^2}}}$$

$$= \frac{8.199 \times 10^{-14}}{\sqrt{1 - 0.9998}}$$

$$= \frac{8.199 \times 10^{-14}}{\sqrt{1.9999 \times 10^{-4}}}$$

$$= \quad 5.80 \times 10^{-12}\ J$$

$$or \quad = \quad \frac{5.80 \times 10^{-12}}{1.6 \times 10^{-19}\ eV}$$

$$= \quad 36.2\ MeV$$

29. *The total relativistic energy of the electrons is given by*

$$E = \frac{mc^2}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$(3.0 \times 10^9)(1.6 \times 10^{-19}) = \frac{(9.11 \times 10^{-31})(3.0 \times 10^8)^2}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$\sqrt{1 - \frac{v^2}{c^2}} = 1.7081 \times 10^{-4}$$

$$1 - \frac{v^2}{c^2} = (1.7081 \times 10^{-4})^2$$

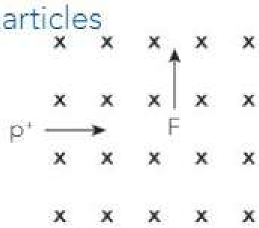
$$v^2 = (1 - 2.92 \times 10^{-8})c^2$$

$$v = \text{very, very close to } c$$

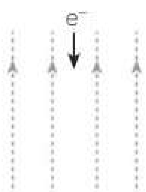
Charged particles

30.

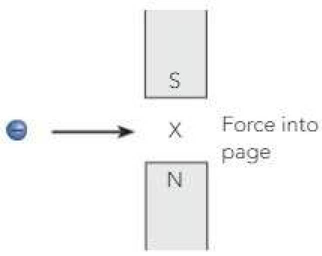
(a)



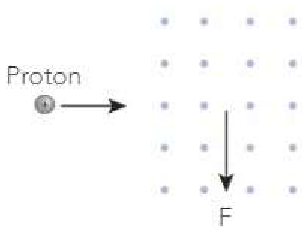
(b) *No force.*



(c)

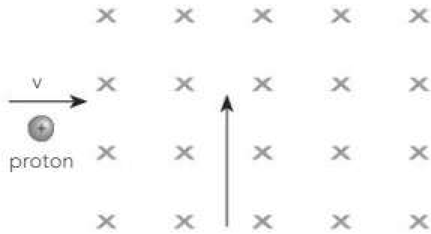


(d)



31.

(a) *The force will be upwards.*



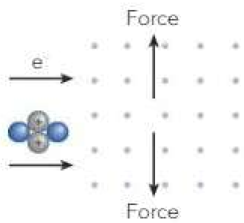
(b) $F = qvB = (1.6 \times 10^{-19})(6.25 \times 10^7)(0.125) = 1.25 \times 10^{-12}\ N$

(c) $$r = \frac{mv}{Bq} = \frac{(9.11 \times 10^{-31})(6.25 \times 10^7)}{(0.125)(1.6 \times 10^{-19})} = 2.85 \times 10^{-3}\ m$$

(d) *Force would be the same magnitude (since charge is the same magnitude) but opposite in direction. Radius of curvature would also be the same but in opposite directions.*

32.

(a)



(b) *Since $F = q\,v\,B$, the force on the alpha particle (× 2) will be twice as great since it has twice the charge.*

(c) *Since mass of the electron is far less than that of the alpha particle, it will have the greatest acceleration.*

33.

(a) $$\frac{mv^2}{r} = Bqv$$

$$r = \frac{mv^2}{Bqv}$$

$$r = \frac{mv}{Bq}$$

(b)

(i) $$r = \frac{mv}{Bq} = \frac{(1.67 \times 10^{-27})(8.0 \times 10^4)}{(1.6 \times 10^{-19})(4.5 \times 10^{-2})} = 1.86 \times 10^{-2}\ m$$

(ii) $$r \propto \frac{m}{q}$$

$$\therefore r_\alpha = 1.86 \times 10^{-2} \times \frac{4}{2} = 3.71 \times 10^{-2}\ m$$

(iii) $$\frac{r_\alpha}{r_p} = 2$$

34. *Since* $r = \frac{mv}{Bq}$ $\therefore m = \frac{rBq}{v}$

$$\therefore m = \frac{(9.40 \times 10^{-2})(5.5 \times 10^{-2})(2 \times 1.6 \times 10^{-19})}{1.71 \times 10^{4}}$$

$$= 9.67 \times 10^{-26}\ kg$$

35.

(a) *Assume alpha particle is approximately 4 × mass of proton and × 2 its charge.*

$\therefore$ *Since* $r = \frac{mv}{Bq}$ *and v, B constant*

alpha $\alpha = \frac{4}{2} = 2$

(b) *Twice the radius of curvature of the proton.*

36.

(a) *At a particular speed the force exerted by the electric field (Eq) is exactly equal and opposite to that exerted by the magnetic field (Bqv).*

(b) *By eliminating velocity as a variable the radius of curvature gives a direct measurement of the charged particles' mass.*

37. $Eq = Bqv$

$$\therefore v = \frac{E}{B} = \frac{6.40 \times 10^{3}}{4.26 \times 10^{-2}}$$

$$= 1.50 \times 10^{5}\ ms^{-1}$$

38.

(a) $v = \frac{E}{B}$ $\therefore B = \frac{E}{v} = \frac{8.25 \times 10^{4}}{2.40 \times 10^{5}}$

$$= 3.44 \times 10^{-1}\ T$$

(b) *Velocity would be the same as for the proton,* $2.40 \times 10^{5}\ ms^{-1}$, *since it is independent of mass.*

SOLUTIONS TO TRIAL TESTS

TT 1: Gravity and Motion

Section One

1. (a) *F(down slope)* $= m\,g \sin\theta$
$= (72.5)(9.80)(\sin 12°)$
$= 148$ N

(b) *Since velocity is constant*
$a = 0 \quad \therefore \Sigma F = 0$
i.e. Friction force $= 148$ N

(c) $E_K = \frac{1}{2}mv^2$
$= \frac{1}{2}(72.5)(\frac{65.0}{3.6})^2$
$= 1.18 \times 10^4$ J

Also $P = mv$
$= (72.5)(\frac{65}{3.6})$
$= 1.31 \times 10^3$ kg m s^{-1} [3]

2.

(a) *The ball fell vertically while moving towards the target.*

(b) *Time of flight* $t = \frac{s}{v} = \frac{2.60}{22.0} = 0.118$ s
$\therefore \Delta s = ut + \frac{1}{2}at^2$
$= 0 + \frac{1}{2}(9.80)(0.118)^2$
$= 0.0684$ m

i.e. ball misses by 6.84 cm

[3]

3. *The nylon line cannot be perfectly horizontal since in this situation the tension would not have a vertical component. This vertical component is necessary to counteract the weight of the line.*

[2]

4. *The feet being wide apart provides a large support base. Bending the knees lowers the centre of gravity.*
Both of these factors make the sumo wrestlers more stable (more difficult to topple).

[2]

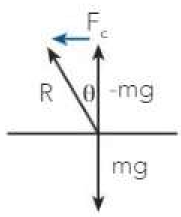
5. *The sum of the two reaction forces is equal to the weight of the truck since they are the only vertical forces. This is providing that the load within the truck does not move between weighing.*

[2]

6.

(a) *The lean is necessary since the circular motion around the track requires a centripetal force.*

(b) *Bending allows the force of gravity to provide, through a reaction with the ground, a centripetal force into the centre of motion. The push of the foot on the ground is at an angle other than 90° when the body leans inwards. This provides a reaction force which is not vertical but inclined. The horizontal component of the reaction force is directed towards the centre of the circular track. This force is the centripetal force.*



(c) *Since* $a_c = \frac{v^2}{r}$ *the angle of lean would depend on velocity and radius of curvature.*

[3]

7.

(a) $T = F.r$
$= (3)(0.050 \times 9.8)(0.200)$
$= 0.294$ Nm *anticlockwise*

(b) *For equilibrium*
Σ *c.w.m.* $= \Sigma$ *a.c.w.m. (about the fulcrum)*
$(mg)(0.200) + (0.050 \times 9.8)(0.45) = 0.294$
$\therefore mg = 0.3675$
$m = 0.0375$ kg
mass of ruler $= 37.5$ g [3]

Section 2

8.

(a) *Since* $g \propto \frac{m_p}{r^2}$ *and* $W = m\,g$

$\therefore W_{(Jumbo)} = \frac{800 \times 4}{(2)^2} = 800$ N

Frank weighs the same.

(b) Volume of a sphere $\alpha\ r^3$

$\therefore$ if density the same and $m\ \alpha\ v$

$$W_{(Jumbo)} = \frac{800 \times (2)^3}{(2)^2} = 1600\ N$$

[4]

9.

(a)

$u_y = u \sin 16^o \quad = (28)(\sin 16^o)$

$\quad = 7.72\ m\ s^{-1}$

$u_x = u \cos 16^o \quad = (28)(\cos 16^o)$

$\quad = 26.9\ m\ s^{-1}$

[2]

(b) vertical motion

$v^2 \ = u^2 + 2as$

$0 \ = (7.72)^2 + 2(-9.8)(s)$

$s \ = 3.04\ m$

[2]

(c) Range (horizontal motion). Find time of flight (vertical up and down).

Note $\uparrow +$ $v \ = u + at$

$-7.72 \ = 7.72 + (-9.8)(t)$

$t \ = 1.58\ s$

$\therefore$ Range $= s = v\ t$

$= (26.9)(1.58)$

$= 42.5\ m$

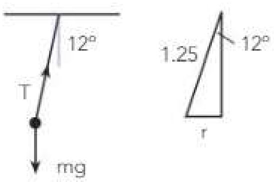
[2]

(d) The low angle allows the ball to reach Paul quickly (v_x is much greater than v_y) and the distance is not a problem.

[1]

10.

(a)



$\sin 12^o \ = \dfrac{r}{1.25}$

$\therefore r \ = 0.260\ m$

$\Sigma F_y \ = 0$

$T \cos 12^o \ = mg = (0.250)(9.80)$

$T \ = 2.50\ N$

[3]

(b) $F_c \ = T \sin 12^o$

$= 0.521\ N$

[2]

(c) $\dfrac{mv^2}{r} = 0.521$

$$v^2 = \frac{(0.521) \times (0.260)}{0.250}$$

$v \ = 0.736\ m\ s^{-1}$

[2]

(d) $v = \dfrac{2\pi r}{T} \therefore T = \dfrac{2\pi r}{v}$

$$T = \frac{(2\pi)(0.260)}{0.736}$$

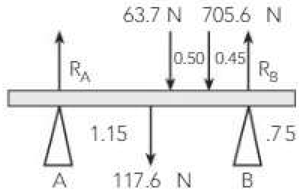
$= 2.22\ s$

NOTE: $\tan\theta = \dfrac{v^2}{rg}$ can also be applied to this problem – TRY IT!

[2]

11.

(a)



[2]

(b) $\Sigma m \ = 0$ Take moments about A

$\Sigma cwm \ = \ \Sigma acwm$

$(117.6)(1.15)+(63.7)(1.35)+(705.6)(1.85) = (R_B)(2.30)$

$\therefore \ R_B = 664\ N$

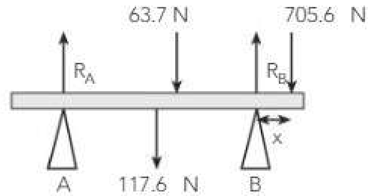
Also $\Sigma F \ = 0$

$R_A + R_B = 117.6 + 63.7 + 705.6$

$\therefore \ R_A = 223\ N$

[3]

(c)



To just balance about point B.

$\Sigma cwm \ = \ \Sigma acwm$

$(705.6)(0.75\text{-}x) = (117.6)(1.15)+(63.7)(0.95)$

$x \ = \ 0.473\ m$

Emilio will just balance if 47.3 cm from the right end of the plank.

[3]

12.

(a) (i) Telephone communication.

(ii) Television broadcasts. [2]

(b) (i) They orbit the earth at the same period as the Earth rotates.

(ii) They don't fall since they have a tangential velocity. The Earth's gravity prevents them from flying off at a tangent. [2]

(c) (i) Dish shaped antennas can focus the signal energy to a point.

(ii) Size varies from 30 cm to 30 m.

(iii) Signal energy collected is proportional to area. Since $A = \pi r^2$

$$\frac{\text{Area 30 m dish}}{\text{Area 30 cm dish}} = \frac{(30)^2}{(0.30)^2} = 10{,}000$$

[3]

(d) (i) The fuel is on board to fire small directional thrusters.
(ii) Drift is due to the influence of the gravitational field of the moon and sun and also due to the Earth's unevenness of shape and density.

[2]

(e) (i) $T^2 = \dfrac{4\pi^2 r^3}{Gm_E}$

$= \dfrac{(4\pi^2)(6.38 \times 10^6 + 3.6 \times 10^7)^3}{(6.67 \times 10^{-11})(5.97 \times 10^{24})}$

$T = 86840$ s

$T = 24.1$ hours

[2]

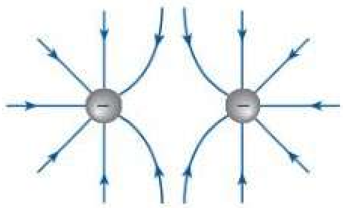
(ii) To remain in a geostationary orbit the satellite must have a period of 24.0 hours. This means that the assumption that he satellite is 36,000 km from the Earth's surface is not quite accurate. It should be a little less. (It is actually 42,250 km from the centre of the Earth or 35,880 km from the surface)

[1]

TT 2: Electromagnetism

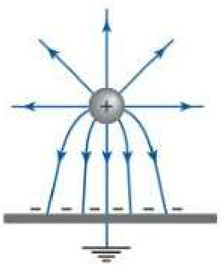
Section One

1.
(a)



[1]

(b)



[1]

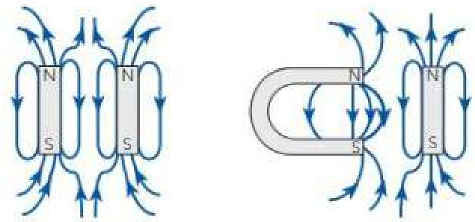
2.
(a) Potential difference is equal to the work done per unit charge (by an external force) to move an electric charge from one point to another in an electric field.

[1]

(b) $W = Vq$
$= 3.00 \times 10^3 \times 1.60 \times 10^{-19}$
$= 4.80 \times 10^{-16}$ J

[1]

3.



[2]

4.
(a) E
(b) N, in line with Earth's magnetic field or possibly directionless
(c) N
(d) into page

[2]

5.
(a) As the copper sheet cuts across the magnetic field eddy currents are induced within it. The resistance of the copper to this current produces heat.

[1]

(b) (i) More heat produced since the field being cut would be stronger.

[1]

(ii) Since Aluminium has a higher resistance less current would flow even though the induced EMF is the same. Hence less heat.

(Heat = $P\,t = \dfrac{V^2}{R}\,t$) [1]

6.
(a) $F = IlB = (3.60)(0.50)(0.55)$
$= 0.99$ N out of page

[1]

(b) $T = Fr = (0.99)(0.20)(2)$
$= 0.396$ Nm [1]

(c) Torque could be increased by
- more turns of coil
- larger current
- stronger magnets (any 2)

[1]

7.
(a) The induced voltage in the secondary coil will be greater since there are more coils of wire.
This is since emf is proportional to N
(i.e. $emf = -N \dfrac{\Delta\phi}{\Delta t}$). [1]

(b) The secondary wire will have a lower current flowing through it.

[1]

(c) The laminations reduce eddy currents and minimise heat losses.

[1]

(d) DC current will not work. A changing magnetic field is required to produce an emf and hence a changing applied voltage (AC) is necessary.

8.

(a) $E = \frac{V}{d} = \frac{275}{15.0 \times 10^{-3}} = 1.83 \times 10^4\ Vm^{-1}$

[3]

(b) $F = Eq = (1.83 \times 10^4)(4.00 \times 10^{-17})$
$= 7.33 \times 10^{-13}\ N$

[3]

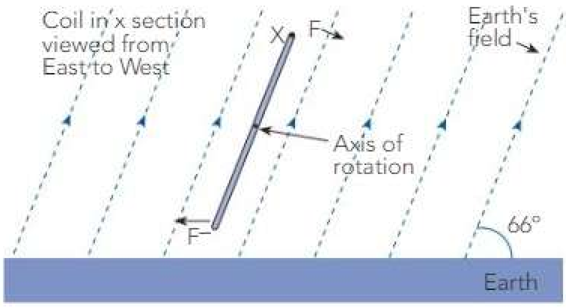
(c) *No change in force occurs. Field is uniform between the plates.*

[1]

Section Two

9.

(a)



The axis of the coil should be horizontal and in an East-West direction. Maximum initial torque will occur with the plane of the coil parallel with the Earth's field (ie. 66° to the horizontal).

[2]

(b) $F = IlB$
$= (5.0)(0.50)(5.90 \times 10^{-5})$
$= 1.48 \times 10^{-4}\ N$

$\therefore$ Torque $= 2 \times Fr$
$= (2)(1.48 \times 10^{-4})(0.25)$
$= 7.38 \times 10^{-5}\ Nm$

[2]

(c) *The torque produced will be far too small to overcome the likely friction forces in a practical situation.*

[1]

(d) *Use many coils of wire.*
Use a large current.
Use a soft iron core.

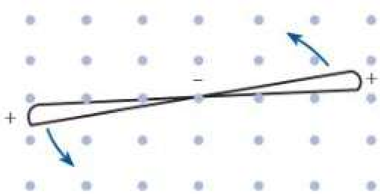
[1]

(e) *The Earth's field is much stronger at the poles and a greater torque would be achieved there. Bring a thick overcoat however.*

[1]

10.

(a)



Blades viewed from above are moving a.c.w. The ends will be positive (+) while the centre is negative (−).

[1]

(b) $B_{(vertical)} = B \cos 24^\circ$
$= (5.85 \times 10^{-5})(\cos 24^\circ)$
$= 5.34 \times 10^{-5}\ T$

[1]

(c) $\phi = BA = (5.34 \times 10^{-5})(\pi)(5.35)^2$
$= 4.80 \times 10^{-3}\ Wb$

[1]

(d) *Consider total flux cut by each blade during one rotation. Time given by*

$$T = \frac{1}{f} = \frac{60}{375} = 0.16\ s$$

$$\therefore emf = \frac{\Delta\phi}{\Delta t} = \frac{4.80 \times 10^{-3}}{0.16}$$
$$= 3.00 \times 10^{-2}\ V$$

∴ A maximum emf of 30 mV exists between the ends and the centre of the blades.

[3]

(e) *Maximum emf will exist between the tips of the blades and the centre.*

[1]

(f) *If the helicopter dips its nose the plane of movement of its blades will be at a more acute angle with the earth's magnetic field. The blades will cut fewer magnetic field lines and the emf will be less.*

[1]

11.

(a) *High voltages mean lower currents and less energy loss due to resistive heating.*

[1]

(b) *High voltages require large separation of wires, large and visually intrusive transmission towers and may have a long term effect on our health. Arcing may occur causing possible fires.*

[1]

(c) $P = 20 \times 10^6\ W \quad I = ? \quad V = 220 \times 10^3\ V$

(i) $P = V I$

$$I = \frac{20 \times 10^6}{220 \times 10^3} = 90.9\ A$$

(ii) $\therefore$ Power Loss $= I^2R$
$= (90.9)^2(45)$
$= 3.72 \times 10^5\ W$
This is $\approx 1.9\%$ loss.

[3]

(d) $I = \frac{P}{V} = \frac{20 \times 10^6}{66000} = 303\ A$

$\therefore$ Power Loss $= I^2R$
$= (303)^2(45)$
$= 4.13 \times 10^6\ W$

This is impractical. Most of the power is consumed as resistive heating.

[3]

Section Three

12.

(a) Approximately 1850 MW [1]

(b) (i) Summer 2 - 5 pm
(ii) Winter 6 - 8 pm [1]

(c) Warm hot days – large use of airconditioners. Winter evenings – heating and cooking at a maximum. [2]

(d) Approx. 1650 MW × 12 h
$\approx 2 \times 10^7$ kWh [3]

(e) Cost = $(2 \times 10^7)(25.0¢) = \$5.00 \times 10^6$ [3]

(f) Base load ≈ 800 MW [2]

TT 3: Wave particle duality and Quantum theory

Section One

1.

(a) Light travels in straight lines.
Light will refract.
Light will diffract.
Interference patterns from light sources are similar to those of water or sound.
Any 2 of above: [1]

(b) The photoelectric effect cannot be explained by the wave theory. This effect depends on the frequency of the light used. The wave theory would predict that it could occur at any frequency if the light was of sufficient intensity. This is not the case. [1]

(c) The particle theory cannot explain diffraction as occurs with Young's double slit experiment. This theory predicts that only two bright spots would occur. [1]

2.

(a) $\lambda = \dfrac{c}{f} = \dfrac{3 \times 10^8}{1.52 \times 10^9} = 1.97 \times 10^{-1}\, m$ [1]

(b) $E = hf = (6.63 \times 10^{-34})(1.52 \times 10^9)$
$= 1.01 \times 10^{-24}\, J$ [1]

(c) No. photons = $\dfrac{1.40}{1.01 \times 10^{-24}}$
$= 1.39 \times 10^{24}$ ph/s [1]

3.

(a) He would see a continuous range of colours from red to violet. This is a continuous emission spectra.

(b) As for (a) except that he would notice many thin black lines within the continuous spectrum. This is a line absorption spectra.

(c) He would see discrete lines of colour on a black background. This is a line emission spectra.

(d) Dark bands would appear across an otherwise continuous spectrum. This is a band absorption spectra. [2]

4.

(a) The work function of a metal is the energy required for an electron to just escape from the metal with no remaining kinetic energy.

(b) Einstein's photoelectric equation applies.

$$E_k = hf - W$$

hence $hf = Ek + W = (3.66 + 1.75)$ eV

$$\frac{hc}{\lambda} = 5.41 \times 1.6 \times 10^{-19}\, J$$

$$\lambda = \frac{(6.63 \times 10^{-34})(3.00 \times 10^8)}{(8.66 \times 10^{-19})}$$

$$= 2.30 \times 10^{-7}\, m = 230\, nm$$

5.

(a) The wavelengths predicted by his theory were extremely small for typical masses moving slowly. This made them difficult to detect by diffraction.

(b) $p = mv = (0.160)(\dfrac{140}{3.6})$

$= 6.22\ kg\ m\ s^{-1}$

$$\lambda = \frac{h}{p} = \frac{(6.63 \times 10^{-34})}{6.22}$$

$$= 1.07 \times 10^{-34}\, m$$ [2]

6.

(a) The longest wavelength will be given by A since photons of a lower energy will be emitted.

(b) $\lambda = \dfrac{hc}{E_g}$

$$= \frac{(6.63 \times 10^{-34})(3.00 \times 10^8)}{(2.25 \times 1.6 \times 10^{-19})}$$

$$= 5.52 \times 10^{-7}\, m \text{ or } 552\, nm$$

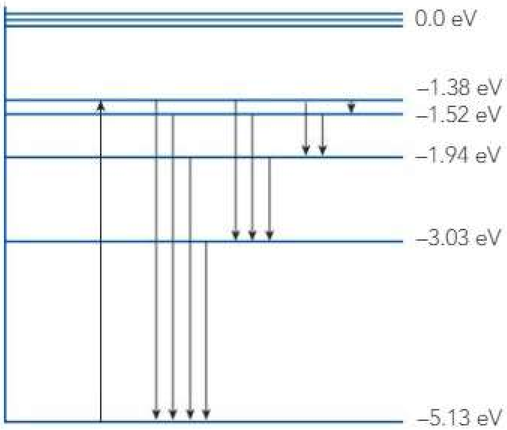
This wavelength is in the green colour range. [2]

7.

(a) There are 10 different possible transitions from this level as shown.

(b) The highest frequency photon emitted will be the one with the highest energy. This will occur for the transition E_4 to E_1.

Hence



$E_4 - E_1 = hf$
$hf = -1.38 - (-5.13) = 3.75\ eV$
$hf = 3.75 \times 1.6 \times 10^{-19}\ J = 6.0 \times 10^{-19}\ J$

$$f = \frac{6.00 \times 10^{-19}}{6.63 \times 10^{-34}}$$

$= 9.05 \times 10^{14}\ Hz$

[3]

Section Two

8.

(a) $E_3 - E_1 = 10.66 \times 10^{-19}\ J$
$E_3 - E_2 = 2.89 \times 10^{-19}\ J$
$E_2 - E_1 = 7.77 \times 10^{-19}\ J$

Possible wavelengths

$$\lambda = \frac{hc}{E} = \frac{(6.63 \times 10^{-34})(3 \times 10^{8})}{10.66 \times 10^{-19}}$$

$\lambda_1 = 1.87 \times 10^{-7}\ m$

Also $\lambda_2 = 6.88 \times 10^{-7}\ m$

$\lambda_3 = 2.56 \times 10^{-7}\ m$

[3]

(b) λ_1 – Ultraviolet
λ_2 – Red
λ_3 – Ultraviolet

[1]

(c) The white powder on the inside of the fluorescent tube absorbs high energy photons (UV) and re-emits the energy as lower energy photons (visible range).

[2]

9.

(a) The number of electrons ejected and hence the current produced depends on the light intensity, that is, the number of photons reaching the metal target. One photon ejects one electron. At any positive voltage all available electrons reach the anode.

[2]

(b) Result B shows a smaller stopping voltage. Ejected electrons must have less kinetic energy due to less energetic photons. Light of a longer wavelength was used.

[2]

(c) Stopping voltage from graph ≈ - 2.0 V
We can use this to calculate the $E_{k(max)}$ of the ejected electrons.

$W = qV = E_{k(max)}$

$E_{k(max)} = qV = (1.6 \times 10^{-19})(2.0)\ J$

$= 3.2 \times 10^{-19}\ J = 2.0\ eV$

[2]

(d) To find the work function (W) we have:

$$W = \frac{hc}{\lambda} - E_{k(max)}$$

$$= \frac{(6.63 \times 10^{-34})(3.00 \times 10^{8})}{2.20 \times 10^{-7}} - 3.2 \times 10^{-19}$$

$= 5.84 \times 10^{-19}\ J = 3.65\ eV$

[2]

10.

(a) The work done on the electrons by the electrical field is given by:

$W = qV = (1.6 \times 10^{-19})(9.50 \times 10^{4})$

$= 1.52 \times 10^{-14}\ J$

[2]

(b) $\Delta E_k = \frac{1}{2} mv^2 = 1.52 \times 10^{-14}\ J$

$$v^2 = \frac{(1.52 \times 10^{-14})(2)}{(9.11 \times 10^{-31})}$$

$v = 1.83 \times 10^{8}\ m\ s^{-1}$

[2]

(c) $p = mv = (9.11 \times 10^{-31})(1.83 \times 10^{8})$

$= 1.66 \times 10^{-22}\ kg\ m\ s^{-1}$

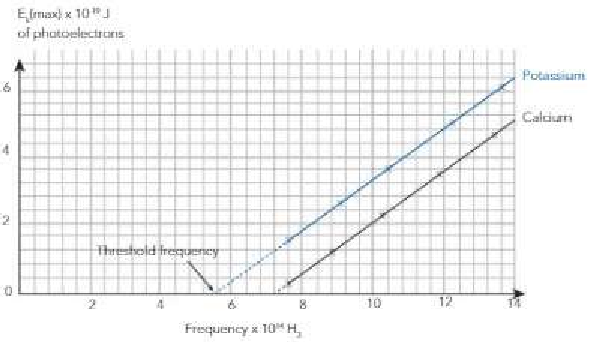
$$\lambda = \frac{h}{p} = \frac{(6.63 \times 10^{-34})}{1.67 \times 10^{-22}}$$

$= 3.98 \times 10^{-12}\ m$

[2]

11.

(a)



[3]

(b) At threshold frequencies $E_{k(max)} = 0$. Values from graph are:

Potassium, $f_0 \approx 5.50 \times 10^{14}$ Hz

Calcium, $f_0 \approx 7.00 \times 10^{14}$ Hz

[1]

(c) At the threshold frequency the incident photon energy is exactly equal to the work function.

$W = hf_0$

For potassium

$W = (6.63 \times 10^{-34})(5.50 \times 10^{14})$

$= 3.65 \times 10^{-19}\ J = 2.28\ eV$

For sodium

$W = (6.63 \times 10^{-34})(7.00 \times 10^{14})$

$= 4.64 \times 10^{-19}\ J = 2.90\ eV$

[2]

(d) The gradient for the two lines of best fit are:

For potassium

$$= \frac{(5.22 - 1.31)(10^{-19})}{(13.4 - 7.50)(10^{14})}$$

$$= \frac{3.91 \times 10^{-19}\ J}{5.90 \times 10^{14}\ s^{-1}}$$

$$= 6.63 \times 10^{-34}\ J\ s$$

For calcium

$$= \frac{(4.29 - 0.380)(10^{-19})}{(13.4 - 7.50)(10^{14})}$$

$$= \frac{3.91 \times 10^{-19}\ J}{5.90 \times 10^{14}\ s^{-1}}$$

$$= 6.63 \times 10^{-34}\ J\ s$$

[2]

(e) The gradients are Planck's constant. They are the same for each metal as essentially the maximum kinetic energy of the photoelectrons is proportional to the frequency of the incident radiation. The intercept at the x axis is a measure of work function (W).

The results confirm the Einstein equation, that is: $E_{k(max)} = hf - W$

[2]

Section Three

12.

(a) Distance and time. [1]

(b) The time interval involved was extremely small (approx 50 μs) and not possible to be measured.

[1]

(c) Roemer was considering distances on a much greater scale. The Earth's orbit around the Sun is some 300 million km in diameter compared to a few km between the hills used by Galileo with the shuttered lanterns. This meant that the time intervals involved in Roemer's calculation were readily measurable.

[1]

(d) Roemer estimated value was $2.26 \times 10^8\ m\ s^{-1}$ using 22 min as the time interval. For 17 min his result would have been

$$v = (2.26 \times 10^8)\left(\frac{22}{17}\right)$$

$$= 2.92 \times 10^8\ m\ s^{-1}$$

[1]

(e) (i) Both methods attempt to measure the time taken by light to reach a distant point and return.

[1]

(ii) The fixed mirror eliminates the reaction time of an observer and time taken to operate lantern.

[1]

(iii) $v = \frac{s}{t} \quad \therefore t = \frac{s}{v}$

for Galileo $t = \frac{16.0 \times 10^3}{3.00 \times 10^8} = 5.33 \times 10^{-5}\ s$

for Michelson $t = \frac{70.8 \times 10^3}{3.00 \times 10^8} = 2.36 \times 10^{-4}\ s$

[2]

(iv) The octagonal mirror would need to turn a minimum of 1/8 of a rotation (one face) during the time it took the light to reflect to the mountain and back. Hence period of rotation

$$T = (8)(2.36 \times 10^{-4})$$

$$= 1.89 \times 10^{-3}\ s$$

$$\therefore f = \frac{1}{T} = \frac{1}{1.89 \times 10^{-3}}$$

$$= 530\ Hz\ (\approx 32100\ rpm)$$

[4]

TT 4: Special Relativity and Standard Model

Section One

1.

(a) $v^2 = u^2 + 2as$

$= 0 + (2)(9.80)(1.85)$

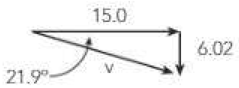
$v = 6.02 \text{ m s}^{-1}$ vertically down [1]

(b) (i) Jason would see $v = 6.02 \text{ m s}^{-1}$ vertically downwards.

(ii) Shane would see the ball moving both horizontally and vertically. Using vectors

$v^2 = (15.0)^2 + (6.02)^2$

$v = 16.2 \text{ m s}^{-1}$ at 21.9° to horizontal



[1]

2.

(a) $v = \frac{s}{t} = \frac{(3240 - 1616)}{0.99 \times 3 \times 10^8}$

$= 5.47 \ \mu s$

(b) The distance travelled by the muons was much shorter in their frame of reference.

Alternatively, time was slower in their frame of reference.

(c) Distance travelled in:

(i) Earth's RF $= 3240 - 1616 = 1624 \text{ m}$

(ii) Muons RF

$l = l_o \sqrt{1 - (\frac{v^2}{c^2})}$

$= 1624 \sqrt{1 - 0.9801}$

$= 229 \text{ m}$

[2]

3.

(a) $t = \dfrac{t_o}{\sqrt{1 - (\frac{v^2}{c^2})}}$

$= \dfrac{4.00}{\sqrt{1 - \frac{(0.80c)^2}{c^2}}}$

$= \dfrac{4.00}{\sqrt{1 - 0.64}}$

$= 6.67 \text{ s}$

(b) Time between flashes will also be longer by the same factor.

$t = (1.00 \text{ min})(\frac{6.67}{4.00})$

$= 1.67$ minutes between flashes.

[2]

4.

(a) The particle is a baryon as it is made up of three quarks.

(b) u, d, d will give charge

$= \frac{2}{3} + \frac{-1}{3} + \frac{-1}{3} = 0$

baryon number $= \frac{1}{3} + \frac{1}{3} + \frac{1}{3} = 1$

(c) The particle is a neutron.

[3]

5.

(a) proton [1]

(b) At A South, At B East [1]

(c) The radius would halve since $F = q\,v\,B$ $\therefore$ the greater the charge the greater the force. Hence smaller radius.

[1]

6.

(a) When a light source is moving away from an observer its apparent frequency will be lower (longer wavelength) and its colour shifts towards the red end of the spectrum. The red shift from distant galaxies indicates that they are moving away from Earth.

(b) Hubble found that there was a linear relationship between the amount of red shift (hence recession velocity from Earth) and distance of the galaxies from the Earth.

(c) Mathematically $v = Hd$

(d) The relationship indicates that galaxies are moving apart at increasing speed. It can be argued that at some time in the past they all originated from some single point and are the result of an explosion or Big Bang.

[2]

7.

(a) The relativistic momentum is given by

$p = \dfrac{mv}{\sqrt{1 - (\frac{v^2}{c^2})}}$

$p = \dfrac{(9.11 \times 10^{-31})(0.85 \times 3 \times 10^8)}{\sqrt{1 - \frac{(0.85c)^2}{c^2}}}$

$p = \dfrac{2.323 \times 10^{-22}}{\sqrt{1 - 0.7225}} = \dfrac{2.323 \times 10^{-22}}{0.5268}$

$p = 4.41 \times 10^{-22} \text{ kg m s}^{-1}$

(b) The total relativistic energy of the electrons is given by

$$E = \frac{mc^2}{\sqrt{1 - (\frac{v^2}{c^2})}}$$

$$= \frac{(9.11 \times 10^{-31})(3.0 \times 10^8)^2}{\sqrt{1 - \frac{(0.85c)^2}{c^2}}}$$

$$= \frac{8.199 \times 10^{-14}}{\sqrt{1 - 0.7225}}$$

$$= \frac{8.199 \times 10^{-14}}{0.5268}$$

$$= 1.56 \times 10^{-13}\ J$$

(c) The electrons kinetic energy is given by

$$\begin{aligned} E_k &= \text{total energy - rest energy} \\ &= 1.56 \times 10^{-13} - mc^2 \\ &= 1.56 \times 10^{-13} - 8.199 \times 10^{-14} \\ &= 7.40 \times 10^{-14}\ J \end{aligned}$$

[3]

Section Two

8.

(a) To detect the luminiferous aether.

(b) The half silvered mirror was used to split the light beam.

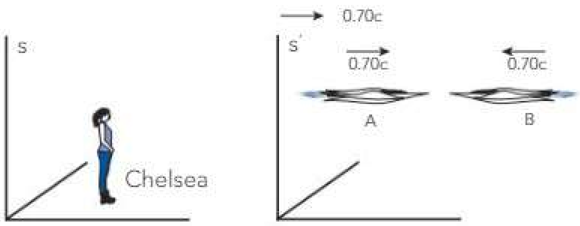
(c) The beams were at right angles so that if one was travelling parallel to the presumed aether 'flow' then the other would not be affected by this 'flow'.

(d) If the aether existed there would be a time delay for the beam going back and forth in line with the aether. This would be detected by a difference in the interference pattern created when the two beams recombined.

[8]

9.

(a) Consider Chelsea on Earth to be in one reference frame, S, and the two spaceships in reference frame S' as shown below.



Reference frame S' is moving at a velocity of 0.70c away from frame S. As we know the velocity of spaceship B as viewed from earth (u = - 0.70c) we need to use the inverse velocity transformation equation to find u'.

u = the velocity of B relative to S
= - 0.70c

u' = the velocity of B relative to S'.
= ?

v = the velocity of S' relative to S
= 0.70c

$$u' = \frac{(u - v)}{1 - (\frac{(uv)}{c^2})}$$

$$u' = \frac{(-0.70c - (0.70c)}{1 - (\frac{(-0.70c)(0.70c)}{c^2})}$$

$$u' = \frac{-1.40c}{1 + 0.490}$$

$$u' = -0.94c$$

The velocity of spaceship B will be – 0.94c relative to spaceship A. The negative sign indicates it is moving in the opposite direction to spaceship A, towards it and the Earth.

(b) (i) The velocity of spaceship A is 0.94c relative to spaceship B and 0.70c relative to Chelsea on Earth.

Hence

$$l = l_o \sqrt{1 - (\frac{v^2}{c^2})}$$

$$l = 225 \sqrt{1 - \frac{(0.94c)^2}{c^2}}$$

$$l = 225 \sqrt{1 - 0.8836}$$

l = 76.7 m (length relative to spaceship B)

(ii) Similarly

$$l = l_o \sqrt{1 - (\frac{v^2}{c^2})}$$

$$l = 225 \sqrt{1 - \frac{(0.70c)^2}{c^2}}$$

l = 161 m (length relative to Earth)

[8]

10.

(a) $W = qV = \frac{1}{2} mv^2$

$$\therefore\ v^2 = \frac{2qV}{m} = \frac{(2)(3.20 \times 10^{-19})(2000)}{6.65 \times 10^{-27}}$$

$$v = 4.39 \times 10^5\ m\ s^{-1}$$

[2]

(b) $F = Bqv$

$= (3.25 \times 10^{-2})(3.20 \times 10^{-19})(4.39 \times 10^{5})$

$= 4.57 \times 10^{-15}$ N *downwards*

[2]

(c) *The alpha particle will move downwards in a circular path. It may be trapped in continual circular motion (clockwise).*

[2]

(d) *An electric field is placed at right angles to the magnetic field in the same area of influence. If the magnitudes of the fields is such that Eq = Bqv then the alpha particles will pass through undeviated.*

Since

$Eq = Bqv$

Required

$E = Bv = (3.25 \times 10^{-2})(4.39 \times 10^{5})$

$= 1.43 \times 10^{4}\ Vm^{-1}$

[2]

11.

(a) *The electron gun provides a fast beam of electrons.*

(b) *A hot tungsten cathode provides a source of electrons at its surface. A very high voltage anode attracts and accelerates these electrons through its hollow centre and onwards.*

(c) (i) $W = qV = (1.6 \times 10^{-19})(8.50 \times 10^{4})$

$= 1.36 \times 10^{-14}\ J$

(ii) $W = qV = \frac{1}{2}\ mv2$

$\frac{1}{2}mv^2 = 1.36 \times 10^{-14}\ J$

$v^2 = \frac{(1.36 \times 10^{-14})(2)}{9.11 \times 10^{-31}}$

$v = 1.73 \times 10^{8}\ m\ s^{-1}$

[6]

Section Three

12.

(a) $\frac{mv^2}{r} = Bqv$

$r = \frac{mv^2}{Bqv}$

$r = \frac{mv}{Bq}$

[2]

(b) (i) Cl^{+2} *ions at C and D.*

(ii) Cl^{37} *isotopes at A and C.*

[2]

(c) (i) $r = \frac{mv}{Bq}$

$\therefore \frac{r_A}{r_C} = \frac{2}{1}$ *i.e. for* $\frac{(Cl^{37})^{+}}{(Cl^{37})^{+2}}$

[2]

(ii) $\therefore \frac{r_A}{r_B} = \frac{37}{35}$ *i.e. for* $\frac{(Cl^{37})^{+}}{(Cl^{37})^{+}}$

[2]

(d) $qvB = \frac{mv^2}{r}$

$\therefore m = \frac{rBq}{v}$

$= \frac{(0.292)(1.80 \times 10^{-3})(1.6 \times 10^{-19})}{1.45 \times 10^{3}}$

$= 5.80 \times 10^{-26}\ kg$

[3]

SI Base Units

Quantity	Unit	Symbol
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
temperature	kelvin	K
luminous intensity	candela	Cd
amount of substance	mole	mol

SI Derived Units With Special Names (Common Examples)

Quantity	Unit	Symbol	Expressed in Other SI Units
charge	coulomb	C	A s
electric potential	volt	V	W A^{-1}
electromotive force	volt	V	W A^{-1}
force	newton	N	kg m s^{-2}
frequency	hertz	Hz	s^{-1}
gravitational field strength	newtons per kg	g	N kg^{-1}
magnetic flux	weber	Wb	J A^{-1}
magnetic field intensity	tesla	B	N $P^{-1}m^{-1}$
potential difference	volt	V	W A^{-1}
power	watt	W	J s^{-1}
pressure	pascal	Pa	N m^{-2}
quantity of electricity	coulomb	C	A s^{-1}
resistance	ohm	Ω	V A^{-1}
work, energy, quantity of heat	joule	J	N m

Other SI Derived Units (Selected Examples)

Quantity	Unit	Expressed in Other SI Units
acceleration	metre per second squared	m s^{-2}
area	square metre	m^{2}
density	kilogram per cubic metre	kg m^{-3}
impulse	newton second	kg m s^{-1}
momentum	kilogram metre per second	kg m s^{-1}
velocity	metre per second	m s^{-1}
volume	cubic metre	m^{3}

Table of Common Prefixes

Prefix	Symbol	Factor	Prefix	Symbol	Factor
tera	T	10^{12}	milli	m	10^{-3}
giga	G	10^{9}	micro	µ	10^{-6}
mega	M	10^{6}	nano	n	10^{-9}
kilo	k	10^{3}	pico	p	10^{-12}

Physical Constants		
Speed of light in air	c =	3.00×10^8 m s^{-1}
Electron charge	e =	-1.60×10^{-19} C
Electron volt	1eV =	1.60×10^{-19} J
Electronic constant	ε_o =	8.85×10^{-12} F m^{-1}
Magnetic constant	μ_o =	$4\pi \times 10^{-7}$ N A^{-2} = 1.26×10^{-6} N A^{-2}
Mass of an electron	m_e =	9.11×10^{-31} kg
Mass of a proton	m_p =	1.67×10^{-27} kg
Mass of a neutron	m_n =	1.68×10^{-27} kg
Mass of an alpha particle	m_α =	6.65×10^{-27} kg
Planck's constant	h =	6.63×10^{-34} J s
Universal gravitational constant	G =	6.67×10^{-11} N m^2 kg^{-2}

Conversion Factors			
1 astronomical unit (AU)	AU =	1.496×10^8 km	
1 atomic mass unit	u =	1.6606×10^{-27} kg	
mass-energy equivalent	=	931.5 M eV	
1 electron volt	eV =	1.602×10^{-19} J	
1 light year	=	9.460×10^{12} km	
1 parsec	=	3.086×10^{13} km	= 3.26 light years
1 tonne	=	10^3 kg = 10^6 g	
1 m s^{-1}	=	3.6 km h^{-1}	

Selected Physical Data				
	Mass (kg)	*Radius (m)*	*Period of rotation (s)*	*Mean orbit radius (m)*
Sun	1.99×10^{30}	6.96×10^8	2.14×10^6	-
Earth	5.97×10^{24}	6.38×10^6	8.61×10^4	1.50×10^{11}
Mars	6.37×10^{23}	3.43×10^6	8.85×10^4	2.28×10^{11}
Jupiter	1.90×10^{27}	7.18×10^7	3.54×10^4	7.78×10^{11}
Moon	7.35×10^{22}	1.74×10^6	2.36×10^6	3.84×10^8

Universal Gravitational Constant	G	=	6.67×10^{-11} Nm2 kg^{-2}
Acceleration due to gravity on Earth (mean)	g	=	9.80 ms^{-2}
Acceleration due to gravity on the Moon (mean)	g_{moon}	=	1.62 ms^{-2}
Mean density of the Earth		=	5.52×10^3 kg m^{-3}

APPENDIX 3 - List of the Elements

Element	Symbol	Atomic Number	Mass Number (most common isotope)
Hydrogen	H	1	1
Helium	He	2	4
Lithium	Li	3	7
Beryllium	Be	4	9
Boron	B	5	11
Carbon	C	6	12
Nitrogen	N	7	14
Oxygen	O	8	16
Fluorine	F	9	19
Neon	Ne	10	20
Sodium	Na	11	23
Magnesium	Mg	12	24
Aluminium	Al	13	27
Silicon	Si	14	28
Phosphorus	P	15	31
Sulfur	S	16	32
Chlorine	Cl	17	35
Argon	Ar	18	40
Potassium	K	19	39
Calcium	Ca	20	40
Scandium	Sc	21	45
Titanium	Ti	22	48
Vanadium	V	23	51
Chromium	Cr	24	52
Manganese	Mn	25	55
Iron	Fe	26	56
Cobalt	Co	27	59
Nickel	Ni	28	58
Copper	Cu	29	63
Zinc	Zn	30	64
Gallium	Ga	31	69
Germanium	Ge	32	74
Arsenic	As	33	75
Selenium	Se	34	80
Bromine	Br	35	79
Krypton	Kr	36	84
Rubidium	Rb	37	85
Strontium	Sr	38	88
Yttrium	Y	39	89
Zirconium	Zr	40	90
Niobium	Nb	41	93
Molybdenum	Mo	42	98
Technetium	Tc	43	99
Ruthenium	Ru	44	102
Rhodium	Rh	45	103
Palladium	Pd	46	106
Silver	Ag	47	107
Cadmium	Cd	48	114
Indium	In	49	115
Tin	Sn	50	120
Antimony	Sb	51	121
Tellurium	Te	52	130

Element	Symbol	Atomic Number	Mass Number (most common isotope)
Iodine	I	53	127
Xenon	Xe	54	132
Caesium	Cs	55	133
Barium	Ba	56	138
Lanthanum	La	57	139
Cerium	Ce	58	140
Praseodymium	Pr	59	141
Neodymium	Nd	60	142
Promethium	Pm	61	145
Samarium	Sm	62	152
Europium	Eu	63	153
Gadolinium	Gd	64	158
Terbium	Tb	65	159
Dysprosium	Dy	66	164
Holmium	Ho	67	165
Erbium	Er	68	166
Thulium	Tm	69	169
Ytterbium	Yb	70	174
Lutetium	Lu	71	175
Hafnium	Hf	72	180
Tantalum	Ta	73	181
Tungsten	W	74	184
Rhenium	Re	75	187
Osmium	Os	76	192
Iridium	Ir	77	193
Platinum	Pt	78	195
Gold	Au	79	197
Mercury	Hg	80	202
Thallium	Tl	81	205
Lead	Pb	82	208
Bismuth	Bi	83	209
Polonium	Po	84	210
Astatine	At	85	210
Radon	Rn	86	222
Francium	Fr	87	233
Radium	Ra	88	226
Actinium	Ac	89	227
Thorium	Th	90	232
Protactinium	Pa	91	231
Uranium	U	92	238
Neptunium	Np	93	237
Plutonium	Pu	94	244
Americium	Am	95	243
Curium	Cm	96	247
Berkelium	Bk	97	247
Californium	Cf	98	251
Einsteinium	Es	99	254
Fermium	Fm	100	257
Mendelevium	Md	101	256
Nobelium	No	102	259
Lawrencium	Lr	103	257

Alkali Metals | Alkali Earth Metals | Halogens | Noble Gases

TRANSITION ELEMENTS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.97	4 Be Beryllium 9.01											5 B Boron 10.82	6 C Carbon 12.01	7 N Nitrogen 14.01	8 O Oxygen 16.00	9 F Fluorine 19.00	10 Ne Neon 20.18
11 Na Sodium 22.99	12 Mg Magnesium 24.31											13 Al Aluminium 26.98	14 Si Silicon 28.09	15 P Phosphorus 30.97	16 S Sulfur 32.07	17 Cl Chlorine 35.45	18 Ar Argon 39.95
19 K Potassium 39.10	20 Ca Calcium 40.08	21 Sc Scandium 44.96	22 Ti Titanium 47.87	23 V Vanadium 50.94	24 Cr Chromium 52.00	25 Mn Manganese 54.94	26 Fe Iron 55.85	27 Co Cobalt 58.93	28 Ni Nickel 58.69	29 Cu Copper 63.55	30 Zn Zinc 65.38	31 Ga Gallium 69.72	32 Ge Germanium 72.64	33 As Arsenic 74.92	34 Se Selenium 78.96	35 Br Bromine 79.90	36 Kr Krypton 83.80
37 Rb Rubidium 85.47	38 Sr Strontium 87.62	39 Y Yttrium 88.91	40 Zr Zirconium 91.22	41 Nb Niobium 92.91	42 Mo Molybdenum 95.96	43 Tc Technetium (98)	44 Ru Ruthenium 101.1	45 Rh Rhodium 102.9	46 Pd Palladium 106.4	47 Ag Silver 107.9	48 Cd Cadmium 112.4	49 In Indium 114.8	50 Sn Tin 118.7	51 Sb Antimony 121.8	52 Te Tellurium 127.6	53 I Iodine 126.9	54 Xe Xenon 131.3
55 Cs Caesium 132.9	56 Ba Barium 137.3	57 La Lanthanum 138.9	72 Hf Hafnium 178.5	73 Ta Tantalum 180.9	74 W Tungsten 183.8	75 Re Rhenium 186.2	76 Os Osmium 190.2	77 Ir Iridium 192.2	78 Pt Platinum 195.1	79 Au Gold 197.0	80 Hg Mercury 200.6	81 Tl Thallium 204.4	82 Pb Lead 207.2	83 Bi Bismuth 209.0	84 Po Polonium (209)	85 At Astatine (210)	86 Rn Radon (222)
87 Fr Francium (223)	88 Ra Radium 226.0	89 Ac Actinium (227)	104 Rf Rutherfordium 101.1	105 Db Dubnium (281)	106 Sg Seaborgium (271)	107 Bh Bohrium (272)	108 Hs Hassium (270)	109 Mt Meitnerium (276)	110 Ds Darmstadtium (281)	111 Rg Roentgenium (280)	112 Cn Copernicium (285)		114 Fl Flevorium (289)		116 Lv Livermorium (292)		

RARE EARTHS (LANTHANIDES)

58 Ce Cerium 140.1	59 Pr Praesodymium 140.9	60 Nd Neodymium 144.2	61 Pm Promethium (145)	62 Sm Samarium 150.4	63 Eu Europium 152.0	64 Gd Gadolinium 157.3	65 Tb Terbium 158.9	66 Dy Dysprosium 162.5	67 Ho Holmium 164.9	68 Er Erbium 167.3	69 Tm Thulium 168.9	70 Yb Ytterbium 173.1	71 Lu Lutetium 175.0
90 Th Thorium 232.0	91 Pa Protactinium 231.0	92 U Uranium 238.0	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium

ACTINIDES

6	Atomic Number
C	Symbol
Carbon	Element Name
12.01	Relative Atomic Mass (Atomic weight)

( ) = mass number of the isotope with the longest half life Atomic weights from data published by IUPAC Commission on Atomic Weights 2013

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