VERSION 0.9 NCS

GRADE 11
PHYSICAL SCIENCE

WRITTEN BY VOLUNTEERS

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TECHNOLOGY-POWERED LEARNING

EVERYTHING SCIENCE

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Periodic Table of the Elements

No	EN	Element	AMU

1 IA	2 IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VII	9 VII	10 VII	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 0
1 2.2 H 1,01																	2 He 4,00
3 0.98 Li 6,94	4 1.57 Be 9,01											5 2.04 B 10,8	6 2.55 C 12,0	7 3.04 N 14,0	8 3.44 O 16,0	9 3.98 F 19,0	10 Ne 20,2
11 0.93 Na 23,0	12 1.31 Mg 24,3											13 1.61 Al 27,0	14 1.90 Si 28,1	15 2.19 P 31,0	16 2.58 S 32,1	17 3.16 Cl 35,45	18 Ar 39,9
19 0.93 K 39,1	20 1.00 Ca 40,1	21 1.36 Sc 45,0	22 1.54 Ti 47,9	23 1.63 V 50,9	24 1.66 Cr 52,0	25 1.55 Mn 54,9	26 1.33 Fe 55,8	27 1.88 Co 58,9	28 1.91 Ni 58,7	29 1.90 Cu 63,5	30 1.65 Zn 65,4	31 1.81 Ga 69,7	32 2.01 Ge 72,6	33 2.18 As 74,9	34 2.55 Se 79,0	35 2.96 Br 79,9	36 Kr 83,8
37 0.82 Rb 85,5	38 0.95 Sr 87,6	39 1.22 Y 88,9	40 1.33 Zr 91,2	41 1.60 Nb 92,9	42 2.16 Mo 95,9	43 1.90 Tc (98)	44 2.20 Ru 101,1	45 2.28 Rh 102,9	46 2.20 Pd 106,4	47 1.93 Ag 107,9	48 1.69 Cd 112,4	49 1.78 In 114,8	50 1.96 Sn 118,7	51 2.05 Sb 121,8	52 2.10 Te 127,6	53 2.66 I 126,9	54 Xe 131,3
55 0.79 Cs 132,9	56 0.89 Ba 137,3	57-71 La-Lu Lanthanides	72 1.30 Hf 178,5	73 1.50 Ta 180,9	74 2.36 W 183,8	75 1.90 Re 186,2	76 2.20 Os 190,2	77 2.20 Ir 192,2	78 2.28 Pt 195,1	79 2.54 Au 197,0	80 2.00 Hg 200,6	81 1.62 Tl 204,4	82 2.33 Pb 207,2	83 2.02 Bi 209,0	84 2.00 Po (209)	85 2.20 At (210)	86 Rn (222)
87 0.7 Fr (223)	88 0.9 Ra 226,0	89-103 Ac-Lr Actinides	104 Rf (261)	105 Db (262)	106 Sg (263)	107 Bh (262)	108 Hs (265)	109 Mt (266)	110 Ds (269)	111 Rg (272)	112 Cn (277)	113 Uut (284)	114 Uuq (289)	115 Uup (288)	116 Uuh (293)	117 Uus (282)	118 Uuo (282)

57 1.10 La 138,9	58 1.12 Ce 140,1	59 1.13 Pr 140,9	60 1.14 Nd 144,2	61 Pm (145)	62 1.17 Sm 150,4	63 Eu 152,0	64 1.20 Gd 157,3	65 Tb 158,9	66 1.22 Dy 162,5	67 1.23 Ho 164,9	68 1.24 Er 167,3	69 1.25 Tm 168,9	70 Yb 173,0	71 1.27 Lu 175,0
89 1.10 Ac 227,0	90 1.30 Th 232,0	91 1.50 Pa 231,0	92 1.38 U 238,0	93 1.36 Np 237,0	94 1.28 Pu (244)	95 1.30 Am (243)	96 1.30 Cm (247)	97 1.30 Bk (247)	98 1.30 Cf (251)	99 1.30 Es (252)	100 1.30 Fm (257)	101 1.30 Md (258)	102 1.30 No (258)	103 Lr (260)

- Transition Metal
- Metal
- Metalloid
- Non-metal
- Noble Gas
- Lanthanide
- Actinide

Everything Science

Grade 11 Physical Science

Version 0.9 – NCS

by Siyavula and volunteers

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When we look outside at everything in nature, look around us at everything manufactured or look up at everything in space we cannot but be struck by the incredible diversity and complexity of life; so many things, that look so different, operating in such unique ways. The physical universe really contains incredible complexity.

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If we look back at some of the things that developed over the last century – space travel, advances in medicine, wireless communication (from television to mobile phones) and materials a thousand times stronger than steel – we see they are not the consequence of magic or some inexplicable phenomena. They were all developed through the study and systematic application of the physical sciences. So as we look forward at the 21st century and some of the problems of poverty, disease and pollution that face us, it is partly to the physical sciences we need to turn.

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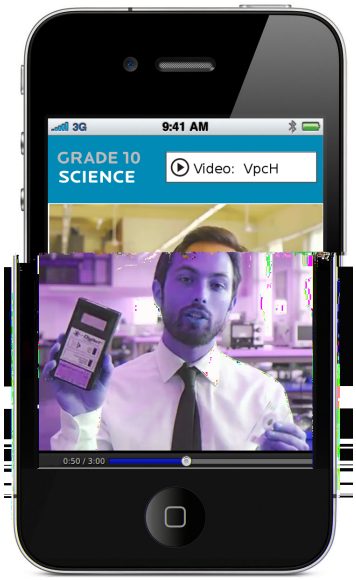

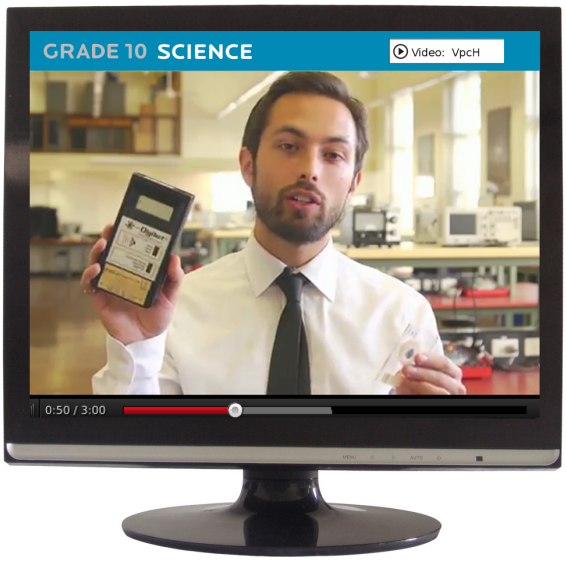

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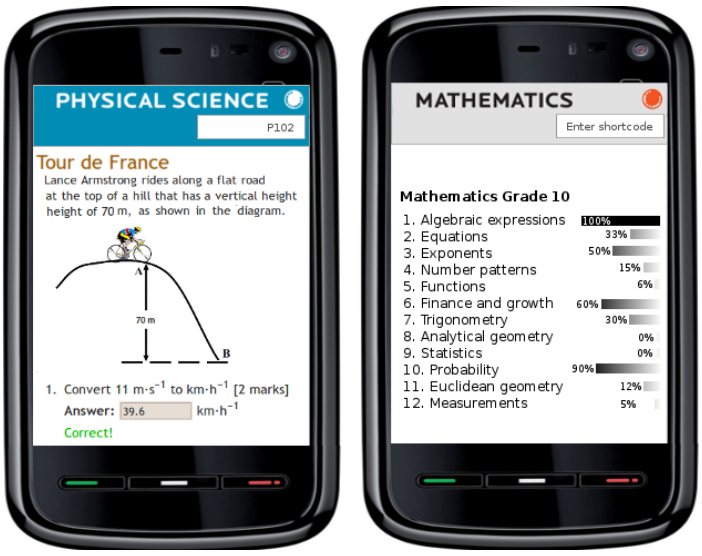

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Part I

Chemistry

Atomic Combinations 1

When you look at the matter, or physical substances, around you, you will realise that atoms seldom exist on their own. More often, the things around us are made up of different atoms that have been joined together. This is called **chemical bonding**. Chemical bonding is one of the most important processes in chemistry because it allows all sorts of different molecules and combinations of atoms to form, which then make up the objects in the complex world around us. There are, however, some atoms that *do* exist on their own, and which do not bond with others. The **noble gases** in Group 8 of the Periodic Table behave in this way. They include elements like neon (Ne), helium (He) and argon (Ar). The important question then is, why do some atoms bond but others do not? ▶ See introductory video: VPgvs at www.everythingscience.co.za

1.1 Why do atoms bond? ESBA

As we begin this section, it's important to remember that what we will go on to discuss is a *model* of bonding, that is based on a particular *model* of the atom. You will remember from the discussion on atoms that a model is a *representation* of what is happening in reality. In the model of the atom that you are familiar with, the atom is made up of a central nucleus, surrounded by electrons that are arranged in fixed energy levels (sometimes called *shells*). Within each energy level, electrons move in *orbitals* of different shapes. The electrons in the outermost energy level of an atom are called the **valence electrons**. This model of the atom is useful in trying to understand how different types of bonding take place between atoms.

You will remember from these earlier discussions of electrons and energy levels in the atom, that electrons always try to occupy the *lowest* possible energy level. In the same way, an atom also prefers to exist in the lowest possible energy state so that it is most *stable*. An atom is most stable when all its valence electron orbitals are *full*. In other words, the outer energy level of the atom contains the maximum number of electrons that it can. A stable atom is also an *unreactive* one, and is unlikely to bond with other atoms. This explains why the noble gases are unreactive and why they exist as atoms, rather than as molecules. Look for example at the electron configuration of neon ($1s^2\ 2s^2\ 2p^6$). Neon has eight valence electrons in its valence energy shell. This is the maximum that it can hold and so neon is very stable and unreactive, and will not form new bonds. Other atoms, whose valence energy levels are not full, are more likely to bond in order to become more stable. We are going to look a bit more closely at some of the energy changes that take place when atoms bond.

1.2 Energy and bonding ESBB

Let's start by imagining that there are two hydrogen atoms approaching one another. As they move closer together, there are three forces that act on the atoms at the same time. These forces are shown in Figure 1.1 and are described below:

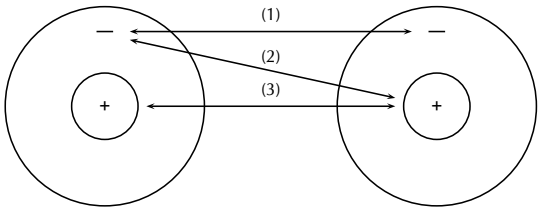


Figure 1.1: Forces acting on two approaching atoms: (1) repulsion between electrons, (2) attraction between protons and electrons and (3) repulsion between protons.

1. **repulsive force** between the electrons of the atoms, since like charges repel
2. **attractive force** between the nucleus of one atom and the electrons of another
3. **repulsive force** between the two positively-charged nuclei

Now look at Figure 1.2 to understand the energy changes that take place when the two atoms move towards each other.

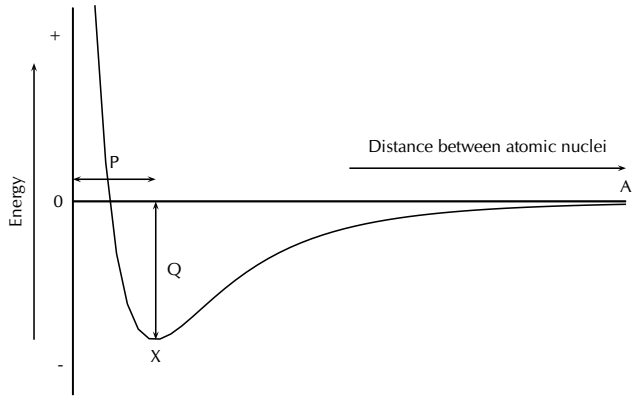


Figure 1.2: Graph showing the change in energy that takes place as atoms move closer together

In the example of the two hydrogen atoms, where the resultant force between them is attraction, the energy of the system is zero when the atoms are far apart (point A), because there is no interaction between the atoms. When the atoms move closer together, attractive forces dominate and the atoms are pulled towards each other. As this happens, the *potential energy* of the system decreases because energy would now need to be *supplied* to the system in order to move the atoms apart. However, as the atoms continue to move closer together (i.e. *left* along the horizontal axis of the graph), repulsive forces start to dominate and this causes the potential energy of the system to rise again. At some point, the attractive and repulsive effects are balanced, and the energy of the system is at its minimum (point X). It is at this point, when the energy is at a minimum, that bonding takes place.

The distance marked 'P' is the **bond length**, i.e. the distance between the nuclei of the atoms when they bond. 'Q' represents the **bond energy** i.e. the amount of energy that must be added to the system to break the bonds that have formed. **Bond strength** means how strongly one atom attracts and is held to another. The strength of a bond is related to the bond length, the size of the bonded atoms and the number of bonds between the atoms. In general, the shorter the bond length, the stronger the bond between the atoms, and the smaller the atoms involved, the stronger the bond. Also, the more bonds that exist between the same atoms, the stronger the bond.
▶ See simulation: VPgxl at www.everythingscience.co.za)

1.3 What happens when atoms bond?

ESBC

A **chemical bond** is formed when atoms are held together by attractive forces. This attraction occurs when electrons are *shared* between atoms, or when electrons are *exchanged* between the atoms that are involved in the bond. The sharing or exchange of electrons takes place so that the outer energy levels of the atoms involved are filled and the atoms are more stable. If an electron is **shared**, it means that it will spend its time moving in the electron orbitals around *both* atoms. If an electron is **exchanged** it means that it is transferred from one atom to another, in other words one atom *gains* an electron while the other *loses* an electron.

> *DEFINITION: Chemical bond*
>
> A chemical bond is the physical process that causes atoms and molecules to be attracted to each other, and held together in more stable chemical compounds.

The type of bond that is formed depends on the elements that are involved. In this section, we will be looking at three types of chemical bonding: **covalent**, **ionic** and **metallic bonding**.

You need to remember that it is the *valence electrons* that are involved in bonding and that atoms will try to fill their outer energy levels so that they are more stable.

1.4 Covalent Bonding

ESBD

The nature of the covalent bond

ESBE

Covalent bonding occurs between the atoms of **non-metals**. The outermost orbitals of the atoms overlap so that unpaired electrons in each of the bonding atoms can be shared. By overlapping orbitals, the outer energy shells of all the bonding atoms are filled. The shared electrons move in the orbitals around *both* atoms. As they move, there is an attraction between these negatively charged electrons and the positively charged nuclei, and this force holds the atoms together in a covalent bond.

> *DEFINITION: Covalent bond*
>
> Covalent bonding is a form of chemical bonding where pairs of electrons are shared between atoms.

Below are a few examples. Remember that it is only the *valence electrons* that are involved in bonding, and so when diagrams are drawn to show what is happening during bonding, it is only these electrons that are shown. Circles and crosses represent electrons in different atoms.

See simulation: VPgye at www.everythingscience.co.za)

Example 1: *Covalent bonding*

QUESTION

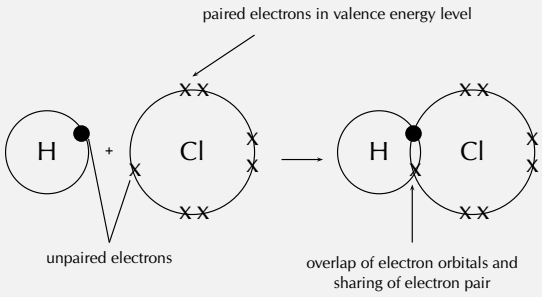
How do hydrogen and chlorine atoms bond covalently in a molecule of hydrogen chloride?

SOLUTION

Step 1 : ***Determine the electron configuration of each of the bonding atoms.***
A chlorine atom has 17 electrons, and an electron configuration of [Ne]$3s^2\ 3p^5$. A hydrogen atom has only 1 electron, and an electron configuration of $1s^1$.

Step 2 : ***Determine the number of valence electrons for each atom, and how many of the electrons are paired or unpaired.***
Chlorine has 7 valence electrons. One of these electrons is unpaired. Hydrogen has 1 valence electron and it is unpaired.

Step 3 : ***Look to see how the electrons can be shared between the atoms so that the outermost energy levels of both atoms are full.***
The hydrogen atom needs one more electron to complete its valence shell. The chlorine atom also needs one more electron to complete its valence shell. Therefore *one pair of electrons* must be shared between the two atoms. In other words, one electron from the chlorine atom will spend some of its time orbiting the hydrogen atom so that hydrogen's valence shell is full. The hydrogen electron will spend some of its time orbiting the chlorine atom so that chlorine's valence shell is also full. A molecule of hydrogen chloride is formed. Notice the shared electron pair in the overlapping orbitals.



Example 2: *Covalent bonding involving multiple bonds*

QUESTION

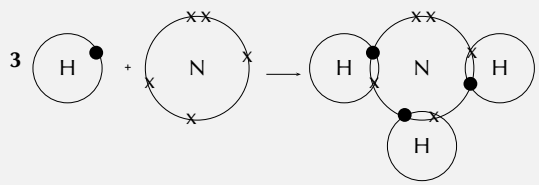
How do nitrogen and hydrogen atoms bond to form a molecule of ammonia (NH_3)?

SOLUTION

Step 1 : ***Determine the electron configuration of each of the bonding atoms.***
A nitrogen atom has 7 electrons, and an electron configuration of [He]$2s^2\ 2p^3$. A hydrogen atom has only 1 electron, and an electron configuration of $1s^1$.

Step 2 : ***Determine the number of valence electrons for each atom, and how many of the electrons are paired or unpaired.***
Nitrogen has 5 valence electrons. 3 of these electrons are unpaired. Hydrogen has 1 valence electron and it is unpaired.

Step 3 : ***Look to see how the electrons can be shared between the atoms so that the outer energy shells of all atoms are full.***
Each hydrogen atom needs one more electron to complete its valence energy shell. The nitrogen atom needs three more electrons to complete its valence energy shell. Therefore *three pairs of electrons* must be shared between the four atoms involved. The nitrogen atom will share three of its electrons so that each of the hydrogen atoms now have a complete valence shell. Each of the hydrogen atoms will share its electron with the nitrogen atom to complete its valence shell.



The above examples all show **single covalent bonds**, where only one pair of electrons is shared between *the same two atoms*. If two pairs of electrons are shared between the same two atoms, this is called a **double bond**. A **triple bond** is formed if three pairs of electrons are shared.

Example 3: *Covalent bonding involving a double bond*

QUESTION

How do oxygen atoms bond covalently to form an oxygen molecule?

SOLUTION

Step 1 : ***Determine the electron configuration of the bonding atoms.***
Each oxygen atom has 8 electrons, and their electron configuration is $1s^2\ 2s^2$

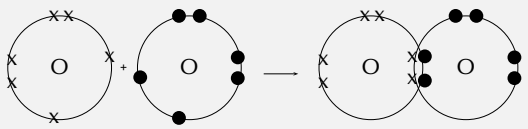
$2p^4$.

Step 2 : ***Determine the number of valence electrons for each atom and how many of these electrons are paired and unpaired.***

Each oxygen atom has 6 valence electrons. Each atom has 2 unpaired electrons.

Step 3 : ***Look to see how the electrons can be shared between atoms so that the outer energy shells of all the atoms are full.***

Each oxygen atom needs two more electrons to complete its valence energy shell. Therefore *two pairs of electrons* must be shared between the two oxygen atoms so that both valence shells are full. Notice that the two electron pairs are being shared between *the same two* atoms, and so we call this a **double bond**.



You will have noticed in the above examples that the number of electrons that are involved in bonding varies between atoms. We say that the **valency** of the atoms is different.

> *DEFINITION: Valency*
>
> The number of electrons in the outer shell of an atom which are able to be used to form bonds with other atoms.

In the first example, the valency of both hydrogen and chlorine is one, therefore there is a single covalent bond between these two atoms. In the second example, nitrogen has a valency of three and hydrogen has a valency of one. This means that three hydrogen atoms will need to bond with a single nitrogen atom. There are three *single* covalent bonds in a molecule of ammonia. In the third example, the valency of oxygen is two. This means that each oxygen atom will form two bonds with another atom. Since there is only one other atom in a molecule of O_2, a *double covalent* bond is formed between these two atoms.

Tip

There is a relationship between the valency of an element and its position on the Periodic Table. For the elements in groups 1 to 2, the valency is the same as the group number. For elements in groups 13 to 17, the valency is calculated by subtracting the group number from 18. For example, the valency of fluorine (group 17) is $18 - 17 = 1$, while the valency of calcium (group 2) is 2. Some elements have more than one possible valency, so you always need to be careful when you are writing a chemical formula. Often, if there is more than one possibility in terms of valency, the valency will be written in a bracket after the element symbol e.g. iron (II) oxide, means that in this molecule iron has a valency of 2.

Exercise 1 - 1

1. Explain the difference between the *valence electrons* and the *valency* of an element.
2. Complete the table below by filling in the number of valence electrons and the valency for each of the elements shown:

Element	No. of valence electrons	No. of electrons needed to fill outer shell	Valency
F			
Ar			
C			
N			
O			

3. Draw simple diagrams to show how electrons are arranged in the following covalent molecules:
   (a) Water (H_2O)
   (b) Chlorine (Cl_2)

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(1.) 01h3 (2.) 01h4 (3.) 01h5

1.5 Lewis notation and molecular structure

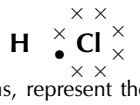
ESBF

Although we have used diagrams to show the structure of molecules, there are other forms of notation that can be used, such as **Lewis notation** and **Couper notation**. **Lewis notation** uses dots and crosses to represent the **valence electrons** on different atoms. The chemical symbol of the element is used to represent the nucleus and the core electrons of the atom.

So, for example, a hydrogen atom would be represented like this:

A chlorine atom would look like this:

A molecule of hydrogen chloride would be shown like this:



The dot and cross in between the two atoms, represent the pair of electrons that are shared in the covalent bond.

Example 4: *Lewis notation: Simple molecules*

QUESTION

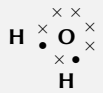
Represent the molecule H_2O using Lewis notation

SOLUTION

Step 1 : ***For each atom, determine the number of valence electrons in the atom, and represent these using dots and crosses.***

The electron configuration of hydrogen is $1s^1$ and the electron configuration for oxygen is $1s^2\ 2s^2\ 2p^4$. Each hydrogen atom has one valence electron, which is unpaired, and the oxygen atom has six valence electrons with two unpaired.

Step 2 : ***Arrange the electrons so that the outermost energy level of each atom is full.***
The water molecule is represented below.



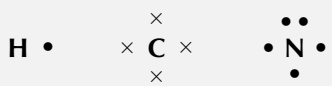
Example 5: *Lewis notation: Molecules with multiple bonds*

QUESTION

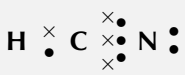
Represent the molecule HCN using Lewis notation

SOLUTION

Step 1 : ***For each atom, determine the number of valence electrons that the atom has from its electron configuration.***
The electron configuration of hydrogen is $1s^1$, the electron configuration of nitrogen is $1s^2\ 2s^2\ 2p^3$ and for carbon is $1s^2\ 2s^2\ 2p^2$. This means that hydrogen has one valence electron which is unpaired, carbon has four valence electrons, all of which are unpaired, and nitrogen has five valence electrons, three of which are unpaired.



Step 2 : ***Arrange the electrons in the HCN molecule so that the outermost energy level in each atom is full.***
The HCN molecule is represented below. Notice the three electron pairs between the nitrogen and carbon atom. Because these three covalent bonds are between the same two atoms, this is a *triple* bond.



Example 6: *Lewis notation: Atoms with variable valencies*

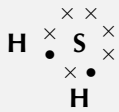
QUESTION

Represent the molecule H_2S using Lewis notation

SOLUTION

Step 1 : ***Determine the number of valence electrons for each atom.***
Hydrogen has an electron configuration of $1s^1$ and sulphur has an electron configuration of [Ne] $3s^2\ 3p^4$. Each hydrogen atom has one valence electron which is unpaired, and sulphur has six valence electrons. Since there are 2 hydrogen atoms to 1 sulphur atom, sulphur must have a valency of 2.

Step 2 : ***Arrange the atoms in the molecule so that the outermost energy level in each atom is full.***
The H_2S molecule is represented below.



Another way of representing molecules is using **Couper notation**. In this case, only the electrons that are involved in the bond between the atoms are shown. A line is used for each covalent bond. Using Couper notation, a molecule of water and a molecule of HCN would be represented as shown in Figures 1.3 and 1.4 below.

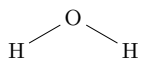


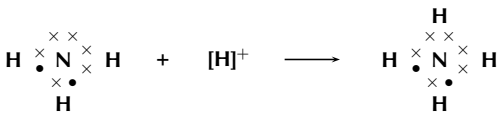
Figure 1.3: A water molecule represented using Couper notation

Figure 1.4: A molecule of HCN represented using Couper notation

Extension:	*Dative covalent bonds*

A **dative covalent bond** (also known as a coordinate covalent bond) is a description of covalent bonding between two atoms in which both electrons shared in the bond come from the same atom. This happens when a Lewis base (an electron donor) donates a pair of electrons to a Lewis acid (an electron acceptor). Lewis acids and bases will be discussed in Section 8.1 in Chapter 8.

One example of a molecule that contains a dative covalent bond is the ammonium ion (NH_4^+) shown in the figure below. The hydrogen ion H^+ does not contain any electrons, and therefore the electrons that are in the bond that forms between this ion and the nitrogen atom, come only from the nitrogen.

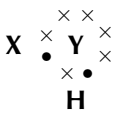


Exercise 1 - 2

1. Represent each of the following *atoms* using Lewis notation:
   (a) beryllium
   (b) calcium
   (c) lithium
2. Represent each of the following *molecules* using Lewis notation:
   (a) bromine gas (Br_2)
   (b) carbon dioxide (CO_2)

   Which of these two molecules contains a double bond?
3. Two chemical reactions are described below.
   - nitrogen and hydrogen react to form NH_3
   - carbon and hydrogen bond to form a molecule of CH_4

   For each reaction, give:
   (a) the valency of each of the atoms involved in the reaction
   (b) the Lewis structure of the product that is formed
   (c) the chemical formula of the product
   (d) the name of the product
4. A chemical compound has the following Lewis notation:



   (a) How many valence electrons does element Y have?
   (b) What is the valency of element Y?

(c) What is the valency of element X?

(d) How many covalent bonds are in the molecule?

(e) Suggest a name for the elements X and Y.

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(1.) 01h6 (2.) 01h7 (3.) 01h8 (4.) 01h9

1.6 Electronegativity

ESBG

Electronegativity is a measure of how strongly an atom pulls a shared electron pair towards it. The table below shows the electronegativities (obtained from www.thecatalyst.org/electabl.html) of a number of elements:

Element	Electronegativity
Hydrogen (H)	2.1
Sodium (Na)	0.9
Magnesium (Mg)	1.2
Calcium (Ca)	1.0
Chlorine (Cl)	3.0
Bromine (Br)	2.8

Table 1.1: Table of electronegativities for selected elements

FACT

The concept of electronegativity was introduced by *Linus Pauling* in 1932, and this became very useful in predicting the nature of bonds between atoms in molecules. In 1939, he published a book called 'The Nature of the Chemical Bond', which became one of the most influential chemistry books ever published. For this work, Pauling was awarded the Nobel Prize in Chemistry in 1954. He also received the Nobel Peace Prize in 1962 for his campaign against above-ground nuclear testing.

DEFINITION: Electronegativity

Electronegativity is a chemical property which describes the power of an atom to attract electrons towards itself.

The greater the electronegativity of an element, the stronger its attractive pull on electrons. For example, in a molecule of hydrogen bromide (HBr), the electronegativity of bromine (2.8) is higher than that of hydrogen (2.1), and so the shared electrons will spend more of their time closer to the bromine atom. Bromine will have a slightly negative charge, and hydrogen will have a slightly positive charge. In a molecule like hydrogen (H_2) where the electronegativities of the atoms in the molecule are the same, both atoms have a neutral charge.

Non-polar and polar covalent bonds

ESBH

Electronegativity can be used to explain the difference between two types of covalent bonds. **Non-polar covalent bonds** occur between two identical non-metal atoms, e.g. H_2, Cl_2 and O_2. Because the two atoms have the same electronegativity, the electron pair in the covalent bond is shared equally between them. However, if two different non-metal atoms bond then the shared electron pair will be

pulled more strongly by the atom with the highest electronegativity. As a result, a **polar covalent bond** is formed where one atom will have a slightly negative charge and the other a slightly positive charge. This is represented using the symbols δ^+ (slightly positive) and δ^- (slightly negative). So, in a molecule such as hydrogen chloride (HCl), hydrogen is $H^{\delta+}$ and chlorine is $Cl^{\delta-}$.

Polar molecules

ESBI

Some molecules with polar covalent bonds are **polar molecules**, e.g. H_2O. But not *all* molecules with polar covalent bonds are polar. An example is CO_2. Although CO_2 has two polar covalent bonds (between $C^{\delta+}$ atom and the two $O^{\delta-}$ atoms), the molecule itself is not polar. The reason is that CO_2 is a linear molecule and is therefore symmetrical. So there is no difference in charge between the two ends of the molecule. The *polarity* of molecules affects properties such as *solubility*, *melting points* and *boiling points*.

DEFINITION: Polar and non-polar molecules

A **polar molecule** is one that has one end with a slightly positive charge, and one end with a slightly negative charge. A **non-polar molecule** is one where the charge is equally spread across the molecule.

Exercise 1 - 3

1. In a molecule of hydrogen chloride (HCl),
   (a) What is the electronegativity of hydrogen
   (b) What is the electronegativity of chlorine?
   (c) Which atom will have a slightly positive charge and which will have a slightly negative charge in the molecule?
   (d) Is the bond a non-polar or polar covalent bond?
   (e) Is the molecule polar or non-polar?
2. Complete the table below:

Molecule	**Difference in electronegativity between atoms**	**Non-polar/polar covalent bond**	**Polar/non-polar molecule**
H_2O			
HBr			
F_2			
CH_4			

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1.7 Ionic Bonding

ESBJ

The nature of the ionic bond

ESBK

You will remember that when atoms bond, electrons are either *shared* or they are *transferred* between the atoms that are bonding. In covalent bonding, electrons are shared between the atoms. There is another type of bonding, where electrons are *transferred* from one atom to another. This is called **ionic bonding**.

Ionic bonding takes place when the difference in electronegativity between the two atoms is more than 1.7. This usually happens when a metal atom bonds with a non-metal atom. When the difference in electronegativity is large, one atom will attract the shared electron pair much more strongly than the other, causing electrons to be transferred from one atom to the other.

> *DEFINITION: Ionic bond*
>
> An ionic bond is a type of chemical bond based on the electrostatic forces between two oppositely-charged ions. When ionic bonds form, an atom of lower electronegativity donates one or more electrons, to form a positive ion or cation. The atom of higher electronegativity readily gains electrons to form a negative ion or anion. The two ions are then attracted to each other by electrostatic forces.

Example 1:

In the case of NaCl, the difference in electronegativity is 2.1. Sodium has only one valence electron, while chlorine has seven. Because the electronegativity of chlorine is higher than the electronegativity of sodium, chlorine will attract the valence electron of the sodium atom very strongly. This electron from sodium is transferred to chlorine. Sodium loses an electron and forms a Na^+ ion. Chlorine gains an electron and forms a Cl^- ion. The attractive force between the positive and negative ion holds the molecule together.

The balanced equation for the reaction is:

$$Na + Cl \rightarrow NaCl$$

This can be represented using Lewis notation:

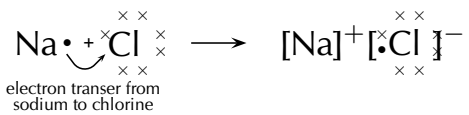

Figure 1.5: Ionic bonding in sodium chloride

Example 2:

Another example of ionic bonding takes place between magnesium (Mg) and oxygen (O) to form magnesium oxide (MgO). Magnesium has two valence electrons and an electronegativity of 1.2, while oxygen has six valence electrons and an electronegativity of 3.5. Since oxygen has a higher electronegativity, it attracts the two valence electrons from the magnesium atom and these electrons are transferred from the magnesium atom to the oxygen atom. Magnesium loses two electrons to form Mg^{2+}, and oxygen gains two electrons to form O^{2-}. The attractive force between the oppositely charged ions is what holds the molecule together.

The balanced equation for the reaction is:

$$2Mg + O_2 \rightarrow 2MgO$$

Because oxygen is a diatomic molecule, two magnesium atoms will be needed to combine with one oxygen molecule (which has two oxygen atoms) to produce two molecules of magnesium oxide (MgO).

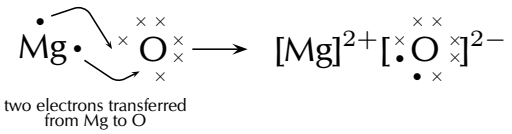

Figure 1.6: Ionic bonding in magnesium oxide

Tip

Notice that the number of electrons that is either lost or gained by an atom during ionic bonding, is the same as the **valency** of that element

Exercise 1 - 4

1. Explain the difference between a *covalent* and an *ionic* bond.
2. Magnesium and chlorine react to form magnesium chloride.
   (a) What is the difference in electronegativity between these two elements?
   (b) Give the chemical formula for:
      - a magnesium ion
      - a chloride ion
      - the ionic compound that is produced during this reaction
   (c) Write a balanced chemical equation for the reaction that takes place.
3. Draw Lewis diagrams to represent the following ionic compounds:
   (a) sodium iodide (NaI)
   (b) calcium bromide ($CaBr_2$)
   (c) potassium chloride (KCl)

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The crystal lattice structure of ionic compounds

ESBL

Ionic substances are actually a combination of lots of ions bonded together into a giant molecule. The arrangement of ions in a regular, geometric structure is called a **crystal lattice**. So in fact NaCl does

not contain one Na and one Cl ion, but rather a lot of these two ions arranged in a crystal lattice where the ratio of Na to Cl ions is 1:1. The structure of a crystal lattice is shown in Figure 1.7.

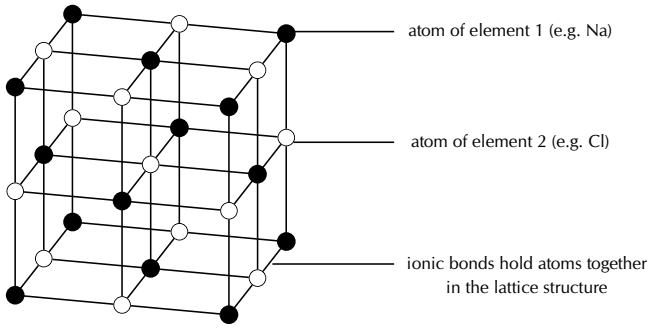

Figure 1.7: The crystal lattice arrangement in an ionic compound (e.g. NaCl)

Properties of Ionic Compounds

ESBM

Ionic compounds have a number of properties:

- Ions are arranged in a lattice structure
- Ionic solids are crystalline at room temperature
- The ionic bond is a strong electrical attraction. This means that ionic compounds are often hard and have high melting and boiling points
- Ionic compounds are brittle, and bonds are broken along planes when the compound is stressed
- Solid crystals don't conduct electricity, but ionic solutions do

1.8 Metallic bonds

ESBN

The nature of the metallic bond

ESBO

The structure of a metallic bond is quite different from covalent and ionic bonds. In a metal bond, the valence electrons are *delocalised*, meaning that an atom's electrons do not stay around that one nucleus. In a metallic bond, the positive atomic nuclei (sometimes called the 'atomic kernels') are surrounded by a sea of delocalised electrons which are attracted to the nuclei (Figure 1.8).

DEFINITION: Metallic bond

Metallic bonding is the electrostatic attraction between the positively charged atomic nuclei of metal atoms and the delocalised electrons in the metal.

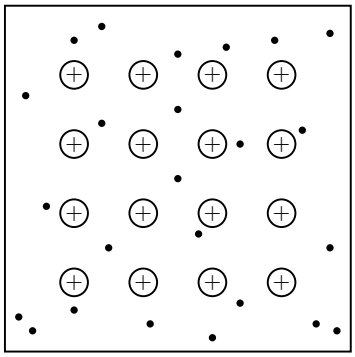

Figure 1.8: Positive atomic nuclei (+) surrounded by delocalised electrons (•)

The properties of metals

ESBP

Metals have several unique properties as a result of this arrangement:

- **Thermal conductors**

  Metals are good conductors of heat and are therefore used in cooking utensils such as pots and pans. Because the electrons are loosely bound and are able to move, they can transport heat energy from one part of the material to another.

- **Electrical conductors**

  Metals are good conductors of electricity, and are therefore used in electrical conducting wires. The loosely bound electrons are able to move easily and to transfer charge from one part of the material to another.

- **Shiny metallic lustre**

  Metals have a characteristic shiny appearance and are often used to make jewellery. The loosely bound electrons are able to absorb and reflect light at all frequencies, making metals look polished and shiny.

- **Malleable and ductile**

  This means that they can be bent into shape without breaking (malleable) and can be stretched into thin wires (ductile) such as copper, which can then be used to conduct electricity. Because the bonds are not fixed in a particular direction, atoms can slide easily over one another, making metals easy to shape, mould or draw into threads.

- **Melting point**

  Metals usually have a high melting point and can therefore be used to make cooking pots and other equipment that needs to become very hot, without being damaged. The high melting point is due to the high strength of metallic bonds.

- **Density**
  Metals have a high density because their atoms are packed closely together.

Exercise 1 - 5

1. Give two examples of everyday objects that contain.
   (a) covalent bonds
   (b) ionic bonds
   (c) metallic bonds
2. Complete the table which compares the different types of bonding:

	Covalent	**Ionic**	**Metallic**
Types of atoms involved			
Nature of bond between atoms			
Melting Point (high/low)			
Conducts electricity? (yes/no)			
Other properties			

3. Complete the table below by identifying the type of bond (covalent, ionic or metallic) in each of the compounds:

Molecular formula	**Type of bond**
H_2SO_4	
FeS	
NaI	
$MgCl_2$	
Zn	

   Which of these substances will conduct electricity most effectively? Give a reason for your answer.
4. Use your knowledge of the different types of bonding to explain the following statements:
   (a) Swimming during a lightning storm can be very dangerous.
   (b) Most jewellery items are made from metals.
   (c) Plastics are good insulators.

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(1.) 00vi (2.) 00vj (3.) 00vk (4.) 00vm

1.9 Writing chemical formulae

ESBQ

The formulae of covalent compounds

ESBR

To work out the formulae of covalent compounds, we need to use the valency of the atoms in the compound. This is because the valency tells us how many bonds each atom can form. This in turn

can help to work out how many atoms of each element are in the compound, and therefore what its formula is. The following are some examples where this information is used to write the chemical formula of a compound.

Example 7: *Formulae of covalent compounds*

QUESTION

Write the chemical formula for water

SOLUTION

Step 1 : ***Write down the elements that make up the compound.***
A molecule of water contains the elements *hydrogen* and *oxygen*.

Step 2 : ***Determine the valency of each element***
The valency of hydrogen is 1 and the valency of oxygen is 2. This means that oxygen can form two bonds with other elements and each of the hydrogen atoms can form one.

Step 3 : ***Write the chemical formula***
Using the valencies of hydrogen and oxygen, we know that in a single water molecule, two hydrogen atoms will combine with one oxygen atom. The chemical formula for water is therefore:

$$\mathbf{H_2O}$$

Example 8: *Formulae of covalent compounds*

QUESTION

Write the chemical formula for magnesium oxide

SOLUTION

Step 1 : ***Write down the elements that make up the compound.***
A molecule of magnesium oxide contains the elements *magnesium* and *oxygen*.

Step 2 : ***Determine the valency of each element***
The valency of magnesium is 2, while the valency of oxygen is also 2. In a molecule of magnesium oxide, one atom of magnesium will combine with one atom of oxygen.

Step 3 : ***Write the chemical formula***
The chemical formula for magnesium oxide is therefore:

MgO

Example 9: *Formulae of covalent compounds*

QUESTION

Write the chemical formula for copper (II) chloride.

SOLUTION

Step 1 : ***Write down the elements that make up the compound.***
A molecule of copper (II) chloride contains the elements *copper* and *chlorine*.

Step 2 : ***Determine the valency of each element***
The valency of chlorine is 1. Since we are given copper (II) in the problem the valency of copper must be 2. In a molecule of copper (II) chloride, two atoms of chlorine will combine with one atom of copper.

Step 3 : ***Write the chemical formula***
The chemical formula for copper (II) chloride is therefore:

$CuCl_2$

The formulae of ionic compounds

ESBS

The overall charge of an ionic compound will always be zero and so the negative and positive charge must be the same size. We can use this information to work out what the chemical formula of an ionic compound is if we know the charge on the individual ions. In the case of NaCl for example, the charge on the sodium is $+1$ and the charge on the chlorine is -1. The charges balance ($+1 - 1 = 0$) and therefore the ionic compound is neutral. In MgO, magnesium has a charge of $+2$ and oxygen has a charge of -2. Again, the charges balance and the compound is neutral. Positive ions are called **cations** and negative ions are called **anions**.

Some ions are made up of groups of atoms, and these are called **compound ions**. It is a good idea to learn the compound ions that are shown in Table 1.2

In the case of ionic compounds, the valency of an ion is the same as its charge (Note: valency is always expressed as a *positive* number e.g. valency of the chloride ion is 1 and not -1). Since an ionic compound is always *neutral*, the positive charges in the compound must balance out the negative. The following are some examples:

Name of compound ion	formula
Carbonate	CO_3^{2-}
Sulfate	SO_4^{2-}
Hydroxide	OH^-
Ammonium	NH_4^+
Nitrate	NO_3^-
Hydrogen carbonate	HCO_3^-
Phosphate	PO_4^{3-}
Chlorate	ClO_3^-
Cyanide	CN^-
Chromate	CrO_4^{2-}
Permanganate	MnO_4^-

Table 1.2: Table showing common compound ions and their formulae

Example 10: *Formulae of ionic compounds*

QUESTION

Write the chemical formula for potassium iodide.

SOLUTION

Step 1 : ***Write down the ions that make up the compound.***
Potassium iodide contains potassium and iodide ions.

Step 2 : ***Determine the valency and charge of each ion.***
Potassium iodide contains the ions K^+ (valency = 1; charge = +1) and I^- (valency = 1; charge = -1). In order to balance the charge in a single molecule, one atom of potassium will be needed for every one atom of iodine.

Step 3 : ***Write the chemical formula***
The chemical formula for potassium iodide is therefore:

KI

Example 11: *Formulae of ionic compounds*

QUESTION

Write the chemical formula for sodium sulfate.

SOLUTION

Step 1 : ***Write down the ions that make up the compound.***
Sodium sulfate contains sodium ions and sulfate ions.

Step 2 : ***Determine the valency and charge of each ion.***
Na^{+} (valency = 1; charge = $+1$) and SO_4^{2-} (valency = 2; charge = -2).

Step 3 : ***Write the chemical formula.***
Two sodium ions will be needed to balance the charge of the sulfate ion. The chemical formula for sodium sulfate is therefore:

$$\mathbf{Na_2SO_4}$$

Example 12: *Formulae of ionic compounds*

QUESTION

Write the chemical formula for calcium hydroxide.

SOLUTION

Step 1 : ***Write down the ions that make up the compound.***
Calcium hydroxide contains calcium ions and hydroxide ions.

Step 2 : ***Determine the valency and charge of each ion.***
Calcium hydroxide contains the ions Ca^{2+} (charge = $+2$) and OH^{-} (charge = -1). In order to balance the charge in a single molecule, two hydroxide ions will be needed for every ion of calcium.

Step 3 : ***Write the chemical formula.***
The chemical formula for calcium hydroxide is therefore:

$$\mathbf{Ca(OH)_2}$$

Exercise 1 - 6

1. Copy and complete the table below:

Compound	Cation	Anion	Formula
	Na^+	Cl^-	
potassium bromide		Br^-	
	NH_4^+	Cl^-	
potassium chromate			
			PbI
potassium permanganate			
calcium phosphate			

2. Write the chemical formula for each of the following compounds:

   (a) hydrogen cyanide
   (b) carbon dioxide
   (c) sodium carbonate
   (d) ammonium hydroxide
   (e) barium sulphate

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(1.) 00vp (2.) 00vq

1.10 The Shape of Molecules

ESBT

Valence Shell Electron Pair Repulsion (VSEPR) theory

ESBU

The shape of a covalent molecule can be predicted using the Valence Shell Electron Pair Repulsion (VSEPR) theory. This is a model in chemistry that tries to predict the shapes of molecules. Very simply, VSEPR theory says that the valence electron pairs in a molecule will arrange themselves around the central atom of the molecule so that the repulsion between their negative charges is as small as possible. In other words, the valence electron pairs arrange themselves so that they are as far apart as they can be. The number of valence electron pairs in the molecule determines the shape of that molecule.

DEFINITION: Valence Shell Electron Pair Repulsion Theory

Valence shell electron pair repulsion (VSEPR) theory is a model in chemistry, which is used to predict the shape of individual molecules, based upon the extent of their electron-pair repulsion.

VSEPR theory is based on the idea that the geometry of a molecule is mostly determined by repulsion among the pairs of electrons around a central atom. The pairs of electrons may be bonding or non-bonding (also called lone pairs). Only valence electrons of the central atom influence the molecular shape in a meaningful way.

Determining the shape of a molecule ESBV

To predict the shape of a covalent molecule, follow these steps:

Step 1: Draw the molecule using Lewis notation. Make sure that you draw *all* the valence electrons around the molecule's central atom.

Step 2: Count the number of electron pairs around the central atom.

Step 3: Determine the basic geometry of the molecule using the table below. For example, a molecule with two electron pairs around the central atom has a *linear* shape, and one with four electron pairs around the central atom would have a *tetrahedral* shape. The situation is actually more complicated than this, but this will be discussed later in this section.

Number of electron pairs	Geometry
2	linear
3	trigonal planar
4	tetrahedral
5	trigonal bipyramidal
6	octahedral

Table 1.3: The effect of electron pairs in determining the shape of molecules

Figure 1.9 shows each of these shapes. Remember that the shapes are 3-dimensional, and so you need to try to imagine them in this way. In the diagrams, the thicker lines represents those parts of the molecule that are 'in front' (or coming out of the page), while the dashed lines represent those parts that are 'at the back' (or going into the page) of the molecule.

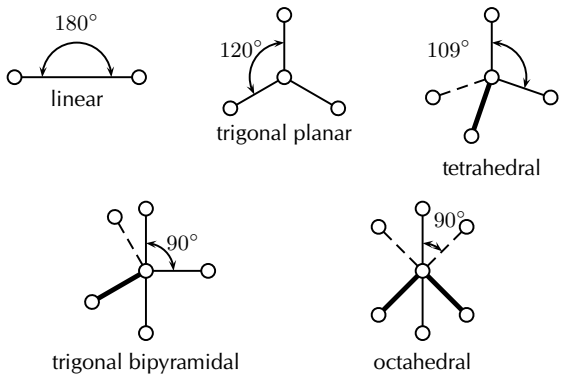


Figure 1.9: Some common molecular shapes

Example 13: *Molecular shape I*

QUESTION

Determine the shape of a molecule of O_2

SOLUTION

Step 1 : ***Draw the molecule using Lewis notation***

Step 2 : ***Count the number of electron pairs around the central atom***

There are two electron pairs.

Step 3 : ***Determine the basic geometry of the molecule***
Since there are two electron pairs, the molecule must be linear.

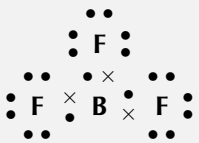
Example 14: *Molecular shape II*

QUESTION

Determine the shape of a molecule of BF_3

SOLUTION

Step 1 : ***Draw the molecule using Lewis notation***



Step 2 : ***Count the number of electron pairs around the central atom***
There are three electron pairs.

Step 3 : ***Determine the basic geometry of the molecule***
Since there are three electron pairs, the molecule must be trigonal planar.

Extension: *More about molecular shapes*

Determining the shape of a molecule can be a bit more complicated. In the examples we have used above, we looked only at the number of **bonding electron pairs** when we were trying to decide on the molecules' shape. But there are also other electron pairs in the molecules. These electrons, which are not involved in bonding but which are also around the central atom, are called **lone pairs**. The worked example below will give you an idea of how these lone pairs can affect the shape of the molecule.

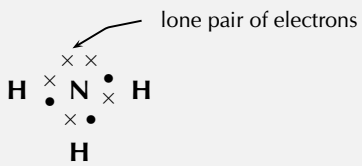
Example 15: *Molecular shape III*

QUESTION

Determine the shape of a molecule of NH_3

SOLUTION

Step 1 : ***Draw the molecule using Lewis notation***



Step 2 : ***Count the number of electron pairs around the central atom***
There are four electron pairs.

Step 3 : ***Determine the basic geometry of the molecule***
Since there are four electron pairs, the molecule must be tetrahedral.

Step 4 : ***Determine how many lone pairs are around the central atom***
There is one lone pair of electrons and this will affect the shape of the molecule.

Step 5 : ***Determine the final shape of the molecule***
The lone pair needs more space than the bonding pairs, and therefore pushes the three hydrogen atoms together a little more. The bond angles between the hydrogen and nitrogen atoms in the molecule become 106 degrees, rather than the usual 109 degrees of a tetrahedral molecule. The shape of the molecule is

trigonal pyramidal.

Activity: *Building molecular models*

In groups, you are going to build a number of molecules using jellytots to represent the atoms in the molecule, and toothpicks to represent the bonds between the atoms. In other words, the toothpicks will hold the atoms (jellytots) in the molecule together. Try to use different coloured jellytots to represent different elements.

You will build models of the following molecules:

HCl, CH_4, H_2O, HBr and NH_3

For each molecule, you need to:

- Determine the basic geometry of the molecule
- Build your model so that the atoms are as far apart from each other as possible (remember that the electrons around the central atom will try to avoid the repulsions between them).
- Decide whether this shape is accurate for that molecule or whether there are any lone pairs that may influence it.
- Adjust the position of the atoms so that the bonding pairs are further away from the lone pairs.
- How has the shape of the molecule changed?
- Draw a simple diagram to show the shape of the molecule. It doesn't matter if it is not 100% accurate. This exercise is only to help you to visualise the 3-dimensional shapes of molecules.

Do the models help you to have a clearer picture of what the molecules look like? Try to build some more models for other molecules you can think of.

1.11 Oxidation numbers

ESBW

When reactions occur, an exchange of electrons takes place. **Oxidation** is the *loss* of electrons from an atom, while **reduction** is the *gain* of electrons by an atom. By giving elements an oxidation number, it is possible to keep track of whether that element is losing or gaining electrons during a chemical reaction. The loss of electrons in one part of the reaction must be balanced by a gain of electrons in another part of the reaction.

Tip

You can remember this by using OiLRiG: Oxidation is Loss Reduction is Gain.

DEFINITION: Oxidation number

Oxidation number is the charge an atom would have if it was in a compound composed of ions.

There are a number of rules that you need to know about oxidation numbers, and these are listed below. These will probably not make much sense at first, but once you have worked through some examples, you will soon start to understand!

Rule 1 : An element always has an oxidation number of zero, since it is neutral.

In the reaction $H_2 + Br_2 \rightarrow 2HBr$, the oxidation numbers of hydrogen and bromine on the left hand side of the equation are both zero.

Rule 2 : In most cases, an atom that is part of a molecule will have an oxidation number that has the same numerical value as its valency.

Rule 3 : Monatomic ions have an oxidation number that is equal to the charge on the ion.

The chloride ion Cl^- has an oxidation number of -1, and the magnesium ion Mg^{2+} has an oxidation number of $+2$.

Rule 4 : In a molecule, the oxidation number for the whole molecule will be zero, unless the molecule has a charge, in which case the oxidation number is equal to the charge.

Rule 5 : Use a table of electronegativities to determine whether an atom has a positive or a negative oxidation number. For example, in a molecule of water, oxygen has a higher electronegativity so it must be negative because it attracts electrons more strongly. It will have a negative oxidation number (-2). Hydrogen will have a positive oxidation number ($+1$).

Rule 6 : An oxygen atom usually has an oxidation number of -2, although there are some cases where its oxidation number is -1.

Rule 7 : The oxidation number of hydrogen is usually $+1$. There are some exceptions where its oxidation number is -1.

Rule 8 : The oxidation number of the halogens is -1.

Tip

You will notice that the oxidation number of an atom is usually the same as its valency. Whether an oxidation number is positive or negative, is determined by the electronegativities of the atoms involved.

Example 16: Oxidation numbers I

QUESTION

Give the oxidation numbers for all the atoms in the reaction between sodium and chlorine to form sodium chloride.

$$2Na + Cl_2 \rightarrow 2NaCl$$

SOLUTION

Step 1 : ***Determine which atom will have a positive or negative oxidation number***
Sodium will have a positive oxidation number and chlorine will have a negative oxidation number.

Step 2 : ***Determine the oxidation number for each atom***
Sodium (group 1) will have an oxidation number of $+1$. Chlorine (group 17) will have an oxidation number of -1.

Step 3 : ***Check whether the oxidation numbers add up to the charge on the molecule***
In the equation $2Na + Cl_2 \rightarrow 2NaCl$, the overall charge on the NaCl molecule is $+1 - 1 = 0$. This is correct since NaCl is neutral. This means that, in a molecule of NaCl, sodium has an oxidation number of $+1$ and chlorine has an oxidation

number of -1. The oxidation numbers for sodium and chlorine (on the left hand side of the equation) are zero since these are elements.

Example 17: *Oxidation numbers II*

QUESTION

Give the oxidation numbers for all the atoms in the reaction between hydrogen and oxygen to produce water. The unbalanced equation is shown below:

$$H_2 + O_2 \rightarrow H_2O$$

SOLUTION

Step 1 : ***Determine which atom will have a positive or negative oxidation number***
Hydrogen will have a positive oxidation number and oxygen will have a negative oxidation number.

Step 2 : ***Determine the oxidation number for each atom***
Hydrogen (group 1) will have an oxidation number of $+1$. Oxygen (group 16) will have an oxidation number of -2.

Step 3 : ***Check whether the oxidation numbers add up to the charge on the molecule***
In the reaction $H_2 + O_2 \rightarrow H_2O$, the oxidation numbers for hydrogen and oxygen (reactants, left hand side of the equation) are zero since these are elements. In the water molecule (product), the sum of the oxidation numbers is $2(+1) - 2 = 0$. This is correct since the oxidation number of water is zero. Therefore, in water, hydrogen has an oxidation number of $+1$ and oxygen has an oxidation number of -2.

Example 18: *Oxidation numbers III*

QUESTION

Give the oxidation number of sulphur in a sulphate (SO_4^{2-}) ion

SOLUTION

Step 1 : ***Determine which atom will have a positive or negative oxidation number***
Sulphur has a positive oxidation number and oxygen will have a negative oxidation number.

Step 2 : ***Determine the oxidation number for each atom***
Oxygen (group 16) will have an oxidation number of -2. The oxidation number of sulphur at this stage is uncertain.

Step 3 : ***Determine the oxidation number of sulphur by using the fact that the oxidation numbers of the atoms must add up to the charge on the molecule***
In the polyatomic SO_4^{2-} ion, the sum of the oxidation numbers must be -2. Since there are four oxygen atoms in the ion, the total charge of the oxygen is -8. If the overall charge of the ion is -2, then the oxidation number of sulphur must be $+6$.

Exercise 1 - 7

1. Give the oxidation numbers for each element in the following chemical compounds:
   (a) NO_2
   (b) $BaCl_2$
   (c) H_2SO_4
2. Give the oxidation numbers for the reactants and products in each of the following reactions:
   (a) $C + O_2 \rightarrow CO_2$
   (b) $N_2 + 3H_2 \rightarrow 2NH_3$
   (c) Magnesium metal burns in oxygen

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(1.) 00vr (2.) 00vs

Chapter 1 — Summary

See the summary presentation (Presentation: VPgyp at www.everythingscience.co.za)

- A **chemical bond** is the physical process that causes atoms and molecules to be attracted together and to be bound in new compounds.
- Atoms are more **reactive**, and therefore more likely to bond, when their outer electron orbitals are not full. Atoms are less reactive when these outer orbitals contain the maximum number of electrons. This explains why the noble gases do not combine to form molecules.
- There are a number of **forces** that act between atoms: attractive forces between the positive nucleus of one atom and the negative electrons of another; repulsive forces between like-charged electrons, and repulsion between like-charged nuclei.
- Chemical bonding occurs when the **energy** of the system is at its lowest.
- **Bond length** is the distance between the nuclei of the atoms when they bond.

- **Bond energy** is the energy that must be added to the system for the bonds to break.
- When atoms bond, electrons are either shared or exchanged.
- **Covalent bonding** occurs between the atoms of non-metals and involves a sharing of electrons so that the orbitals of the outermost energy levels in the atoms are filled.
- The **valency** of an atom is the number of electrons in the outer shell of that atom and valence electrons are able to form bonds with other atoms.
- A **double** or **triple bond** occurs if there are two or three electron pairs that are shared between the same two atoms.
- A **dative covalent bond** is a bond between two atoms in which both the electrons that are shared in the bond come from the same atom.
- **Lewis** and **Couper** notation are two ways of representing molecular structure. In Lewis notation, dots and crosses are used to represent the valence electrons around the central atom. In Couper notation, lines are used to represent the bonds between atoms.
- **Electronegativity** measures how strongly an atom draws electrons to it.
- Electronegativity can be used to explain the difference between two types of covalent bonds: **polar covalent bonds** (between non-identical atoms) and **non-polar covalent bonds** (between identical atoms).
- An **ionic bond** occurs between atoms where the difference in electronegativity is greater than 1.7. An exchange of electrons takes place and the atoms are held together by the electrostatic force of attraction between oppositely-charged ions.
- Ionic solids are arranged in a **crystal lattice** structure.
- Ionic compounds have a number of specific **properties**, including their high melting and boiling points, brittle nature, the lattice structure of solids and the ability of ionic solutions to conduct electricity.
- A **metallic bond** is the electrostatic attraction between the positively charged nuclei of metal atoms and the delocalised electrons in the metal.
- Metals also have a number of properties, including their ability to conduct heat and electricity, their metallic lustre, the fact that they are both malleable and ductile, and their high melting point and density.
- The valency of atoms, and the way they bond, can be used to determine the **chemical formulae** of compounds.
- The **shape of molecules** can be predicted using the VSEPR theory, which uses the arrangement of electrons around the central atom to determine the most likely shape of the molecule.
- **Oxidation numbers** are used to determine whether an atom has gained or lost electrons during a chemical reaction.

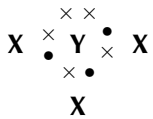
Chapter 1 End of Chapter Exercises

1. Give **one word/term** for each of the following descriptions.
   (a) The distance between two atoms in a molecule

(b) A type of chemical bond that involves the transfer of electrons from one atom to another.

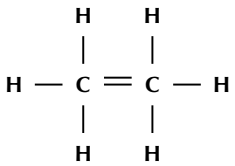
(c) A measure of an atom's ability to attract electrons to it.

2. Which ONE of the following best describes the bond formed between an H^+ ion and the NH_3 molecule?
   (a) Covalent bond
   (b) Dative covalent (coordinate covalent) bond
   (c) Ionic Bond
   (d) Hydrogen Bond
3. Explain the meaning of each of the following terms:
   (a) valency
   (b) bond energy
   (c) covalent bond
4. Which of the following reactions will *not* take place? Explain your answer.
   (a) $H + H \rightarrow H_2$
   (b) $Ne + Ne \rightarrow Ne_2$
   (c) $Cl + Cl \rightarrow Cl_2$
5. Draw the Lewis structure for each of the following:
   (a) calcium
   (b) iodine (Hint: Which group is it in? It will be similar to others in that group)
   (c) hydrogen bromide (HBr)
   (d) nitrogen dioxide (NO_2)
6. Given the following Lewis structure, where X and Y each represent a different element:

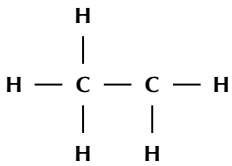


   (a) What is the valency of X?
   (b) What is the valency of Y?
   (c) Which elements could X and Y represent?
7. A molecule of ethane has the formula C_2H_6. Which of the following diagrams (Couper notation) accurately represents this molecule?

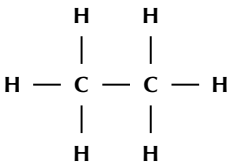
(a)



(b)



(c)



8. Potassium dichromate is dissolved in water.

(a) Give the name and chemical formula for each of the ions in solution.
(b) What is the chemical formula for potassium dichromate?
(c) Give the oxidation number for each element in potassium dichromate.

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(1.) 00vt (2.) 00vu (3.) 00vv (4.) 00vw (5.) 00vx (6.) 00vy
(7.) 00vz (8.) 00w0

Intermolecular Forces 2

In the previous chapter, we discussed the different forces that exist *between atoms* (intramolecular forces). When atoms are joined to one another they form molecules, and these molecules in turn have forces that bind them together. These forces are known as **intermolecular forces**, and we are going to look at them in more detail in this next section.

See introductory video: VPhgb at www.everythingscience.co.za

> *DEFINITION: Intermolecular forces*
>
> Intermolecular forces are forces that act between stable molecules.

You will also recall from the previous chapter, that we can describe molecules as being either **polar** or **non-polar**. A polar molecule is one in which there is a difference in electronegativity between the atoms in the molecule, such that the shared electron pair spends more time close to the atom that attracts it more strongly. The result is that one end of the molecule will have a slightly positive charge (δ^+), and the other end will have a slightly negative charge (δ^+). The molecule is said to be a **dipole**. However, it is important to remember that just because the bonds within a molecule are polar, the molecule itself may not necessarily be polar. The shape of the molecule may also affect its polarity. A few examples are shown in Table 2.1 to refresh your memory!

Table 2.1: Polarity in molecules with different atomic bonds and molecular shapes

Molecule	**Chemical formula**	**Bond between atoms**	**Shape of molecule**	**Polarity of molecule**
Hydrogen	H_2	Covalent	Linear molecule **H** ——— **H**	Non-polar
Hydrogen chloride	HCl	Polar covalent	Linear molecule $\mathbf{H}^{\delta+}$ ——— $\mathbf{Cl}^{\delta-}$	Polar
Carbon tetrafluoride	CF_4	Polar covalent	Tetrahedral molecule $F^{\delta-}$ | $F^{\delta-}$ — $C^{\delta+}$ — $F^{\delta-}$ | $F^{\delta-}$	Non-polar

2.1 Types of Intermolecular Forces

ESBX

It is important to be able to recognise whether the molecules in a substance are polar or non-polar because this will determine what type of intermolecular forces there are. This is important in explaining the properties of the substance.

1. **Van der Waals forces**

   These intermolecular forces are named after a Dutch physicist called Johannes van der Waals (1837 -1923), who recognised that there were weak attractive and repulsive forces between the molecules of a gas, and that these forces caused gases to deviate from 'ideal gas' behaviour. Van der Waals forces are *weak* intermolecular forces, and can be divided into three types:

   (a) *Dipole-dipole forces*

   Figure 2.1 shows a simplified dipole molecule, with one end slightly positive and the other slightly negative.

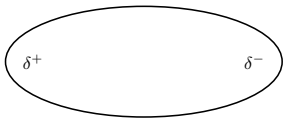

Figure 2.1: A simplified diagram of a dipole molecule

When one dipole molecule comes into contact with another dipole molecule, the positive pole of the one molecule will be attracted to the negative pole of the other, and the molecules will be held together in this way (Figure 2.2). Examples of materials/substances that are held together by dipole-dipole forces are HCl, FeS, KBr, SO_2 and NO_2.

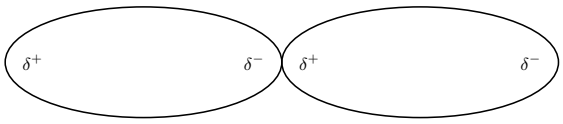

Figure 2.2: Two dipole molecules are held together by the attractive force between their oppositely charged poles

   (b) *Ion-dipole forces*

   As the name suggests, this type of intermolecular force exists between an ion and a dipole molecule. You will remember that an *ion* is a charged atom, and this will be attracted to one of the charged ends of the polar molecule. A positive ion will be attracted to the negative pole of the polar molecule, while a negative ion will be attracted to the positive pole of the polar molecule. This can be seen when sodium chloride (NaCl) dissolves in water. The positive sodium ion (Na^+) will be attracted to the slightly negative oxygen atoms in the water molecule, while the negative chloride ion (Cl^-) is attracted to the slightly positive hydrogen atom. These intermolecular forces weaken the ionic bonds between the sodium and chloride ions so that the sodium chloride dissolves in the water (Figure 2.3).

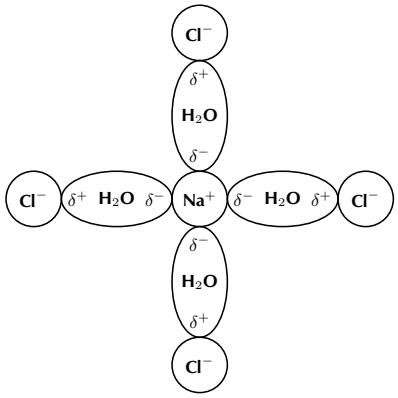

Figure 2.3: Ion-dipole forces in a sodium chloride solution

(c) *London forces*

These intermolecular forces are also sometimes called 'dipole- induced dipole' or 'momentary dipole' forces. Not all molecules are polar, and yet we know that there are also intermolecular forces between non-polar molecules such as carbon dioxide. In non-polar molecules the electronic charge is evenly distributed but it is possible that at a particular moment in time, the electrons might not be evenly distributed. The molecule will have a *temporary dipole*. In other words, each end of the molecules has a slight charge, either positive or negative. When this happens, molecules that are next to each other attract each other very weakly. These London forces are found in the halogens (e.g. F_2 and I_2), the noble gases (e.g. Ne and Ar) and in other non-polar molecules such as carbon dioxide and methane.

2. **Hydrogen bonds**

As the name implies, this type of intermolecular bond involves a hydrogen atom. The hydrogen must be attached to another atom that is strongly electronegative, such as oxygen, nitrogen or fluorine. Water molecules for example, are held together by hydrogen bonds between the hydrogen atom of one molecule and the oxygen atom of another (Figure 2.4). Hydrogen bonds are stronger than van der Waals forces. It is important to note however, that both van der Waals forces and hydrogen bonds are weaker than the covalent and ionic bonds that exist between *atoms*.

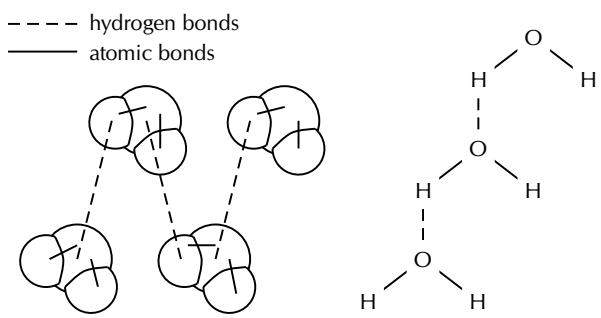

Figure 2.4: Two representations showing the hydrogen bonds between water molecules: space-filling model and structural formula.

Exercise 2 - 1

1. Complete the following table by placing a tick to show which type of intermolecular force occurs in each substance:

Formula	Dipole-dipole	Momentary dipole	Ion-dipole	hydrogen bond
HCl				
CO_2				
I_2				
H_2O				
KI(aq)				
NH_3				

In which of the substances are the intermolecular forces:

(a) strongest

(b) weakest

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(1.) 00wf

2.2 Understanding intermolecular forces

ESBY

The types of intermolecular forces that occur in a substance will affect its properties, such as its **phase**, **melting point** and **boiling point**. You should remember, if you think back to the kinetic theory of matter, that the *phase* of a substance is determined by how strong the forces are between its particles. The weaker the forces, the more likely the substance is to exist as a gas because the particles are able to move far apart since they are not held together very strongly. If the forces are very strong, the particles are held closely together in a solid structure. Remember also that the *temperature* of a material affects the energy of its particles. The more energy the particles have, the more likely they are to be able to overcome the forces that are holding them together. This can cause a change in phase.

DEFINITION: Boiling point

The temperature at which a material will change from a liquid to a gas.

DEFINITION: Melting point

The temperature at which a material will change from a solid to a liquid.

Formula	**Formula mass**	**Melting point** (°C)	**Boiling point** (°C) at 1 atm
He	4	-270	-269
Ne	20	-249	-246
Ar	40	-189	-186
F_2	38	-220	-188
Cl_2	71	-101	-35
Br_2	160	-7	58
NH_3	17	-78	-33
H_2O	18	0	100
HF	20	-83	20

Table 2.2: Melting point and boiling point of a number of chemical substances

Now look at the data in Table 2.2.

The melting point and boiling point of a substance, give us information about the *phase* of the substance at room temperature, and the *strength of the intermolecular forces*. The examples below will help to explain this.

Example 1: Fluorine (F_2)

Phase at room temperature

Fluorine (F_2) has a melting point of $-220°$C and a boiling point of $-188°$C. This means that for any temperature that is greater than $-188°$C, fluorine will be a gas. At temperatures below $-220°$C, fluorine would be a solid, and at any temperature in between these two, fluorine will be a liquid. So, at room temperature ($25°$), fluorine exists as a gas.

Strength of intermolecular forces

What does this information tell us about the intermolecular forces in fluorine? In fluorine, these forces must be very weak for it to exist as a gas at room temperature. Only at temperatures below $-188°$C will the molecules have a low enough energy that they will come close enough to each other for forces of attraction to act between the molecules. The intermolecular forces in fluorine are very weak **van der Waals** forces because the molecules are *non-polar*.

Example 2: Hydrogen fluoride (HF)

Phase at room temperature

For temperatures below $-83°$C, hydrogen fluoride is a solid. Between $-83°$C and $20°$C, it exists as a liquid, and if the temperature is increased above $20°$C, it will become a gas. So on a cool day, a sample of hydrogen fluoride is a liquid and on a warm day it will be a gas!

Strength of intermolecular forces

What does this tell us about the intermolecular forces in hydrogen fluoride? The forces are stronger than those in fluorine, because more energy is needed for hydrogen fluoride to change into the gaseous phase. In other words, more energy is needed for the intermolecular forces to be overcome so that the molecules can move further apart. Intermolecular forces will exist between the hydrogen atom of one molecule of hydrogen fluoride and the fluorine atom of another molecule of hydrogen fluoride. These are **hydrogen bonds**, which are stronger than van der Waals forces.

Now look at water. What do you notice? Luckily for us, water behaves quite differently from the other molecules shown in the table. Imagine if water were like ammonia (NH_3), which is a gas above a temperature of $-33°$C! There would be no liquid water on the planet, and that would mean that no life would be able to survive here. The hydrogen bonds in water are particularly strong and this gives water unique qualities when compared to other molecules with hydrogen bonds. This will be

discussed more in Chapter **??**. You should also note that the strength of the intermolecular forces increases with an increase in formula mass. This can be seen by the increasing melting and boiling points of substances as formula mass increases.

Exercise 2 - 2

Refer to the data in Table 2.2 and then use your knowledge of different types of intermolecular forces to explain the following statements:

1. The boiling point of F_2 is much lower than the boiling point of NH_3
2. At room temperature, many elements exist naturally as gases
3. The boiling point of HF is higher than the boiling point of Cl_2
4. The boiling point of water is much higher than HF, even though they both contain hydrogen bonds

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2.3 Intermolecular forces in liquids ESBZ

Intermolecular forces affect a number of properties in liquids. We will use the example of water to explain this.

- **Surface tension**

  You may have noticed how some insects are able to walk across a water surface, and how leaves float in water. This is because of surface tension. In water, each molecule is held to the surrounding molecules by strong hydrogen bonds. Molecules in the centre of the liquid are completely surrounded by other molecules, so these forces are exerted in all directions. However, molecules at the surface do not have any water molecules above them to pull them upwards. Because they are only pulled sideways and downwards, the water molecules at the surface are held more closely together. This is called **surface tension**.

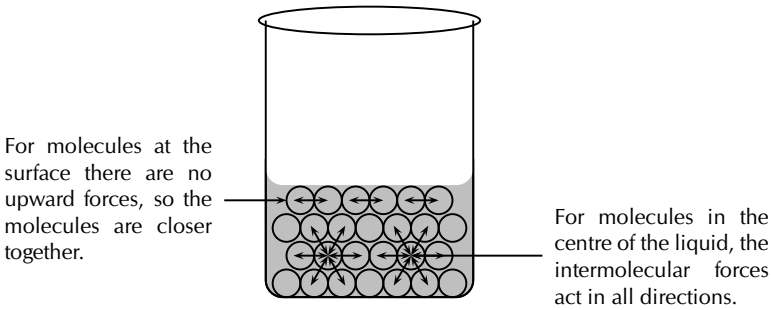


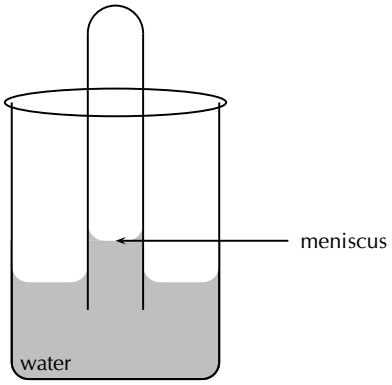
Figure 2.5: Surface tension in a liquid

- **Capillarity**

  Half fill a beaker with water and hold a hollow glass tube in the centre as shown below. Mark the level of the water in the glass tube, and look carefully at the shape of the air-water interface in the tube. What do you notice?

FACT

Transpiration in plants - Did you know that plants also 'sweat'? In plants, this is called *transpiration*, and a plant will lose water through pores in the leaf surface called *stomata*. Although this water loss is important in the survival of a plant, if a plant loses too much water, it will die. Plants that live in very hot, dry places such as deserts, must be specially adapted to reduce the amount of water that transpires (evaporates) from their leaf surface. Desert plants have some amazing adaptations to deal with this problem! Some have hairs on their leaves, which reflect sunlight so that the temperature is not as high as it would be, while others have a thin waxy layer covering their leaves, which reduces water loss. Some plants are even able to close their stomata during the day when temperatures (and therefore transpiration) are highest.



At the air-water interface, you will notice a **meniscus**, where the water appears to dip in the centre. In the glass tube, the attractive forces between the glass and the water are stronger than the intermolecular forces between the water molecules. This causes the water to be held more closely to the glass, and a meniscus forms. The forces between the glass and the water also mean that the water can be 'pulled up' higher when it is in the tube than when it is in the beaker. Capillarity is the surface tension that occurs in liquids that are inside narrow tubes.

- **Evaporation**

  In a liquid, each particle has kinetic energy, but some particles will have more energy than others. We therefore refer to the *average* kinetic energy of the molecules when we describe the liquid. When the liquid is heated, those particles which have the highest energy will be able to overcome the intermolecular forces holding them in the liquid phase, and will become a gas. This is called **evaporation**. Evaporation occurs when a liquid changes to a gas. The stronger the intermolecular forces in a liquid, the higher the temperature of the molecules will have to be for it to become a gas. You should note that a liquid doesn't necessarily have to reach boiling point before evaporation can occur. Evaporation can take place all the time. You will see this if you leave a glass of water outside in the sun. Over a period of time, the water level slowly drops.

  What happens then to the molecules of water that remain in the liquid? Remember that it was the molecules with the highest energy that left the liquid. This means that the average kinetic energy of the remaining molecules will decrease, and so will the *temperature* of the liquid.

  A similar process takes place when a person sweats during exercise. When you exercise, your body temperature increases and you begin to release moisture (sweat) through the pores in your skin. The sweat quickly evaporates and causes the temperature of your skin to drop. This helps to keep your body temperature at a level that is suitable for it to function properly.

In the same way that intermolecular forces affect the properties of liquids, they also affect the properties of solids. For example, the stronger the intermolecular forces between the particles that make up the solid, the *harder* the solid is likely to be, and the higher its *melting point* is likely to be.

Chapter 2 — Summary

See the summary presentation (▶ Presentation: VPhgi at www.everythingscience.co.za)

- **Intermolecular forces** are the forces that act between stable molecules.
- The **type** of intermolecular force in a substance, will depend on the **nature of the molecules**.
- **Polar molecules** have an unequal distribution of charge, meaning that one part of the molecule is slightly positive and the other part is slightly negative. **Non-polar molecules** have an equal distribution of charge.

- There are three types of **Van der Waal's forces**. These are dipole-dipole, ion-dipole and London forces (momentary dipole).
- **Dipole-dipole** forces exist between two **polar molecules**, for example between two molecules of hydrogen chloride.
- **Ion-dipole** forces exist between **ions and dipole molecules**. The ion is attracted to the part of the molecule that has an opposite charge to its own. An example of this is when an ionic solid such as sodium chloride dissolves in water.
- **Momentary dipole** forces occur between two **non-polar molecules**, where at some point there is an unequal distribution of charge in the molecule. For example, there are London forces between two molecules of carbon dioxide.
- **Hydrogen bonds** occur between **hydrogen atoms** and other **atoms that have a high electronegativity** such as oxygen, nitrogen and fluorine. The hydrogen atom in one molecule will be attracted to the nitrogen atom in another molecule, for example. There are hydrogen bonds between water molecules and between ammonia molecules.
- Intermolecular forces affect the **properties** of substances. For example, the stronger the intermolecular forces, the higher the **melting point** of that substance, and the more likely that substance is to exist as a solid or liquid. Its **boiling point** will also be higher.
- In **liquids**, properties such as **surface tension**, **capillarity** and **evaporation** are the result of intermolecular forces.

Chapter 2 End of Chapter Exercises

1. Give one word or term for each of the following descriptions:
   (a) The tendency of an atom in a molecule to attract bonding electrons.
   (b) A molecule that has an unequal distribution of charge.
   (c) A charged atom.
2. The following table gives the melting points of various hydrides:

Hydride	**Melting point** (°C)
HI	-50
NH_3	-78
H_2S	-83
CH_4	-184

   In which of these hydrides does hydrogen bonding occur?
   (a) HI only
   (b) NH_3 only
   (c) HI and NH_3 only
   (d) HI, NH_3 and H_2S
   (IEB Paper 2, 2003)
3. Refer to the list of substances below:

$$HCl,\ Cl_2,\ H_2O,\ NH_3,\ N_2,\ HF$$

   Select the true statement from the list below:
   (a) NH_3 is a non-polar molecule
   (b) The melting point of NH_3 will be higher than for Cl_2

(c) Ion-dipole forces exist between molecules of HF

(d) At room temperature N_2 is usually a liquid

4. The respective boiling points for four chemical substances are given below:

   Hydrogen sulphide $-60°C$

   Ammonia $-33°C$

   Hydrogen fluoride $20°C$

   Water $100°C$

   (a) Which one of the substances exhibits the strongest forces of attraction between its molecules in the liquid state?

   (b) Give the name of the force responsible for the relatively high boiling points of ammonia and water and explain how this force originates.

   (c) The shapes of the molecules of hydrogen sulfide and water are similar, yet their boiling points differ. Explain.

   (IEB Paper 2, 2002)

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(1.) 00wh (2.) 00wi (3.) 00wj (4.) 01xy

Solutions and solubility 3

We are surrounded by different types of solutions in our daily lives. Any solution is made up of a **solute** and a **solvent**. A **solute** is a substance that dissolves in a solvent. In the case of a sodium chloride (NaCl) solution, the sodium chloride crystals are the solute. A **solvent** is the substance in which the solute dissolves. In the case of the NaCl solution, the solvent would be the water. In most cases, there is always more of the solvent than there is of the solute in a solution.
See introductory video: VPhgw at www.everythingscience.co.za

> *DEFINITION: Solutes and solvents*
>
> A **solute** is a substance that is dissolved in another substance. A solute can be a solid, liquid or gas. A **solvent** is the liquid that dissolves a solid, liquid, or gaseous solute.

3.1 Types of solutions

ESBAA

When a solute is mixed with a solvent, a *mixture* is formed, and this may be either *heterogeneous* or *homogeneous*. If you mix sand and water for example, the sand does not dissolve in the water. This is a **heterogeneous** mixture. (Hetero is Greek for different). When you mix salt and water, the resulting mixture is **homogeneous** because the solute has dissolved in the solvent. (Homo is Greek for the same).

> *DEFINITION: Solution*
>
> A solution is a homogeneous mixture that consists of a solute that has been dissolved in a solvent.

A solution then is a homogeneous mixture of a solute and a solvent. Examples of solutions are:

- A *solid solute* dissolved in a *liquid solvent* e.g. sodium chloride dissolved in water.
- A *gas solute* dissolved in a *liquid solvent* e.g. carbon dioxide dissolved in water (fizzy drinks) or oxygen dissolved in water (aquatic ecosystems).
- A *liquid solute* dissolved in a *liquid solvent* e.g. ethanol in water.
- A *solid solute* in a *solid solvent* e.g. metal alloys.
- A *gas solute* in a *gas solvent* e.g. the homogeneous mixture of gases in the air that we breathe.

While there are many different types of solutions, most of those we will be discussing are *liquids*.

3.2 Forces and solutions

ESBAB

An important question to ask is why some solutes dissolve in certain solvents and not in others. The answer lies in understanding the interaction between the intramolecular and intermolecular forces between the solute and solvent particles.

General experiment: Solubility

Aim: To investigate the solubility of solutes in different solvents.
Apparatus: Salt (NaCl), vinegar (CH_3CHOOH), iodine (I_2) (CAUTION! Iodine stains the skin.) , ethanol (CH_3CH_2OH)
Method:

1. Mix half a teaspoon of salt in 100 cm^3 of water
2. Mix half a teaspoon of vinegar (acetic acid) in 100 cm^3 of water
3. Mix a few grains of iodine in ethanol
4. Mix a few grains of iodine in 100 cm^3 of water

Results: Record your observations in the table below:

Solute	Polar, non-polar or ionic solute	Solvent	Polar, non-polar or ionic solvent	Does the solute dissolve?
Iodine		Ethanol		
Iodine		Water		
Vinegar		Water		
Salt		Water		

You should have noticed that in some cases, the solute dissolves in the solvent, while in other cases it does not.
Conclusions: In general, polar and ionic solutes dissolve well in polar solvents, while non-polar solutes dissolve well in non-polar solvents. An easy way to remember this is that 'like dissolves like', in other words, if the solute and the solvent have similar intermolecular forces, there is a high possibility that dissolution will occur. This will be explained in more detail below.

- **Non-polar solutes and non-polar solvents** (e.g. iodine and ether)

  Iodine molecules are non-polar, and the forces between the molecules are weak van der Waals forces. There are also weak van der Waals forces between ether molecules. Because the intermolecular forces in both the solute and the solvent are similar, it is easy for these to be broken in the solute, allowing the solute to move into the spaces between the molecules of the solvent. The solute dissolves in the solvent.

- **Polar and ionic solutes and polar solvents** (e.g. salt and water)

  There are strong electrostatic forces between the ions of a salt such as sodium chloride. There are also strong hydrogen bonds between water molecules. Because the strength of the intermolecular forces in the solute and solvent are similar, the solute will dissolve in the solvent.

3.3 Solubility

ESBAC

You may have noticed sometimes that, if you try to dissolve sodium chloride (or some other solute) in a small amount of water, it will initially dissolve, but then appears not to be able to dissolve any further when you keep adding more solute to the solvent. This is called the **solubility** of the solution. Solubility refers to the maximum amount of solute that will dissolve in a solvent under certain conditions.

> *DEFINITION: Solubility*
>
> Solubility is the ability of a given substance, the solute, to dissolve in a solvent. If a substance has a high solubility, it means that lots of the solute is able to dissolve in the solvent.

So what factors affect solubility? Below are some of the factors that affect solubility:

- the quantity of solute and solvent in the solution
- the temperature of the solution
- other compounds in the solvent affect solubility because they take up some of the spaces between molecules of the solvent, that could otherwise be taken by the solute itself
- the strength of the forces between particles of the solute, and the strength of forces between particles of the solvent

See video: VPhmc at www.everythingscience.co.za

General experiment: *Factors affecting solubility*

Aim: To determine the effect of temperature on solubility
Method:

1. Measure 100 cm^3 of water into a beaker
2. Measure 100 g of sodium chloride and place into another beaker
3. Slowly pour the sodium chloride into the beaker with the water, stirring it as you add. Keep adding sodium chloride until you notice that the sodium chloride is not dissolving anymore.
4. Record the amount of sodium chloride that has been added to the water and the temperature of the solution.
5. Now increase the temperature of the water by heating it over a Bunsen burner.
6. Repeat the steps above so that you obtain the solubility limit of salt at this higher temperature.
7. Continue to increase the temperature as many times as possible and record your results.

Results: Record your results in the table below:

Temp (°C)	**Amount of solute that dissolves in 100 cm^3 of water** (g)

As you increase the temperature of the water, are you able to dissolve *more* or *less* sodium chloride?

Conclusions: As the temperature of the solution increases, so does the amount of sodium chloride that will dissolve. The solubility of sodium chloride increases as the temperature increases.

Exercise 3 - 1

1. The data table below gives the solubility (measured in grams of salt per 100 g water) of a number of different salts at various temperatures. Look at the data and then answer the questions that follow.

	Solubility (g salt per 100 g H_2O)		
Temp (°C)	**KNO_3**	**K_2SO_4**	**NaCl**
0	13.9	7.4	35.7
10	21.2	9.3	35.8
20	31.6	11.1	36.0
30	45.3	13.0	36.2
40	61.4	14.8	36.5
50	83.5	16.5	36.8
60	106.0	18.2	37.3

   (a) On the same set of axes, draw line graphs to show how the solubility of the three salts changes with an increase in temperature.

   (b) Describe what happens to salt solubility as temperature increases. Suggest a reason why this happens.

   (c) Write an equation to show how each of the following salts dissociates in water:

      i. KNO_3

      ii. K_2SO_4

   (d) You are given three beakers, each containing the same amount of water. 5 g KNO_3 is added to beaker 1,5 g K_2SO_4 is added to beaker 2 and 5 g NaCl is added to beaker 3. The beakers are heated over a Bunsen burner until the temperature of their solutions is 60°C.

      i. Which salt solution will have the highest conductivity under these conditions? (Hint: Think of the number of solute ions in solution)

      ii. Explain your answer.

2. Two grade 10 learners, Siphiwe and Ann, wish to separately investigate the solubility of potassium chloride at room temperature.

   On completion of the experiment, their results were as follows:

	Siphiwe's results	Ann's results
Temperature (°C)	15	26
Mass of evaporating basin (g)	65.32	67.55
Mass of evaporating basin + salt solution (g)	125.32	137.55
Mass of evaporating basin + salt (g)	81.32	85.75

(a) Calculate the solubility of potassium chloride, using the data recorded by:
   i. Siphiwe
   ii. Ann

(b) A reference book lists the solubility of potassium chloride as 35.0 g per 100 ml of water at 25°C. Give a reason why you think Ann and Siphiwe each obtained results different from each other and the value in the reference book.

(c) Siphiwe and Ann now expand their investigation and work together. They now investigate the solubility of potassium chloride at different temperatures and in addition they examine the solubility of copper (II) sulfate at these same temperatures. They collect and write up their results as follows:

In each experiment we used 50 ml of water in the beaker. We found the following masses of substance dissolved in the 50 ml of water. At 0°C, mass of potassium chloride is 14.0 g and copper sulphate is 14.3 g. At 10°C, 15.6 g and 17.4 g respectively. At 20°C, 17.3 g and 20.7 g respectively. At 40°C, potassium chloride mass is 20.2 g and copper sulphate is 28.5 g, at 60°C, 23.1 g and 40.0 g and lastly at 80°C, the masses were 26.4 g and 55.0 g respectively.

   i. From the record of data provided above, draw up a neat table to record Siphiwe and Ann's results.
   ii. Identify the dependent and independent variables in their investigation.
   iii. Choose an appropriate scale and plot a graph of these results.
   iv. From the graph, determine:
      A. the temperature at which the solubility of copper sulphate is 50 g per 50 ml of water.
      B. the maximum number of grams of potassium chloride which will dissolve in 100 ml of water at 70°C.

   (IEB Exemplar Paper 2, 2006)

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(1.) 00wq (2.) 00wr

Chapter 3 — Summary

See the summary presentation (Presentation: VPhrm at www.everythingscience.co.za)

- In chemistry, a **solution** is a homogeneous mixture of a solute in a solvent.
- A **solute** is a substance that dissolves in a solvent. A solute can be a solid, liquid or gas.
- A **solvent** is a substance in which a solute dissolves. A solvent can also be a solid, liquid or gas.
- Examples of solutions include salt solutions, metal alloys, the air we breathe and gases such as oxygen and carbon dioxide dissolved in water.
- Not all solutes will dissolve in all solvents. A general rule is: **like dissolves like**. Solutes and solvents that have similar intermolecular forces are more likely to dissolve.
- Polar and ionic solutes will be more likely to dissolve in polar solvents, while non-polar solutes will be more likely to dissolve in polar solvents.
- **Solubility** is the extent to which a solute is able to dissolve in a solvent under certain conditions.

- Factors that affect solubility are the **quantity of solute and solvent**, **temperature**, the **intermolecular forces** in the solute and solvent and **other substances** that may be in the solvent.

Chapter 3 End of Chapter Exercises

1. Give one word or term for each of the following descriptions:
   (a) A type of mixture where the solute has completely dissolved in the solvent.
   (b) A measure of how much solute is dissolved in a solution.
   (c) Forces between the molecules in a substance.
2. Which one of the following will readily dissolve in water?
   (a) I_2(s)
   (b) NaI(s)
   (c) CCl_4(l)
   (d) $BaSO_4$(s)

   (IEB Paper 2, 2005)
3. In which of the following pairs of substances will the dissolving process happen most readily?

	Solute	**Solvent**
A	S_8	H_2O
B	KCl	CCl_4
C	KNO_3	H_2O
D	NH_4Cl	CCl_4

   (IEB Paper 2, 2004)
4. Which one of the following three substances is the most soluble in pure water at room temperature?

   Hydrogen sulphide, ammonia and hydrogen fluoride
5. Briefly explain in terms of intermolecular forces why solid iodine does not dissolve in pure water, yet it dissolves in xylene (a non-polar, organic liquid) at room temperature.

   (IEB Paper 2, 2002)

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(1.) 00x4 (2.) 00x5 (3.) 00x6 (4.) 00x7 (5.) 01xz

Atomic Nuclei 4

Nuclear physics is the branch of physics which deals with the **nucleus** of the atom. Within this field, some scientists focus their attention on looking at the *particles* inside the nucleus and understanding how they interact, while others classify and interpret the *properties* of nuclei. This detailed knowledge of the nucleus makes it possible for *technological advances* to be made. In this next chapter, we are going to touch on each of these different areas within the field of nuclear physics.
See introductory video: VPhtu at www.everythingscience.co.za

4.1 Nuclear structure and stability

ESBAD

You will remember from grade 10 that an atom is made up of different types of particles, each with a different charge: protons (positive charge) neutrons (neutral) and electrons (negative charge). The nucleus is the part of the atom that contains the protons and the neutrons, while the electrons are found in energy orbitals around the nucleus. The protons and neutrons together are called **nucleons**. It is the nucleus that makes up most of an atom's *atomic mass*, because an electron has a very small mass when compared with a proton or a neutron.

Within the nucleus, there are different forces which act between the particles. The **strong nuclear force** is the force between two or more nucleons, and this force binds protons and neutrons together inside the nucleus. The **electromagnetic force** causes the repulsion between like-charged (positive) protons. In a way then, these forces are trying to produce opposite effects in the nucleus. The strong nuclear force acts to hold all the protons and neutrons close together, while the electromagnetic force acts to push protons further apart. In atoms where the nuclei are small, the strong nuclear force overpowers the electromagnetic force. However, as the nucleus gets bigger (in elements with a higher number of nucleons), the electromagnetic force becomes greater than the strong nuclear force. In these nuclei, it becomes possible for particles and energy to be ejected from the nucleus. These nuclei are called **unstable**. The particles and energy that a nucleus releases are referred to as **radiation**, and the atom is said to be **radioactive**. We are going to look at these concepts in more detail in the next few sections.

4.2 The Discovery of Radiation

ESBAE

Radioactivity was first discovered in 1896 by a French scientist called Henri Becquerel while he was working on phosphorescent materials. He wrapped a photographic plate in black paper and placed various phosphorescent substances on it. When he used uranium salts he noticed that the film blackened even if it was kept in a dark room. He eventually concluded that some rays must be coming out of the uranium crystals to produce this effect and that these rays were able to pass through the paper.

His observations were taken further by the Polish scientists Marie and Pierre Curie, who increased our knowledge of radioactive elements. In 1903, Henri, Marie and Pierre were awarded the Nobel Prize in Physics for their work on radioactive elements. This award made Marie the first woman ever to receive a Nobel Prize. Marie and Pierre Curie went on to discover two new elements, which they named **polonium** (Po) after Marie's home country, and **radium** (Ra) after its highly radioactive characteristics. For these discoveries, Marie was awarded a Nobel Prize in Chemistry in 1911, making her one of very

FACT

Due to the high levels of radioactivity, Marie Curies papers from the 1890's are considered too dangerous to handle. Even her cookbook is highly radioactive. These documents are kept in lead-lined boxes, and those who wish to consult them must wear protective clothing.

few people to receive two Nobel Prizes.

4.3 Radioactivity and Types of Radiation

ESBAF

In Section 4.1, we discussed that when a nucleus is unstable it can emit particles and energy. This process is called **radioactive decay**.

> *DEFINITION: Radioactive decay*
>
> Radioactive decay is the process in which an unstable atomic nucleus loses energy by emitting particles or electromagnetic waves. These emitted particles or electromagnetic waves are called **radiation**.

When a nucleus undergoes radioactive decay, it emits radiation and the nucleus is said to be radioactive. We are exposed to small amounts of radiation all the time. Even the rocks around us emit radiation! However some elements are far more radioactive than others. Even within a single element, there may be some isotopes that are more radioactive than others simply because they contain a larger number of neutrons. Radioactive isotopes are called **radioisotopes**.

Radiation can be emitted in different forms. There are three main types of radiation: alpha, beta and gamma radiation. These are shown in Figure 4.1, and are described below.

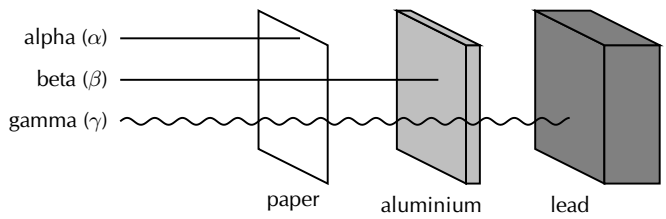


Figure 4.1: Types of radiation

Alpha (α) particles and alpha decay

ESBAG

An alpha particle is made up of two protons and two neutrons bound together. This type of radiation has a *positive charge*. An alpha particle is sometimes represented using the chemical symbol He^{2+}, because it has the same structure as a Helium atom (two neutrons and two protons) ,but without the two electrons to balance the positive charge of the protons, hence the overall charge of $+2$. Alpha particles have a relatively low penetration power. Penetration power describes how easily the particles can pass through another material. Because alpha particles have a *low* penetration power, it means that even something as thin as a piece of paper, or the outside layer of the human skin, will absorb these particles so that they can't penetrate any further.

Alpha decay occurs in nuclei that contain too many protons, which results in strong repulsion forces between these positively charged particles. As a result of these repulsive forces, the nucleus emits an α particle. This can be seen in the decay of americium (Am) to neptunium (Np).

Example:

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

Let's take a closer look at what has happened during this reaction. Americium (Z = 95; A = 241) undergoes α decay and releases one alpha particle (i.e. 2 protons and 2 neutrons). The atom now has only 93 protons (Z = 93). On the periodic table, the element which has 93 protons (Z = 93) is called neptunium. Therefore, the americium atom has become a neptunium atom. The atomic mass of the neptunium atom is 237 (A = 237) because 4 nucleons (2 protons and 2 neutrons) were emitted from the atom of americium.

See simulation: VPhuv at www.everythingscience.co.za)

Beta (β) particles and beta decay

ESBAH

In nuclear physics, β decay is a type of radioactive decay in which a β particle (an electron or a positron) is emitted. In the case of electron emission, it is referred to as beta minus ($\beta-$), while in the case of a positron emission as beta plus ($\beta+$).

An electron and positron have identical physical characteristics except for opposite charge.

In certain types of radioactive nuclei that have too many neutrons, a neutron may be converted into a proton, an electron and another particle called a neutrino. The high energy electrons that are released in this way are the β - particles. This process can occur for an isolated neutron.

In $\beta+$ decay, energy is used to convert a proton into a neutron (n), a positron ($e+$) and a neutrino ($\bar{\nu}$):

$$\text{energy} + p \rightarrow n + e^{+} + \bar{\nu}$$

So, unlike $\beta-$, $\beta+$ decay cannot occur in isolation, because it requires energy, the mass of the neutron being greater than the mass of the proton. $\beta+$ decay can only happen inside nuclei when the value of the binding energy of the mother nucleus is less than that of the daughter nucleus. The difference between these energies goes into the reaction of converting a proton into a neutron, a positron and a neutrino and into the kinetic energy of these particles.

The diagram below shows what happens during β decay:

During beta decay, the number of neutrons in the atom decreases by one, and the number of protons increases by one. Since the number of protons before and after the decay is different, the atom has changed into a different element. In Figure 4.2, hydrogen has become helium. The beta decay of the hydrogen-3 atom can be represented as follows:

$$^{3}_{1}\text{H} \rightarrow ^{3}_{2}\text{He} + \beta \text{ particle} + \bar{\nu}$$

See simulation: VPhwi at www.everythingscience.co.za)

FACT

When scientists added up all the energy from the neutrons, protons and electrons involved in $\beta-$decay, they noticed that there was always some energy missing. We know that energy is always conserved, which led Wolfgang Pauli in 1930 to come up with the idea that another particle, which was not detected yet, also had to be involved in the decay. He called this particle the neutrino (Italian for "little neutral one"), because he knew it had to be neutral, have little or no mass, and interact only very weakly, making it very hard to find experimentally! The neutrino was finally identified experimentally about 25 years after Pauli first thought of it.

Gamma (γ) rays and gamma decay

ESBAI

When particles inside the nucleus collide during radioactive decay, energy is released. This energy can leave the nucleus in the form of waves of electromagnetic energy called gamma rays. Gamma

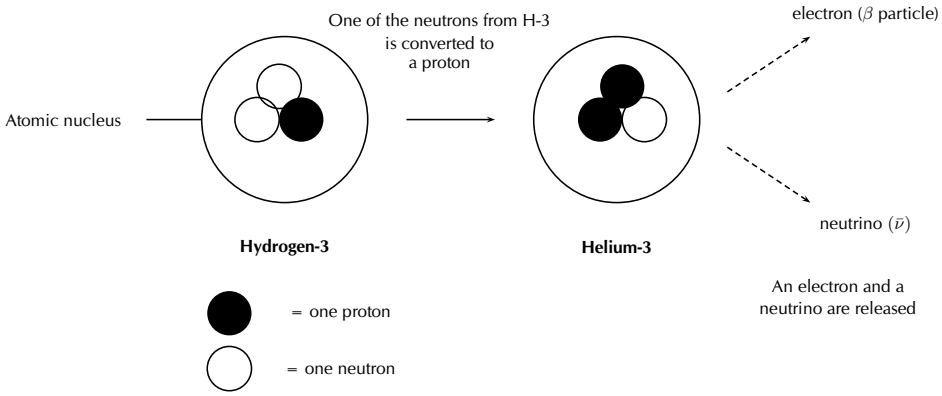


Figure 4.2: β decay in a hydrogen atom

FACT

Due to the radioactive processes inside the sun, each 1 cm^2 patch of the earth receives 70 billion (70×10^9) neutrinos each second! Luckily neutrinos only interact very weakly so they do not harm our bodies when billions of them pass through us every second.

radiation is part of the electromagnetic spectrum, just like visible light. However, unlike visible light, humans cannot see gamma rays because they are at a much higher frequency and a higher energy. Gamma radiation has no mass or charge. This type of radiation is able to penetrate most common substances, including metals. Only substance with high atomic masses (like lead) and high densities (like concrete or granite) are effective at absorbing gamma rays.

Gamma decay occurs if the nucleus is at a very high an energy state. Since gamma rays are part of the electromagnetic spectrum, they can be thought of as waves *or* particles. Therefore in gamma decay, we can think of a ray or a particle (called a photon) being released. The atomic number and atomic mass remain unchanged.

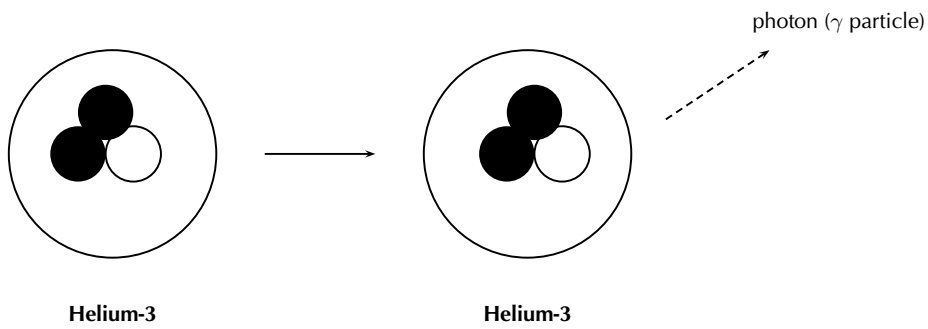


Figure 4.3: γ decay in a helium atom

Table 4.1 summarises and compares the three types of radioactive decay that have been discussed.

Type of decay	**Particle/ray released**	**Change in element**	**Penetration power**
Alpha (α)	α particle (2 protons and 2 neutrons)	Yes	Low
Beta (β)	β particle (electron)	Yes	Medium
Gamma (γ)	γ ray (electromagnetic energy)	No	High

Table 4.1: A comparison of alpha, beta and gamma decay

See video: VPhyr at www.everythingscience.co.za

Example 1: *Radioactive decay*

QUESTION

The isotope $^{241}_{95}$Am undergoes radioactive decay and loses two alpha particles.

1. *Write the chemical formula of the element that is produced as a result of the decay.*
2. *Write an equation for this decay process.*

SOLUTION

Step 1 : ***Work out the number of protons and/or neutrons that the radioisotope loses during radioactive decay***

One α particle consists of two protons and two neutrons. Since two α particles are released, the total number of protons lost is four and the total number of neutrons lost is also four.

Step 2 : ***Calculate the atomic number (Z) and atomic mass number (A) of the element that is formed.***

$$Z = 95 - 4 = 91$$

$$A = 241 - 8 = 233$$

Step 3 : ***Refer to the periodic table to see which element has the atomic number that you have calculated.***

The element that has Z = 91 is protactinium (Pa).

Step 4 : ***Write the symbol for the element that has formed as a result of radioactive decay.***

$$^{233}_{91}\text{Pa}$$

Step 5 : ***Write an equation for the decay process.***

$$^{241}_{95}\text{Am} \rightarrow ^{233}_{91}\text{Pa} + 4 \text{ protons} + 4 \text{ neutrons}$$

Activity: *Radiation*

In groups of 3-4, discuss the following questions:

- Which of the three types of radiation is most dangerous to living creatures (including humans!)
- What can happen to people if they are exposed to high levels of radiation?
- What can be done to protect yourself from radiation (Hint: Think of what a radiologist (person who takes X-rays) does when you go for an X-ray)?

Exercise 4 - 1

1. There are two main forces inside an atomic nucleus:
   (a) Name these two forces.
   (b) Explain why atoms that contain a greater number of nucleons are more likely to be radioactive.
2. The isotope $^{241}_{95}$Am undergoes radioactive decay and loses three alpha particles.
   (a) Write the chemical formula of the element that is produced as a result of the decay.
   (b) How many nucleons does this element contain?
3. Complete the following equation:
   $$^{210}_{82}\text{Pb} \rightarrow \text{(alpha decay)}$$
4. Radium-228 decays by emitting a beta particle. Write an equation for this decay process.
5. Describe how gamma decay differs from alpha and beta decay.

More practice video solutions or help at www.everythingscience.co.za

(1.) 00x8 (2.) 00x9 (3.) 00xa (4.) 00xb (5.) 00xc

4.4 Sources of radiation

ESBAJ

The sources of radiation can be either **natural** or **man-made**.

Natural background radiation

ESBAK

- *Cosmic radiation*

The Earth, and all living things on it, are constantly bombarded by radiation from space. Charged particles from the sun and stars interact with the Earth's atmosphere and magnetic field to produce a shower of radiation, which is mostly beta and gamma radiation. The amount of cosmic radiation varies in different parts of the world because of differences in elevation and also the effects of the Earth's magnetic field.

FACT

Cosmic and terrestrial radiation are not the only natural sources. All people have radioactive potassium-40, carbon-14, lead-210 and other isotopes inside their bodies from birth.

- *Terrestrial Radiation*

  Radioactive material is found throughout nature. It occurs naturally in the soil, water, and vegetation. The major isotopes that are of concern are uranium and the decay products of uranium, such as thorium, radium, and radon. Low levels of uranium, thorium, and their decay products are found everywhere. Some of these materials are ingested (taken in) with food and water, while others are breathed in. The dose of radiation from terrestrial sources varies in different parts of the world.

Man-made sources of radiation

ESBAL

Although all living things are exposed to natural background radiation, there are other sources of radiation. Some of these will affect most members of the public, while others will only affect those people who are exposed to radiation through their work.

- *Members of the public*

  Man-made radiation sources that affect members of the public include televisions, tobacco (polonium-210), combustible fuels, smoke detectors (americium), luminous watches (tritium) and building materials. By far, the most significant source of man-made radiation exposure to the public is from medical procedures, such as diagnostic X-rays, nuclear medicine, and radiation therapy. Some of the major isotopes involved are I $-$ 131, Tc $-$ $99m$, Co $-$ 60, Ir $-$ 192, and Cs $-$ 137. The production of nuclear fuel using uranium is also a source of radiation for the public, as is fallout from nuclear weapons testing or use.

- *Individuals who are exposed through their work*

  Any people who work in the following environments are exposed to radiation at some time: radiology (X-ray) departments, nuclear power plants, nuclear medicine departments, high-energy physics, X-ray crystallography (study of crystal structure) and radiation oncology (the study of cancer) departments. Some of the isotopes that are of concern are cobalt-60, cesium-137, and americium-241

4.5 The 'half-life' of an element

ESBAM

> *DEFINITION: Half-life*
>
> The half-life of an element is the time it takes for half the atoms of a radioisotope to decay into other atoms.

So, in the case of Sr $-$ 90, it will take 28 days for half of the atoms to decay into other atoms. It will take another 28 days for half of the remaining atoms to decay. Let's assume that we have a sample of strontium that weighs 8 g. After the first 28 days there will be:

$$\frac{1}{2} \times 8 \text{ g} = 4 \text{ g Sr} - 90 \text{ left}$$

Radioisotope	Chemical symbol	Half-life
Polonium-212	Po-212	0.16 seconds
Sodium-24	Na-24	15 hours
Strontium-90	Sr-90	28 days
Cobalt-60	Co-60	5.3 years
Caesium-137	Cs-137	30 years
Carbon-14	C-14	5 760 years
Calcium-41	Ca-41	100 000 years
Beryllium-10	Be-10	2 700 000 years
Uranium-235	U-235	7.1 billion years

Table 4.2: The half-life of a number of elements

After 56 days, there will be:

$$\frac{1}{2} \times 4 \text{ g} = 2 \text{ g Sr} - 90 \text{ left}$$

After 84 days, there will be:

$$\frac{1}{2} \times 2 \text{ g} = 1 \text{ g Sr} - 90 \text{ left}$$

If we convert these amounts to a *fraction* of the original sample, then after 28 days $\frac{1}{2}$ of the sample remains undecayed. After 56 days $\frac{1}{4}$ is undecayed and after 84 days, $\frac{1}{8}$ and so on.
See video: VPibv at www.everythingscience.co.za

Activity: *Understanding half-life*

Work in groups of 4-5
You will need:
16 sheets of A4 paper per group, scissors, 2 boxes per group, a marking pen and timer/stopwatch.
What to do:

- Your group should have two boxes. Label one 'decayed' and the other 'radioactive'.
- Take the A4 pages and cut each into 4 pieces of the same size. You should now have 64 pieces of paper. Stack these neatly and place them in the 'radioactive' box. The paper is going to represent some radioactive material.
- Set the timer for one minute. After one minute, remove half the sheets of paper from the radioactive box and put them in the 'decayed' box.
- Set the timer for another minute and repeat the previous step, again removing half the pieces of paper that are left in the radioactive box and putting them in the decayed box.
- Repeat this process until 8 minutes have passed. You may need to start cutting your pieces of paper into even smaller pieces as you progress.

Questions:

1. How many pages were left in the radioactive box after:
   (a) 1 minute
   (b) 3 minutes
   (c) 5 minutes
2. What percentage (%) of the pages were left in the radioactive box after:
   (a) 2 minutes
   (b) 4 minutes
3. After how many minutes is there $\frac{1}{128}$ of radioactive material remaining?
4. What is the half-life of the 'radioactive' material in this exercise?

Example 2: *Half-life 1*

QUESTION

A 100 g sample of Cs − 137 is allowed to decay. Calculate the mass of Cs − 137 that will be left after 90 years

SOLUTION

Step 1 : ***You need to know the half-life of Cs*** -137
The half-life of Cs -137 is 30 years.

Step 2 : ***Determine how many times the quantity of sample will be halved in 90 years.***
If the half-life of Cs -137 is 30 years, and the sample is left to decay for 90 years, then the number of times the quantity of sample will be halved is $\frac{90}{30} = 3$.

Step 3 : ***Calculate the quantity that will be left by halving the mass of Cs*** -137 ***three times***

1. After 30 years, the mass left is $100\text{ g} \times \frac{1}{2} = 50\text{ g}$
2. After 60 years, the mass left is $50\text{ g} \times \frac{1}{2} = 25\text{ g}$
3. After 90 years, the mass left is $25\text{ g} \times \frac{1}{2} = 12.5\text{ g}$

Note that a quicker way to do this calculation is as follows:
Mass left after 90 years $= (\frac{1}{2})^3 \times 100\text{ g} = 12.5\text{ g}$ (The exponent is the number of times the quantity is halved)

Example 3: *Half-life II*

QUESTION

An 80 g sample of Po−212 decays until only 10 g is left. How long did it take for this decay to take place?

SOLUTION

Step 1 : ***Calculate the fraction of the original sample that is left after decay***
Fraction remaining $= \frac{10\text{ g}}{80\text{ g}} = \frac{1}{8}$

Step 2 : ***Calculate how many half-life periods of decay (x) must have taken place for*** $\frac{1}{8}$ ***of the original sample to be left***

$$(\frac{1}{2})^x = \frac{1}{8}$$

Therefore, $x = 3$

Step 3 : ***Use the half-life of Po-212 to calculate how long the sample was left to decay***
The half-life of Po-212 is 0.16 seconds. Therefore if there were three periods of decay, then the total time is 0.16×3. The time that the sample was left to decay is 0.48 seconds.

Exercise 4 - 2

1. Imagine that you have 100 g of Na-24.
   (a) What is the half life of Na-24?
   (b) How much of this isotope will be left after 45 hours?
   (c) What percentage of the original sample will be left after 60 hours?
2. A sample of Sr-90 is allowed to decay. After 84 days, 10 g of the sample remains.
   (a) What is the half life of Sr-90?
   (b) How much Sr-90 was in the original sample?
   (c) How much Sr-90 will be left after 112 days?

More practice video solutions or help at www.everythingscience.co.za

(1.) 00xd (2.) 00xe

4.6 The Dangers of Radiation

ESBAN

Natural radiation comes from a variety of sources such as the rocks, sun and from space. However, when we are exposed to large amounts of radiation, this can cause damage to cells. γ radiation is particularly dangerous because it is able to penetrate the body, unlike α and β particles whose penetration power is less. Some of the dangers of radiation are listed below:

- **Damage to cells**
  Radiation is able to penetrate the body, and also to penetrate the membranes of the cells within our bodies, causing massive damage. *Radiation poisoning* occurs when a person is exposed to large amounts of this type of radiation. Radiation poisoning damages tissues within the body, causing symptoms such as diarrhoea, vomiting, loss of hair and convulsions.
- **Genetic abnormalities**
  When radiation penetrates cell membranes, it can damage chromosomes within the nucleus of the cell. The chromosomes contain all the genetic information for that person. If the chromosomes are changed, this may lead to genetic abnormalities in any children that are born to the person who has been exposed to radiation. Long after the nuclear disaster of Chernobyl in Russia in 1986, babies were born with defects such as missing limbs and abnormal growths.

- **Cancer**

  Small amounts of radiation can cause cancers such as leukemia (cancer of the blood)

4.7 The Uses of Radiation

ESBAO

However, despite the many dangers of radiation, it does have many powerful uses, some of which are listed below:

- **Medical Field**

  Radioactive *chemical tracers* emitting γ rays can give information about a person's internal anatomy and the functioning of specific organs. The radioactive material may be injected into the patient, from where it will target specific areas such as bones or tumours. As the material decays and releases radiation, this can be seen using a special type of camera or other instrument. The radioactive material that is used for this purpose must have a short half-life so that the radiation can be detected quickly and also so that the material is quickly removed from the patient's body. Using radioactive materials for this purpose can mean that a tumour or cancer may be diagnosed long before these would have been detected using other methods such as X-rays.

  Radiation may also be used to sterilise medical equipment.

- **Biochemistry and Genetics**

  Radioisotopes may be used as tracers to label molecules so that chemical processes such as DNA replication or amino acid transport can be traced.

- **Food preservation**

  Irradiation of food can stop vegetables or plants from sprouting after they have been harvested. It also kills bacteria and parasites, and controls the ripening of fruits.

- **Environment**

  Radioisotopes can be used to trace and analyse pollutants.

- **Archaeology and Carbon dating**

  Natural radioisotopes such as C-14 can be used to determine the age of organic remains. All living organisms (e.g. trees, humans) contain carbon. Carbon is taken in by plants and trees through the process of photosynthesis in the form of carbon dioxide and is then converted into organic molecules. When animals feed on plants, they also obtain carbon through these organic compounds. Some of the carbon in carbon dioxide is the radioactive C-14, while the rest is a non-radioactive form of carbon. When an organism dies, no more carbon is taken in and the amount of C-14 in the body stops increasing. From this point onwards, no more C-14 is taken in but C-14 continues its radioactive decay which reduces the amount of C-14 in the body. When scientists uncover remains, they are able to estimate the age of the remains by seeing how much C-14 is left in the body relative to the amount of non-radioactive carbon. The less C-14 there is, the older the remains because radioactive decay must have been taking place for a long time. Because scientists know the exact rate of decay of C-14, they can calculate a relatively accurate estimate of the age of the remains. Carbon dating has been an important tool in building up historical records.

Activity:	*The medical uses of radioisotopes*

Carry out your own research to find out more about the radioisotopes that are used to diagnose diseases in the following parts of the body:

- thyroid gland
- kidneys
- brain

In each case, try to find out:

1. which radioisotope is used
2. what the sources of this radioisotope are
3. how the radioisotope enters the patient's body and how it is monitored

Activity: *Using radiocarbon dating*

Radiocarbon dating has played an important role in uncovering many aspects of South Africa's history. Read the following extract from an article that appeared in Afrol news on 10th February 2007 and then answer the questions that follow.

> The world famous rock art in South Africa's uKhahlamba-Drakensberg, a World Heritage Site, is three times older than previously thought, archaeologists conclude in a new study. The more than 40,000 paintings were made by the San people some 3000 years ago, a new analysis had shown.
>
> Previous work on the age of the rock art in uKhahlamba-Drakensberg concluded it is less than 1,000 years old. But the new study - headed by a South African archaeologist leading a team from the University of Newcastle upon Tyne (UK) and Australian National University in Canberra - estimates the panels were created up to 3,000 years ago. They used the latest radio-carbon dating technology.
>
> The findings, published in the current edition of the academic journal 'South African Humanities', have "major implications for our understanding of how the rock artists lived and the social changes that were taking place over the last three millennia," according to a press release from the British university.

Questions:

1. What is the half-life of carbon-14?
2. In the news article, what role did radiocarbon dating play in increasing our knowledge of South Africa's history?
3. Radiocarbon dating can also be used to analyse the remains of once-living organisms. Imagine that a set of bones are found between layers of sediment and rock in a remote area. A group of archaeologists carries out a series of tests to try to estimate the age of the bones. They calculate that the bones are approximately 23 040 years old.

   What percentage of the original carbon-14 must have been left in the bones for them to arrive at this estimate?

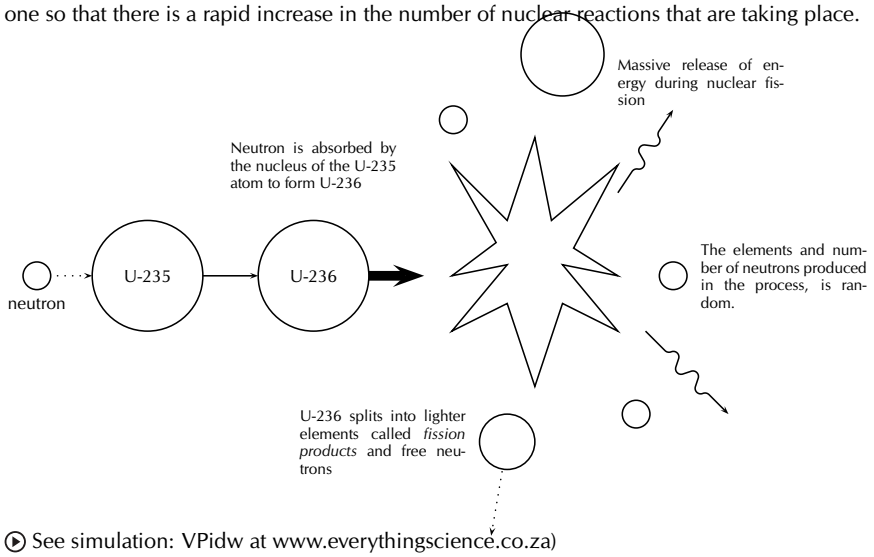
4.8 Nuclear Fission

ESBAP

Nuclear fission is a process where the nucleus of an atom is split into two or more smaller nuclei, known as *fission products*. The fission of heavy elements is an **exothermic reaction** and huge amounts of energy are released in the process. This energy can be used to produce *nuclear power* or to make *nuclear weapons*, both of which we will discuss a little later.

> *DEFINITION: Nuclear fission*
>
> The splitting of an atomic nucleus into smaller nuclei

Below is a diagram showing the nuclear fission of Uranium-235. An atom of Uranium-235 is bombarded with a neutron to initiate the fission process. This neutron is absorbed by Uranium-235, to become Uranium-236. Uranium-236 is highly unstable and breaks down into a number of lighter elements, releasing energy in the process. Free neutrons are also produced during this process, and these are then available to bombard other fissionable elements. This process is known as a **fission chain reaction**, and occurs when one nuclear reaction starts off another, which then also starts off another one so that there is a rapid increase in the number of nuclear reactions that are taking place.



See simulation: VPidw at www.everythingscience.co.za)

The Atomic bomb - an abuse of nuclear fission

ESBAQ

A nuclear chain reaction can happen very quickly, releasing vast amounts of energy in the process. In 1939, it was discovered that uranium could undergo nuclear fission. In fact, it was uranium that was used in the first atomic bomb. The bomb contained large amounts of uranium-235, enough to start a runaway nuclear fission chain reaction. Because the process was uncontrolled, the energy from the fission reactions was released in a matter of *seconds*, resulting in the massive explosion of that first bomb. Since then, more atomic bombs have been detonated, causing massive destruction and loss of life.

Activity:	*Nuclear weapons testing - an ongoing issue*

Read the article below which has been adapted from one that appeared in 'The Globe' in Washington on 10th October 2006, and then answer the questions that follow.

> US officials and arms control specialists warned yesterday that North Korea's test of a small nuclear device could start an arms race in the region and threaten the landmark global treaty designed nearly four decades ago to halt the spread of nuclear weapons. US officials expressed concern that North Korea's neighbours, including

Japan, Taiwan, and South Korea, could eventually decide to develop weapons of their own. They also fear that North Korea's moves could embolden Iran, and that this in turn could encourage Saudi Arabia or other neighbours in the volatile Middle East to one day seek nuclear deterrents, analysts say.

North Korea is the first country to conduct a nuclear test after pulling out of the Nuclear Nonproliferation Treaty. The treaty, which was created in 1968, now includes 185 nations (nearly every country in the world). Under the treaty, the five declared nuclear powers at the time (United States, the Soviet Union, France, China, and Great Britain) agreed to reduce their supplies of nuclear weapons. The treaty has also helped to limit the number of new nuclear weapons nations.

But there have also been serious setbacks. India and Pakistan, which never signed the treaty, became new nuclear powers, shocking the world with test explosions in 1998. The current issue of nuclear weapons testing in North Korea, is another such setback and a blow to the treaty.

Group discussion questions:

1. Discuss what is meant by an 'arms race' and a 'treaty'.
2. Do you think it is important to have such treaties in place to control the testing and use of nuclear weapons? Explain your answer.
3. Discuss some of the reasons why countries might not agree to be part of a nuclear weapons treaty.
4. How would you feel if South Africa decided to develop its own nuclear weapons?

Nuclear power - harnessing energy

ESBAR

However, nuclear fission can also be carried out in a controlled way in a *nuclear reactor*. A nuclear reactor is a piece of equipment where nuclear chain reactions can be started in a controlled and sustained way. This is different from a nuclear *explosion* where the chain reaction occurs in seconds. The most important use of nuclear reactors at the moment is to produce **electrical power**, and most of these nuclear reactors use nuclear fission. A **nuclear fuel** is a chemical isotope that can keep a fission chain reaction going. The most common isotopes that are used are uranium-235 and plutonium-239. The amount of free energy that is in nuclear fuels is far greater than the energy in a similar amount of other fuels such as gasoline. In many countries, nuclear power is seen as a relatively environmentally friendly alternative to fossil fuels, which release large amounts of greenhouse gases, and are also non-renewable resources. However, one of the concerns around the use of nuclear power is the production of *nuclear waste*, which contains radioactive chemical elements.

Activity: *Nuclear Power*

The use of nuclear power as a source of energy has been a subject of much debate. There are many advantages of nuclear power over other energy sources. These include the large amount of energy that can be produced at a small plant, little atmospheric pollution and the small quantity of waste. However there are also disadvantages. These include the expense of maintaining nuclear power stations, the huge impact that an accident could have as well as the disposal of dangerous nuclear waste.

Use these ideas as a starting point for a class debate.

Nuclear power - An energy alternative or environmental hazard?

Your teacher will divide the class into teams. Some of the teams will be 'pro' nuclear power while the others will be 'anti' nuclear power.

4.9 Nuclear Fusion

ESBAS

Nuclear fusion is the joining together of the nuclei of two atoms to form a heavier nucleus. If the atoms involved are small, this process is accompanied by the release of energy. It is the nuclear fusion of elements that causes stars to shine and hydrogen bombs to explode. As with nuclear *fission* then, there are both positive and negative uses of nuclear fusion.

DEFINITION: Nuclear fusion

The joining together of the nuclei of two atoms to form a larger nucleus.

You will remember that nuclei naturally repel one another because of the electrostatic force between their positively charged protons. So, in order to bring two nuclei together, a lot of energy must be supplied if fusion is to take place. If two nuclei can be brought close enough together however, the electrostatic force is overwhelmed by the more powerful strong nuclear force which only operates over short distances. If this happens, nuclear fusion can take place. Inside the cores of stars, the temperature is high enough for hydrogen fusion to take place but scientists have so far been unsuccessful in making the process work in the laboratory. One of the huge advantages of nuclear fusion, if it could be made to work in the laboratory, is that it is a relatively environmentally friendly source of energy. The helium that is produced is not radioactive or poisonous and does not carry the dangers of nuclear fission.

4.10 Nucleosynthesis

ESBAT

An astronomer named Edwin Hubble discovered in the 1920's that the universe is expanding. He measured that far-away galaxies are moving away from the Earth at great speed, and the further away they are, the faster they are moving.

Extension:	*What are galaxies?*

Galaxies are huge clusters of stars and matter in the universe. The Earth is part of the Milky Way galaxy which is shaped like a very large spiral. Astronomers can measure the light coming from distant galaxies using telescopes. Edwin Hubble was also able to measure the velocities of galaxies. Galaxy zoo (*http://www.galaxyzoo.org/*) is a website that allows you to classify galaxies.

These observations led people to see that the universe is expanding. It also led to the 'Big Bang' hypothesis. The 'Big Bang' hypothesis is an idea about how the universe may have started. According to this theory, the universe started off at the beginning of time as a point which then exploded and

expanded into the universe we live in today. This happened between 10 and 14 billion years ago.

Just after the Big Bang, when the universe was only 10^{-43} s old, it was very hot and was made up of quarks and leptons (an example of a lepton is the electron). As the universe expanded, ($\sim 10^{-2}$ s) and cooled, the quarks started binding together to form protons and neutrons (together called *nucleons*).

Age of Nucleosynthesis (225 s - 10^3 s)

ESBAU

About 225 s after the Big Bang, the protons and neutrons started binding together to form simple *nuclei*. The process of forming nuclei is called *nucleosynthesis*. When a proton and a neutron bind together, they form *deuterium*. Deuteron is like a hydrogen nucleus (which is just a proton) with a neutron added to it so it can be written as ^{2}H. Using protons and neutrons as building blocks, more nuclei can be formed as shown below. For example, the Helium-4 nucleus (also called an *alpha particle*) can be formed in the following ways:

$$\begin{aligned} {}^2\mathrm{H} + \mathrm{n} &\rightarrow {}^3\mathrm{H} \\ \mathrm{deuterium} + \mathrm{neutron} &\rightarrow \mathrm{tritium} \end{aligned}$$

then:

$$\begin{aligned} {}^3\mathrm{H} + \mathrm{p} &\rightarrow {}^4\mathrm{He} \\ \mathrm{tritium} + \mathrm{proton} &\rightarrow \mathrm{Helium4\ (alpha\ particle)} \end{aligned}$$

or

$$\begin{aligned} {}^2\mathrm{H} + \mathrm{p} &\rightarrow {}^3\mathrm{He} \\ \mathrm{deuterium} + \mathrm{proton} &\rightarrow \mathrm{Helium3} \end{aligned}$$

then:

$$\begin{aligned} {}^3\mathrm{He} + \mathrm{n} &\rightarrow {}^4\mathrm{He} \\ \mathrm{Helium3} + \mathrm{neutron} &\rightarrow \mathrm{Helium4\ (alpha\ particle)} \end{aligned}$$

Some ^{7}Li nuclei could also have been formed by the fusion of ^{4}He and ^{3}H.

Age of ions (10^3 s - 10^{13} s)

ESBAV

However, at this time the universe was still very hot and the electrons still had too much energy to become bound to the alpha particles to form helium *atoms*. Also, the nuclei with mass numbers greater than 4 (i.e. greater than ^{4}He) are very short-lived and would have decayed almost immediately after being formed. Therefore, the universe moved through a stage called the age of ions when it consisted of free positively charged H^+ ions and ^{4}He ions, and negatively charged electrons not yet bound into atoms.

Age of atoms (10^{13} s - 10^{15} s)

ESBAW

As the universe expanded further, it cooled down until the electrons were able to bind to the hydrogen and helium nuclei to form hydrogen and helium atoms. Earlier, during the Age of Ions, both the hydrogen and helium ions were positively charged which meant that they repelled each other (electrostatically). During the age of atoms, the hydrogen and helium along with the electrons, were in the form of atoms which are electrically neutral and so they no longer repelled each other and instead pulled together under gravity to form clouds of gas, which eventually formed stars.

Age of stars and galaxies (the universe today)

ESBAX

Inside the core of stars, the densities and temperatures are high enough for fusion reactions to occur. Most of the heavier nuclei that exist today were formed inside stars from thermonuclear reactions! (It's interesting to think that the atoms that we are made of were actually manufactured inside stars!). Since stars are mostly composed of hydrogen, the first stage of thermonuclear reactions inside stars involves hydrogen and is called **hydrogen burning**. The process has three steps and results in four hydrogen atoms being formed into a helium atom with (among other things) two photons (light!) being released.

The next stage is **helium burning** which results in the formation of carbon. All these reactions release a large amount of energy and heat the star which causes heavier and heavier nuclei to fuse into nuclei with higher and higher atomic numbers. The process stops with the formation of $^{56}\mathrm{Fe}$, which is the most strongly bound nucleus. To make heavier nuclei, even higher energies are needed than is possible inside normal stars. These nuclei are most likely formed when huge amounts of energy are released, for example when stars explode (an exploding star is called a **supernova**). This is also how all the nuclei formed inside stars get "recycled" in the universe to become part of new stars and planets.

Chapter 4 — Summary

See the summary presentation (▶ Presentation: VPihd at www.everythingscience.co.za)

- **Nuclear physics** is the branch of physics that deals with the nucleus of an atom.
- There are two forces between the particles of the nucleus. The **strong nuclear force** is an attractive force between the neutrons and the **electromagnetic force** is the repulsive force between like-charged protons.
- In atoms with large nuclei, the electromagnetic force becomes greater than the strong nuclear force and particles or energy may be released from the nucleus.
- **Radioactive decay** occurs when an unstable atomic nucleus loses energy by emitting particles or electromagnetic waves.
- The particles and energy released are called **radiation** and the atom is said to be **radioactive**.
- Radioactive isotopes are called **radioisotopes**.
- Radioactivity was first discovered by Henri Becquerel and Marie and Pierre Curie.

- There are three types of radiation from radioactive decay: **alpha (α)**, **beta (β)** and **gamma (γ)** radiation.
- During **alpha decay**, an alpha particle is released. An alpha particle consists of two protons and two neutrons bound together. Alpha radiation has low penetration power.
- During **beta decay**, a beta particle is released. During beta decay, a neutron is converted to a proton, an electron and a neutrino. A beta particle is the electron that is released. Beta radiation has greater penetration power than alpha radiation.
- During **gamma decay**, electromagnetic energy is released as gamma rays. Gamma radiation has the highest penetration power of the three radiation types.
- There are many **sources of radiation**. Some sources are natural and others are man-made.
- Natural sources of radiation include cosmic and terrestrial radiation.
- Man-made sources of radiation include televisions, smoke detectors, X-rays and radiation therapy.
- The **half-life** of an element is the time it takes for half the atoms of a radioisotope to decay into other atoms.
- Radiation can be very damaging. Some of the **negative impacts of radiation** exposure include damage to cells, genetic abnormalities and cancer.
- Radiation can also have many **positive uses**. These include use in the medical field (e.g. chemical tracers), biochemistry and genetics, use in food preservation, the environment and in archaeology.
- **Nuclear fission** is the splitting of an atomic nucleus into smaller fission products. Nuclear fission produces large amounts of energy, which can be used to produce nuclear power, and to make nuclear weapons.
- **Nuclear fusion** is the joining together of the nuclei of two atoms to form a heavier nucleus. In stars, fusion reactions involve the joining of hydrogen atoms to form helium atoms.
- **Nucleosynthesis** is the process of forming nuclei. This was very important in helping to form the universe as we know it.

Chapter 4 End of Chapter Exercises

1. Explain each of the following terms:
   (a) electromagnetic force
   (b) radioactive decay
   (c) radiocarbon dating
2. The part of the atom that undergoes radioactive decay is the...
   (a) neutrons
   (b) nucleus
   (c) electrons
   (d) entire atom
3. The radioisotope Po-212 undergoes alpha decay. Which of the following statements is **true**?

(a) The number of protons in the element remains unchanged.
(b) The number of nucleons after decay is 212.
(c) The number of protons in the element after decay is 82.
(d) The end product after decay is Po-208.

4. 20 g of sodium-24 undergoes radioactive decay. Calculate the percentage of the original sample that remains after 60 hours.
5. Nuclear physics can be controversial. Many people argue that studying the nucleus has led to devastation and huge loss of life. Others would argue that the benefits of nuclear physics far outweigh the negative things that have come from it.
   (a) Outline some of the ways in which nuclear physics has been used in negative ways.
   (b) Outline some of the benefits that have come from nuclear physics.

More practice video solutions or help at www.everythingscience.co.za

(1.) 00xf (2.) 00xg (3.) 00xh (4.) 00xi (5.) 01y0

Thermal Properties and Ideal Gases 5

We are surrounded by gases in our atmosphere which support and protect life on this planet. In this chapter, we are going to learn more gases, and learn how to predict their behaviour under different conditions. The kinetic theory of matter was discussed in Grade 10. This theory is very important in understanding how gases behave.
See introductory video: VPihe at www.everythingscience.co.za

5.1 A review of the kinetic theory of matter

ESBAY

The main assumptions of the kinetic theory of matter are as follows:

- Matter is made up of **particles** (e.g. atoms or molecules)
- These particles are constantly moving because they have kinetic energy.
- There are **spaces** between the particles
- There are **attractive forces** between particles and these become stronger as the particles move closer together.
- All particles have **energy**. The **temperature** of a substance is a measure of the **average kinetic energy** of the particles.
- A change in **phase** may occur when the energy of the particles is changed.

The kinetic theory applies to all matter, including gases. In a gas, the particles are far apart and have a high kinetic energy. They move around freely, colliding with each other or with the sides of the container if the gas is enclosed. The **pressure** of a gas is a measure of the frequency of collisions of the gas particles with each other and with the sides of the container that they are in. If the gas is heated, the average kinetic energy of the gas particles will increase and if the temperature is decreased, the average kinetic energy of the particles decreases. If the energy of the particles decreases significantly, the gas liquefies (becomes a liquid). An **ideal gas** is one that obeys all the assumptions of the kinetic theory of matter. A **real gas** behaves like an ideal gas, except at high pressures and low temperatures. This will be discussed in more detail later in this chapter.

DEFINITION: Ideal gas

An ideal gas or perfect gas is a hypothetical gas that obeys all the assumptions of the kinetic theory of matter. In other words, an ideal gas would have identical particles of zero volume, with no intermolecular forces between them. The atoms or molecules in an ideal gas would also undergo elastic collisions with the walls of their container.

DEFINITION: Real gas

Real gases behave more or less like ideal gases except under certain conditions e.g. high pressures and low temperatures.

There are a number of laws that describe how gases behave. It will be easy to make sense of these laws if you understand the kinetic theory of gases that was discussed above.

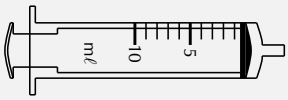
5.2 Boyle's Law: Pressure and volume of an enclosed gas

ESBAZ

If you have ever tried to force in the plunger of a syringe or a bicycle pump while sealing the opening with your finger, you will have seen Boyle's Law in action! This will now be demonstrated using a 10 ml syringe.

General experiment: *Boyle's Law*

Aim: To demonstrate Boyle's law.
Apparatus: A syringe.



Method:

1. Hold the syringe in one hand, and with the other pull the plunger out towards you so that the syringe is now full of air.
2. Seal the opening of the syringe with your finger so that no air can escape the syringe.
3. Slowly push the plunger in, and notice whether it becomes *more* or *less* difficult to push the plunger in.

Results: What did you notice when you pushed the plunger in? What happens to the **volume** of air inside the syringe? Did it become *more* or *less* difficult to push the plunger in as the volume of the air in the syringe decreased? In other words, did you have to apply more or less **force** to the plunger as the volume of air in the syringe decreased?

As the volume of air in the syringe decreases, you have to apply more force to the plunger to keep pressing it down. The pressure of the gas inside the syringe pushing back on the plunger is greater. Another way of saying this is that as the volume of the gas in the syringe *decreases*, the pressure of that gas *increases*.

Conclusion: If the volume of the gas decreases, the pressure of the gas increases. If the volume of the gas increases, the pressure decreases. These results support Boyle's law.

In the previous experiment, the volume of the gas decreased when the pressure increased, and the volume increased when the pressure decreased. This is called an **inverse relationship** (or more-less relationship). The inverse relationship between pressure and volume is shown in Figure 5.1.

Can you use the kinetic theory of gases to explain this inverse relationship between the pressure and volume of a gas? Let's think about it. If you decrease the volume of a gas, this means that the same number of gas particles are now going to come into contact with each other and with the sides of the container much more often. You may remember from earlier that we said that *pressure* is a measure of the *frequency of collisions* of gas particles with each other and with the sides of the container they are

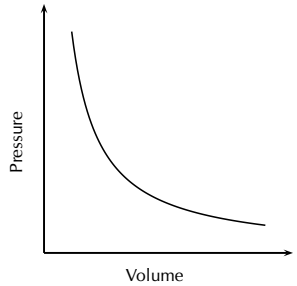


Figure 5.1: Graph showing the inverse relationship between pressure and volume

in. So, if the volume decreases, the pressure will naturally increase. The opposite is true if the volume of the gas is increased. Now, the gas particles collide less frequently and the pressure will decrease.

It was an Englishman named Robert Boyle who was able to take very accurate measurements of gas pressures and volumes using high-quality vacuum pumps. He discovered the startlingly simple fact that the pressure and volume of a gas are not just vaguely inversely related, but are *exactly* **inversely proportional**. This can be seen when a graph of pressure against the inverse of volume is plotted. When the values are plotted, the graph is a straight line. This relationship is shown in Figure 5.2.

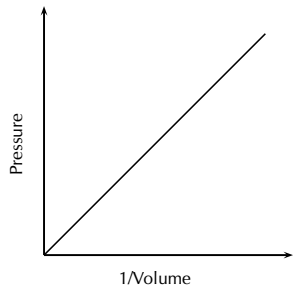


Figure 5.2: The graph of pressure plotted against the inverse of volume, produces a straight line. This shows that pressure and volume are exactly inversely proportional.

DEFINITION: Boyle's Law

The pressure of a fixed quantity of gas is inversely proportional to the volume it occupies so long as the temperature remains constant.

Proportionality

During this chapter, the terms **directly proportional** and **inversely proportional** will be used a lot, and it is important that you understand their meaning. Two quantities are said to be **proportional** if they vary in such a way that one of the quantities is a constant multiple of the other, or if they have a constant ratio. We will look at two examples to show the difference between *directly proportional* and *inversely proportional*.

1. *Directly proportional* A car travels at a constant speed of 120 km/h. The time and the distance covered are shown in the table below.

Time (mins)	**Distance** (km)
10	20
20	40
30	60
40	80

What you will notice is that the two quantities shown are constant multiples of each other. If you divide each distance value by the time the car has been driving, you will always get 2. This shows that the values are proportional to each other. They are **directly proportional** because both values are increasing. In other words, as the driving time increases, so does the distance covered. The same is true if the values decrease. The shorter the driving time, the smaller the distance covered. This relationship can be described mathematically as:

$$y = kx$$

where y is distance, x is time and k is the *proportionality constant*, which in this case is 2. Note that this is the equation for a straight line graph! The symbol $\propto$ is also used to show a directly proportional relationship.

2. *Inversely proportional*
   Two variables are inversely proportional if one of the variables is directly proportional to the multiplicative inverse of the other. In other words,

$$y \propto \frac{1}{x}$$

or

$$y = \frac{k}{x}$$

This means that as one value gets bigger, the other value will get smaller. For example, the time taken for a journey is inversely proportional to the speed of travel. Look at the table below to check this for yourself. For this example, assume that the distance of the journey is 100 km.

Speed (km/h)	**Time** (mins)
100	60
80	75
60	100
40	150

According to our definition, the two variables are inversely proportional if one variable is *directly* proportional to the *inverse* of the other. In other words, if we divide one of the variables by the inverse of the other, we should always get the same number. For example,

$$\frac{100}{\frac{1}{60}} = 6000$$

If you repeat this using the other values, you will find that the answer is always 6 000. The variables are inversely proportional to each other.

We know now that the pressure of a gas is *inversely proportional* to the volume of the gas, provided the temperature stays the same. We can write this relationship symbolically as

$$p \propto \frac{1}{V}$$

This equation can also be written as follows:

$$p = \frac{k}{V}$$

where k is a proportionality constant. If we rearrange this equation, we can say that:

$$pV = k$$

Tip

In the gas equations, k is a "variable constant". This means that k is constant in a particular set of situations, but in two different sets of situations it has different constant values.

This equation means that, assuming the temperature is constant, multiplying any pressure and volume values for a fixed amount of gas will always give the same value. So, for example, p_1V_1 = k and p_2V_2 = k, where the subscripts 1 and 2 refer to two pairs of pressure and volume readings for the same mass of gas at the same temperature.

From this, we can then say that:

$$p_1V_1 = p_2V_2$$

Remember that Boyle's Law requires two conditions. First, the amount of gas must stay constant. Clearly, if you let a little of the air escape from the container in which it is enclosed, the pressure of the gas will decrease along with the volume, and the inverse proportion relationship is broken. Second, the temperature must stay constant. Cooling or heating matter generally causes it to contract or expand, or the pressure to decrease or increase. In our original syringe demonstration, if you were to heat up the gas in the syringe, it would expand and require you to apply a greater force to keep the plunger at a given position. Again, the proportionality would be broken.

Activity: *Boyle's Law*

Shown below are some of Boyle's original data. Note that pressure would originally have been measured using a *mercury manometer* and the units for pressure would have been *millimetres mercury* or mm Hg. However, to make things a bit easier for you, the pressure data have been converted to a unit that is more familiar. Note that the volume is given in terms of arbitrary marks (evenly made).

Volume (graduation mark)	**Pressure** (kPa)	**Volume** (graduation mark)	**Pressure** (kPa)
12	398	28	170
14	340	30	159
16	298	32	150
18	264	34	141
20	239	36	133
22	217	38	125
24	199	40	120
26	184		

1. Plot a graph of pressure (p) against volume (V). Volume will be on the x-axis and pressure on the y-axis. Describe the relationship that you see.
2. Plot a graph of p against $1/V$. Describe the relationship that you see.
3. Do your results support Boyle's Law? Explain your answer.

See simulation: VPiiu at www.everythingscience.co.za)

FACT

Did you know that the mechanisms involved in *breathing* also relate to Boyle's Law? Just below the lungs is a muscle called the **diaphragm**. When a person breathes in, the diaphragm moves down and becomes more 'flattened' so that the volume of the lungs can increase. When the lung volume *increases*, the pressure in the lungs *decreases* (Boyle's law). Since air always moves from areas of high pressure to areas of lower pressure, air will now be drawn into the lungs because the air pressure *outside* the body is higher than the pressure *in* the lungs. The opposite process happens when a person breathes out. Now, the diaphragm moves upwards and causes the volume of the lungs to *decrease*. The pressure in the lungs will *increase*, and the air that was in the lungs will be forced out towards the lower air pressure outside the body.

Example 1: *Boyle's Law 1*

QUESTION

A sample of helium occupies a volume of 160 cm^3 *at 100 kPa and 25 °C. What volume will*

it occupy if the pressure is adjusted to 80 kPa and the temperature remains unchanged?

SOLUTION

Step 1 : ***Write down all the information that you know about the gas.***
$V_1 = 160$ cm^3 and $V_2 = ?$
$p_1 = 100$ kPa and $p_2 = 80$ kPa

Step 2 : ***Use an appropriate gas law equation to calculate the unknown variable.***
Because the temperature of the gas stays the same, the following equation can be used:

$$p_1V_1 = p_2V_2$$

If the equation is rearranged, then

$$V_2 = \frac{p_1V_1}{p_2}$$

Step 3 : ***Substitute the known values into the equation, making sure that the units for each variable are the same. Calculate the unknown variable.***

$$V_2 = \frac{100 \text{ kPa} \times 160 \text{ cm}^3}{80 \text{ kPa}} = 200 \text{ cm}^3$$

The volume occupied by the gas at a pressure of 80 kPa, is 200 cm^3

Tip

It is not necessary to convert to Standard International (SI) units in the examples we have used above. Changing pressure and volume into different units involves *multiplication*. If you were to change the units in the above equation, this would involve multiplication on both sides of the equation, and so the conversions cancel each other out. However, although *SI* units don't have to be used, you must make sure that for each variable you use the *same* units throughout the equation. This is not true for some of the calculations we will do at a later stage, where SI units *must* be used.

Example 2: *Boyle's Law 2*

QUESTION

The pressure on a 2.5ℓ volume of gas is increased from 695 Pa to 755 Pa while a constant temperature is maintained. What is the volume of the gas under these pressure conditions?

SOLUTION

Step 1 : ***Write down all the information that you know about the gas.***
$V_1 = 2.5\ \ell$ and $V_2 = ?$
$p_1 = 695$ Pa and $p_2 = 755$ Pa

Step 2 : ***Choose a relevant gas law equation to calculate the unknown variable.***

At constant temperature,

$$p_1V_1 = p_2V_2$$

Therefore,

$$V_2 = \frac{p_1V_1}{p_2}$$

Step 3 : ***Substitute the known values into the equation, making sure that the units for each variable are the same. Calculate the unknown variable.***

$$V_2 = \frac{695 \text{ Pa} \times 2.5\ \ell}{755 \text{ Pa}} = 2.3\ell$$

Exercise 5 - 1

1. An unknown gas has an initial pressure of 150 kPa and a volume of $1\ \ell$. If the volume is increased to $1.5\ \ell$, what will the pressure be now?
2. A bicycle pump contains 250 cm^3 of air at a pressure of 90 kPa. If the air is compressed, the volume is reduced to 200 cm^3. What is the pressure of the air inside the pump?
3. The air inside a syringe occupies a volume of 10 cm^3 and exerts a pressure of 100 kPa. If the end of the syringe is sealed and the plunger is pushed down, the pressure increases to 120 kPa. What is the volume of the air in the syringe?
4. During an investigation to find the relationship between the pressure and volume of an enclosed gas at constant temperature, the following results were obtained.

Volume (cm^3)	Pressure (kPa)
40	125.0
30	166.7
25	200.0

   (a) For the results given in the above table, plot a graph of **pressure** (y-axis) against the **inverse of volume** (x-axis).
   (b) From the graph, deduce the relationship between the pressure and volume of an enclosed gas at constant temperature.
   (c) Use the graph to predict what the volume of the gas would be at a pressure of 40 kPa. Show on your graph how you arrived at your answer.

   (*IEB 2004 Paper 2*)

More practice video solutions or help at www.everythingscience.co.za

(1.) 00xj (2.) 00xk (3.) 00xm (4.) 00xn

5.3 Charles' Law: Volume and Temperature of an enclosed gas

ESBBA

Charles' law describes the relationship between the **volume** and **temperature** of a gas. The law was first published by Joseph Louis Gay-Lussac in 1802, but he referenced unpublished work by Jacques Charles from around 1787. This law states that at constant pressure, the volume of a given mass of an ideal gas increases or decreases by the same factor as its temperature (in Kelvin) increases or decreases. Another way of saying this is that temperature and volume are **directly proportional**.

DEFINITION: Charles' Law

The volume of an enclosed sample of gas is directly proportional to its absolute temperature provided the pressure is kept constant.

FACT

Charles's Law is also known as Gay-Lussac's Law. Charles did not publish his work. Gay-Lussac later rediscovered this law and referenced Charles's work, but said that it was only by great luck that he knew of it and that his experiment was different.

General experiment: *Charles's Law*

Aim: To demonstrate Charles's Law using simple materials.
Apparatus: glass bottle (e.g. empty glass coke bottle), balloon, Bunsen burner, retort stand
Method:

1. Place the balloon over the opening of the empty bottle.
2. Place the bottle on the retort stand over the Bunsen burner and allow it to heat up. Observe what happens to the balloon. WARNING: Be careful when handling the heated bottle. You may need to wear gloves for protection.

Results: You should see that the balloon starts to expand. As the air inside the bottle is heated, the pressure also increases, causing the volume to increase. Since the volume of the glass bottle can't increase, the air moves into the balloon, causing it to expand.
Conclusion: The temperature and volume of the gas are directly related to each other. As one increases, so does the other.

Mathematically, the relationship between temperature and pressure can be represented as follows:

$$V \propto T$$

or

$$V = kT$$

If the equation is rearranged, then:

$$\frac{V}{T} = k$$

and, following the same logic that was used for Boyle's law:

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

The equation relating volume and temperature produces a straight line graph (refer back to the notes on proportionality if this is unclear). This relationship is shown in Figure 5.3.

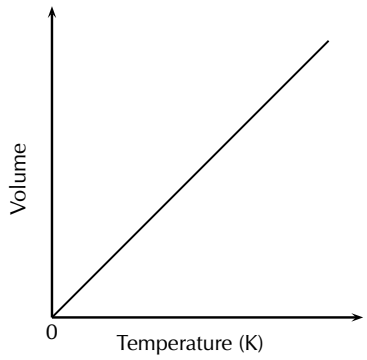


Figure 5.3: The volume of a gas is directly proportional to its temperature, provided the pressure of the gas is constant.

However, if this graph is plotted on a **Celsius** temperature scale (i.e. using °C), the zero point of temperature doesn't correspond to the zero point of volume. When the volume is zero, the temperature is actually -273.15°C (Figure 5.4).

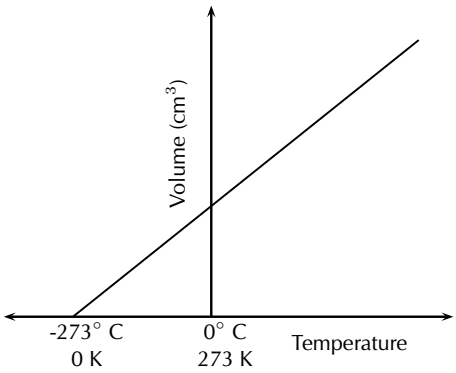


Figure 5.4: The relationship between volume and temperature, shown on a Celsius temperature scale.

A new temperature scale, the **Kelvin scale** must be used instead. Since zero on the Celsius scale corresponds with a Kelvin temperature of -273.15°C, it can be said that:

$$\text{Kelvin temperature (T)} = \text{Celsius temperature (t)} + 273.15$$

We can write:

$$T = t + 273$$
$$\text{or}$$
$$t = T - 273$$

Can you explain Charles' law in terms of the kinetic theory of gases? When the temperature of a gas increases, so does the average speed of its molecules. The molecules collide with the walls of the container more often and with greater impact. These collisions will push back the walls, so that the

gas occupies a greater volume than it did at the start. We saw this in the first demonstration. Because the glass bottle couldn't expand, the gas pushed out the balloon instead.

Exercise 5 - 2

The table below gives the temperature (in °C) of a number of gases under different volumes at a constant pressure.

Volume (ℓ)	He	H_2	N_2O
0	-272.4	-271.8	-275.0
0.25	-245.5	-192.4	-123.5
0.5	-218.6	-113.1	28.1
0.75	-191.8	-33.7	179.6
1.0	-164.9	45.7	331.1
1.5	-111.1	204.4	634.1
2	-57.4	363.1	937.2
2.5	-3.6	521.8	1240.2
3.0	50.2	680.6	1543.2
3.5	103.9	839.3	1846.2

1. On the same set of axes, draw graphs to show the relationship between temperature and volume for each of the gases.
2. Describe the relationship you observe.
3. If you extrapolate the graphs (in other words, extend the graph line even though you may not have the exact data points), at what temperature do they intersect?
4. What is significant about this temperature?

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(1.) 00xp

Example 3: Charles's Law 1

QUESTION

Ammonium chloride and calcium hydroxide are allowed to react. The ammonia that is released in the reaction is collected in a gas syringe and sealed in. This gas is allowed to come to room temperature which is 32°C. The volume of the ammonia is found to be 122 ml. It is now placed in a water bath set at 7°C. What will be the volume reading after the syringe has been left in the bath for a some time (e.g. 1 hour) (assume the plunger moves completely freely)?

SOLUTION

Step 1 : ***Write down all the information that you know about the gas.***
$V_1 = 122$ ml and $V_2 = ?$ $T_1 = 32°C$ and $T_2 = 7°C$

Step 2 : ***Convert the known values to SI units if necessary.***
Here, temperature must be converted into Kelvin, therefore:
$T_1 = 32 + 273 = 305$ K
$T_2 = 7 + 273 = 280$ K

Step 3 : ***Choose a relevant gas law equation that will allow you to calculate the unknown variable.***

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

Therefore,

$$V_2 = \frac{V_1 \times T_2}{T_1}$$

Step 4 : ***Substitute the known values into the equation. Calculate the unknown variable.***

$$V_2 = \frac{122 \text{ ml} \times 280 \text{ K}}{305 \text{ K}} = 112 \text{ ml}$$

Tip

Note that here the temperature must be converted to Kelvin (SI) since the change from degrees Celsius involves addition, not multiplication by a fixed conversion ratio (as is the case with pressure and volume.)

Example 4: *Charles's Law 2*

QUESTION

At a temperature of 298 K, a certain amount of CO_2 gas occupies a volume of 6 ℓ. What volume will the gas occupy if its temperature is reduced to 273 K?

SOLUTION

Step 1 : ***Write down all the information that you know about the gas.***
$V_1 = 6\ \ell$ and $V_2 = ?$
$T_1 = 298$ K and $T_2 = 273$ K

Step 2 : ***Convert the known values to SI units if necessary.***
Temperature data is already in Kelvin, and so no conversions are necessary.

Step 3 : ***Choose a relevant gas law equation that will allow you to calculate the unknown variable.***

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

Therefore,

$$V_2 = \frac{V_1 \times T_2}{T_1}$$

Step 4 : ***Substitute the known values into the equation. Calculate the unknown variable.***

$$V_2 = \frac{6\ \ell \times 273\ \text{K}}{298\ \text{K}} = 5.5\ \ell$$

5.4 The relationship between temperature and pressure

ESBBB

The pressure of a gas is directly proportional to its temperature, if the volume is kept constant (Figure 5.5). When the temperature of a gas increases, so does the energy of the particles. This causes them to move more rapidly and to collide with each other and with the side of the container more often. Since pressure is a measure of these collisions, the pressure of the gas increases with an increase in temperature. The pressure of the gas will decrease if its temperature decreases.

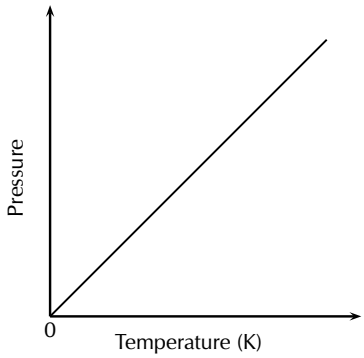

Figure 5.5: The relationship between the temperature and pressure of a gas

In the same way that we have done for the other gas laws, we can describe the relationship between temperature and pressure using symbols, as follows:

$$T \propto p, \text{ therefore } p = kT$$

We can also say that:

$$\frac{p}{T} = k$$

and that, provided the *amount* of gas stays the same:

$$\frac{p_1}{T_1} = \frac{p_2}{T_2}$$

Exercise 5 - 3

1. A gas of unknown volume has a temperature of 14°C. When the temperature of the gas is increased to 100°C, the volume is found to be 5.5 ℓ. What was the initial volume of the gas?

2. A gas has an initial volume of 2 600 ml and a temperature of 350 K.
   (a) If the volume is reduced to 1 500 ml, what will the temperature of the gas be in Kelvin?
   (b) Has the temperature *increased* or *decreased*?
   (c) Explain this change, using the kinetic theory of matter.
3. A cylinder of propane gas at a temperature of 20°C exerts a pressure of 8 atm. When a cylinder has been placed in sunlight, its temperature increases to 25°C. What is the pressure of the gas inside the cylinder at this temperature?

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(1.) 00xt (2.) 00xu (3.) 00xv

5.5 The general gas equation

ESBBC

All the gas laws we have described so far rely on the fact that at least one variable (T, p or V) remains constant. Since this is unlikely to be the case most times, it is useful to combine the relationships into one equation. These relationships are as follows:

Boyle's law: $p \propto \frac{1}{V}$ (constant T)

Relationship between p and T: $p \propto T$ (constant V)

If we combine these relationships, we get $p \propto \frac{T}{V}$

If we introduce the proportionality constant k, we get $p = k\frac{T}{V}$

or, rearranging the equation:

$$pV = kT$$

We can also rewrite this relationship as follows:

$$\frac{pV}{T} = k$$

Provided the mass of the gas stays the same, we can also say that:

$$\frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2}$$

In the above equation, the subscripts 1 and 2 refer to two pressure and volume readings for the same mass of gas under different conditions. This is known as the **general gas equation**. Temperature is always in Kelvin and the units used for pressure and volume must be the same on both sides of the equation.

Tip

Remember that the general gas equation only applies if the mass of the gas is fixed.

Example 5: *General Gas Equation 1*

QUESTION

At the beginning of a journey, a truck tyre has a volume of 30 dm^3 and an internal pressure of 170 kPa. The temperature of the tyre is 16°C. By the end of the trip, the volume of the tyre has increased to 32 dm^3 and the temperature of the air inside the tyre is 35°C. What is the tyre pressure at the end of the journey?

SOLUTION

Step 1 : ***Write down all the information that you know about the gas.***

p_1 = 170 kPa and p_2 = ?
V_1 = 30 dm^3 and V_2 = 32 dm^3
T_1 = 16°C and T_2 = 40°C

Step 2 : ***Convert the known values to SI units if necessary.***
Here, temperature must be converted into Kelvin, therefore:
$T_1 = 16 + 273 = 289$ K
$T_2 = 40 + 273 = 313$ K

Step 3 : ***Choose a relevant gas law equation that will allow you to calculate the unknown variable.***

Use the general gas equation to solve this problem:

$$\frac{p_1 \times V_1}{T_1} = \frac{p_2 \times V_2}{T_2}$$

Therefore,

$$p_2 = \frac{p_1 \times V_1 \times T_2}{T_1 \times V_2}$$

Step 4 : ***Substitute the known values into the equation. Calculate the unknown variable.***

$$p_2 = \frac{170 \text{ kPa} \times 30 \text{ dm}^3 \times 313 \text{ K}}{289 \text{ K} \times 32 \text{ dm}^3} = 173 \text{ kPa}$$

The pressure of the tyre at the end of the journey is 173 kPa.

Example 6: *General Gas Equation 2*

QUESTION

A cylinder that contains methane gas is kept at a temperature of 15°C and exerts a pressure of 7 atm. If the temperature of the cylinder increases to 25°C, what pressure does the gas now exert? (Refer to Table 5.1 to see what an 'atm' is.

SOLUTION

Step 1 : ***Write down all the information that you know about the gas.***

p_1 = 7 atm and p_2 = ?
T_1 = 15°C and T_2 = 25°C

Step 2 : ***Convert the known values to SI units if necessary.***
Here, temperature must be converted into Kelvin, therefore:
$T_1 = 15 + 273 = 288$ K
$T_2 = 25 + 273 = 298$ K

Step 3 : ***Choose a relevant gas law equation that will allow you to calculate the unknown variable.***

Since the volume of the cylinder is constant, we can write:

$$\frac{p_1}{T_1} = \frac{p_2}{T_2}$$

Therefore,

$$p_2 = \frac{p_1 \times T_2}{T_1}$$

Step 4 : ***Substitute the known values into the equation. Calculate the unknown variable.***

$$p_2 = \frac{7 \text{ atm} \times 298 \text{ K}}{288 \text{ K}} = 7.24 \text{ atm}$$

The pressure of the gas is 7.24 atm.

Example 7: *General Gas Equation 3*

QUESTION

A gas container can withstand a pressure of 130 kPa before it will explode. Assuming that the volume of the gas in the container stays the same, at what temperature will the container

explode if the gas exerts a pressure of 100 kPa at 15°C?

SOLUTION

Step 1 : ***Write down all the information that you know about the gas.***

p_1 = 100 kPa and p_2 = 130 kPa
$T_1 = 15°C$ and T_2 = ?

Step 2 : ***Convert the known values to SI units if necessary.***
Here, temperature must be converted into Kelvin, therefore:
$T_1 = 15 + 273 = 288$ K

Step 3 : ***Choose a relevant gas law equation that will allow you to calculate the unknown variable.***

Since the volume of the container is constant, we can write:

$$\frac{p_1}{T_1} = \frac{p_2}{T_2}$$

Therefore,

$$\frac{1}{T_2} = \frac{p_1}{T_1 \times p_2}$$

Therefore,

$$T_2 = \frac{T_1 \times p_2}{p_1}$$

Step 4 : ***Substitute the known values into the equation. Calculate the unknown variable.***

$$T_2 = \frac{288 \text{ K} \times 130 \text{ kPa}}{100 \text{ kPa}} = 374.4 \text{ K} = 101.4°C$$

Exercise 5 - 4

1. A closed gas system initially has a volume of 8 L and a temperature of 100°C. The pressure of the gas is unknown. If the temperature of the gas decreases to 50°C, the gas occupies a volume of 5 L. If the pressure of the gas under these conditions is 1.2 atm, what was the initial pressure of the gas?

2. A balloon is filled with helium gas at 27°C and a pressure of 1.0 atm. As the balloon rises, the volume of the balloon increases by a factor of 1.6 and the temperature decreases to 15°C. What is the final pressure of the gas (assuming none has escaped)?

3. 25 cm^3 of gas at 1 atm has a temperature of 20°C. When the gas is compressed to 20 cm^3, the temperature of the gas increases to 28°C. Calculate the final pressure of the gas.

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(1.) 00xw (2.) 00xx (3.) 00xy

5.6 The ideal gas equation

ESBBD

In the early 1800's, Amedeo Avogadro hypothesised that if you have samples of different gases, of the same volume, at a fixed temperature and pressure, then the samples must contain the same number of freely moving particles (i.e. atoms or molecules).

Tip

1. The value of R is the same for all gases
2. All quantities in the equation $pV = nRT$ must be in the same units as the value of R. In other words, SI units must be used throughout the equation.

DEFINITION: Avogadro's Law

Equal volumes of gases, at the same temperature and pressure, contain the same number of molecules.

You will remember from an earlier section, that we combined different gas law equations to get *one* that included temperature, volume and pressure. In this equation, $pV = kT$, the value of k is different for different masses of gas. If we were to measure the amount of gas in moles, then $k = nR$, where n is the number of moles of gas and R is the universal gas constant. The value of R is 8.3143 J·K^{-1}·mol^{-1}, or for most calculations, 8.3 J · K^{-1} · mol^{-1}. So, if we replace k in the general gas equation, we get the following **ideal gas equation**.

The joule can be defined as: 1 J $= 1$ Pa · m^3.

$$pV = nRT$$

The following table may help you when you convert to SI units.

Variable	Pressure (**p**)	Volume (**V**)	moles (**n**)	universal gas constant (**R**)	temperature (**K**)
SI unit	Pascals (Pa)	m^3	mol	J.K^{-1}.mol^{-1}	Kelvin (K)
Other units and conversions	760 mm Hg = 1 atm = 101325 Pa = 101.325 kPa	1 m^3 = 1 000 000 cm^3 = 1000 dm^3 = 1 000 ℓ			$K =^\circ$ C + 273

Table 5.1: Conversion table showing different units of measurement for volume, pressure and temperature.

See video: VPinh at www.everythingscience.co.za

Example 8: *Ideal gas equation 1*

QUESTION

Two moles of oxygen (O_2) gas occupy a volume of 25 dm^3 at a temperature of 40°C. Calculate the pressure of the gas under these conditions.

SOLUTION

Step 1 : ***Write down all the information that you know about the gas.***

$$p = ?$$
$$V = 25 \text{ dm}^3$$
$$n = 2$$
$$T = 40°\text{C}$$

Step 2 : ***Convert the known values to SI units if necessary.***

$$V = \frac{25}{1000} = 0.025 \text{ m}^3$$

$$T = 40 + 273 = 313 \text{ K}$$

Step 3 : ***Choose a relevant gas law equation that will allow you to calculate the unknown variable.***

$$pV = nRT$$

Therefore,

$$p = \frac{nRT}{V}$$

Step 4 : ***Substitute the known values into the equation. Calculate the unknown variable.***

$$p = \frac{2 \text{ mol} \times 8.3 \text{ J} \cdot \text{K}^{-1} \cdot \text{mol}^{-1} \times 313 \text{ K}}{0.025 \text{ m}^3} = 207\,832 \text{ Pa} = 207.8 \text{ kPa}$$

Example 9: *Ideal gas equation 2*

QUESTION

Carbon dioxide (CO_2) gas is produced as a result of the reaction between calcium carbonate and hydrochloric acid. The gas that is produced is collected in a 20 dm^3 container. The pressure of the gas is 105 kPa at a temperature of 20^{0}C. What mass of carbon dioxide was produced?

SOLUTION

Step 1 : ***Write down all the information that you know about the gas.***

$p = 105$ kPa
$V = 20$ dm^3
$T = 20°$C

Step 2 : ***Convert the known values to SI units if necessary.***

$$p = 105 \times 1\ 000 = 105\ 000 \text{ Pa}$$

$$T = 20 + 273 = 293 \text{ K}$$

$$V = \frac{20}{1000} = 0.02m^3$$

Step 3 : ***Choose a relevant gas law equation that will allow you to calculate the unknown variable.***

$$pV = nRT$$

Therefore,

$$n = \frac{pV}{RT}$$

Step 4 : ***Substitute the known values into the equation. Calculate the unknown variable.***

$$n = \frac{105\ 000 \text{ Pa} \times 0.02 \text{ m}^3}{8.3 \text{ J} \cdot \text{K}^{-1} \cdot \text{mol}^{-1} \times 293 \text{ K}} = 0.86 \text{ mol}$$

Step 5 : ***Calculate mass from moles***

$$n = \frac{m}{M}$$

Therefore,

$$m = n \times M$$

The molar mass of CO_2 is calculated as follows:

$$M = 12 + (2 \times 16) = 44 \text{ g} \cdot \text{mol}^{-1}$$

Therefore,

$$m = 0.86 \times 44 = 37.84 \text{ g}$$

Example 10: *Ideal gas equation 3*

QUESTION

1 mole of nitrogen (N_2) reacts with hydrogen (H_2) according to the following equation:

$$N_2 + 3H_2 \rightarrow 2NH_3$$

The ammonia (NH_3) gas is collected in a separate gas cylinder which has a volume of 25 dm^3. The temperature of the gas is 22°C. Calculate the pressure of the gas inside the cylinder.

SOLUTION

Step 1 : ***Write down all the information that you know about the gas.***

V = 25 dm^3
n = 2 (Calculate this by looking at the mole ratio of nitrogen to ammonia, which is 1:2)
T = 22°C

Step 2 : ***Convert the known values to SI units if necessary.***

$$V = \frac{25}{1000} = 0.025 \text{ m}^3$$

$$T = 22 + 273 = 295 \text{ K}$$

Step 3 : ***Choose a relevant gas law equation that will allow you to calculate the unknown variable.***

$$pV = nRT$$

Therefore,

$$p = \frac{nRT}{V}$$

Step 4 : ***Substitute the known values into the equation. Calculate the unknown variable.***

$$p = \frac{2 \text{ mol} \times 8.3 \text{ J} \cdot \text{K}^{-1}\text{mol}^{-1} \times 295 \text{ K}}{0.025 \text{ m}^3} = 195\,880 \text{ Pa} = 195.89 \text{ kPa}$$

Example 11: *Ideal gas equation 4*

QUESTION

Calculate the number of moles of air particles in a 10 m by 7 m by 2 m classroom on a day when the temperature is 23°C and the air pressure is 98 kPa.

SOLUTION

Step 1 : ***Write down all the information that you know about the gas.***

$$\text{V} = 10 \text{ m} \times 7 \text{ m} \times 2 \text{ m} = 140 \text{ m}^3$$
$$p = 98 \text{ kPa}$$
$$T = 23°\text{C}$$

Step 2 : ***Convert the known values to SI units if necessary.***

$$p = 98 \times 1000 = 98\ 000 \text{ Pa}$$

$$T = 23 + 273 = 296 \text{ K}$$

Step 3 : ***Choose a relevant gas law equation that will allow you to calculate the unknown variable.***

$$pV = nRT$$

Therefore,

$$n = \frac{pV}{RT}$$

Step 4 : ***Substitute the known values into the equation. Calculate the unknown variable.***

$$n = \frac{98\ 000 \text{ Pa} \times 140 \text{ m}^3}{8.3 \text{ J} \cdot \text{K}^{-1}\text{mol}^{-1} \times 296 \text{ K}} = 5584.5 \text{ mol}$$

Example 12: *Applying the gas laws*

QUESTION

Most modern cars are equipped with airbags for both the driver and the passenger. An airbag will completely inflate in 0,05 s. This is important because a typical car collision lasts about 0,125 s. The following reaction of sodium azide (a compound found in airbags) is activated by an electrical signal:

$$2NaN_3(s) \rightarrow 2Na\ (s) + 3N_2(g)$$

1. *Calculate the mass of $N_2(g)$ needed to inflate a sample airbag to a volume of 65 dm^3 at 25 °C and 99,3 kPa. Assume the gas temperature remains constant during the reaction.*
2. *In reality the above reaction is exothermic. Describe, in terms of the kinetic molecular theory, how the pressure in the sample airbag will change, if at all, as the gas temperature returns to 25 °C.*

SOLUTION

Step 1 : ***Look at the information you have been given, and the information you still need.***

Here you are given the volume, temperature and pressure. You are required to work out the mass of N_2.

Step 2 : ***Check that all the units are S.I. units***

Pressure: 93.3×10^3 Pa
Volume: 65×10^{-3} m^3
Temperature: $(273 + 25)$ K
Gas Constant: $8{,}31$ J $\cdot$ K^{-1}mol^{-1}

Step 3 : ***Write out the Ideal Gas formula***

$$pV = nRT$$

Step 4 : ***Solve for the required quantity using symbols***

$$n = \frac{pV}{RT}$$

Step 5 : ***Solve by substituting numbers into the equation to solve for 'n'.***

$$n = \frac{(99{,}3 \times 10^3 \text{ Pa}) \times (65 \times 10^{-3}) \text{ m}^3}{8{,}31 \text{ J} \cdot \text{K}^{-1}\text{mol}^{-1} \times (273 + 25) \text{ K}}$$

Step 6 : ***Convert the number of moles to number of grams***

$$\begin{aligned} m &= n \times M \\ m &= 2{,}61 \times 28 \\ m &= 73{,}0 \text{ g} \end{aligned}$$

Step 7 : ***Theory Question***

When the temperature decreases the intensity of collisions with the walls of the airbag and between particles decreases. Therefore pressure decreases.

Exercise 5 - 5

1. An unknown gas has pressure, volume and temperature of 0.9 atm, 8 ℓ and 120°C respectively. How many moles of gas are present?

2. 6 g of chlorine (Cl_2) occupies a volume of 0.002 m^3 at a temperature of 26°C. What is the pressure of the gas under these conditions?

3. An average pair of human lungs contains about 3.5 ℓ of air after inhalation and about 3.0 ℓ after exhalation. Assuming that air in your lungs is at 37°C and 1.0 atm, determine the number of moles of air in a typical breath.

4. A learner is asked to calculate the answer to the problem below:

   Calculate the pressure exerted by 1.5 moles of nitrogen gas in a container with a volume of 20 dm^3 at a temperature of 37°C.

   The learner writes the solution as follows:

   V = 20 dm^3

   n = 1.5 mol

   R = 8.3 J $\cdot K^{-1} mol^{-1}$

   T = 37 + 273 = 310 K

   pT = nRV, therefore

$$\begin{aligned} p &= \frac{nRV}{T} \\ &= \frac{1.5 \times 8.3 \times 20}{310} \\ &= 0.8 \text{ kPa} \end{aligned}$$

   (a) Identify 2 mistakes the learner has made in the calculation.
   (b) Are the units of the final answer correct?
   (c) Rewrite the solution, correcting the mistakes to arrive at the right answer.

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(1.) 00xz (2.) 00y0 (3.) 00y1 (4.) 00y2

5.7 Molar volume of gases

ESBBE

It is possible to calculate the volume of a mole of gas at STP using what we now know about gases.

1. *Write down the ideal gas equation*

$$pV = nRT, \text{ therefore } V = \frac{nRT}{p}$$

2. *Record the values that you know, making sure that they are in SI units*

   You know that the gas is under STP conditions. These are as follows:

   $p = 101.3$ kPa $= 101300$ Pa

   $n = 1$ mol

   $R = 8.3$ J $\cdot$ $K^{-1} mol^{-1}$

   $T = 273$ K

3. *Substitute these values into the original equation.*

$$V = \frac{nRT}{p}$$

$$V = \frac{1\text{mol} \times 8.3\ \text{J} \cdot \text{K}^{-1}\text{mol}^{-1} \times 273\ \text{K}}{101\ 300\ \text{Pa}}$$

4. *Calculate the volume of 1 mole of gas under these conditions*

   The volume of 1 mole of gas at STP is 22.4×10^{-3} m^3 = 22.4 dm^3.

5.8 Ideal gases and non-ideal gas behaviour

ESBBF

In looking at the behaviour of gases to arrive at the ideal gas law, we have limited our examination to a small range of temperature and pressure. Almost all gases will obey these laws most of the time, and are called **ideal gases**. However, there are deviations at **high pressures** and **low temperatures**. So what is happening at these two extremes?

Earlier when we discussed the kinetic theory of gases, we made a number of assumptions about the behaviour of gases. We now need to look at two of these again because they affect how gases behave either when pressures are high or when temperatures are low.

1. *Molecules do occupy volume*

   When pressures are very high and the molecules are compressed, the volume of the molecules becomes significant. This means that the total volume available for the gas molecules to move is reduced and collisions become more frequent. This causes the pressure of the gas to be *higher* than what would normally have been predicted by Boyle's law (Figure 5.6).

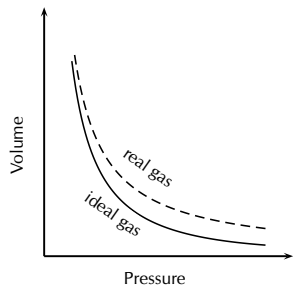


Figure 5.6: Gases deviate from ideal gas behaviour at high pressure.

2. *Forces of attraction do exist between molecules*

   At low temperatures, when the speed of the molecules decreases and they move closer together, the intermolecular forces become more apparent. As the attraction between molecules increases, their movement decreases and there are fewer collisions between them. The pressure of the gas at low temperatures is therefore lower than what would have been expected for an ideal gas (Figure 5.7). If the temperature is low enough or the pressure high enough, a real gas will **liquefy**.

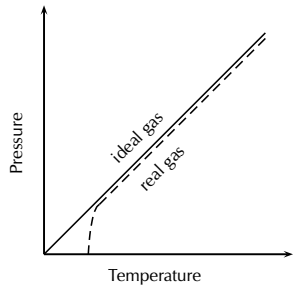


Figure 5.7: Gases deviate from ideal gas behaviour at low temperatures

Chapter 5 — Summary

See the summary presentation (▶ Presentation: VPisz at www.everythingscience.co.za)

- The **kinetic theory of matter** helps to explain the behaviour of gases under different conditions.
- An **ideal gas** is one that obeys all the assumptions of the kinetic theory.
- A **real gas** behaves like an ideal gas, except at high pressures and low temperatures. Under these conditions, the forces between molecules become significant and the gas will liquefy.
- **Boyle's law** states that the pressure of a fixed quantity of gas is inversely proportional to its volume, as long as the temperature stays the same. In other words, pV = k or

$$p_1V_1 = p_2V_2.$$

- **Charles's law** states that the volume of an enclosed sample of gas is directly proportional to its temperature, as long as the pressure stays the same. In other words,

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

- The **temperature** of a fixed mass of gas is directly proportional to its pressure, if the volume is constant. In other words,

$$\frac{p_1}{T_1} = \frac{p_2}{T_2}$$

- In the above equations, temperature must be written in **Kelvin**. Temperature in degrees Celsius (temperature = t) can be converted to temperature in Kelvin (temperature = T) using the following equation:

$$T = t + 273$$

- Combining Boyle's law and the relationship between the temperature and pressure of a gas, gives the **general gas equation**, which applies as long as the amount of gas remains constant. The general gas equation is pV = kT, or

$$\frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2}$$

- Because the mass of gas is not always constant, another equation is needed for these situations. The **ideal gas equation** can be written as

$$pV = nRT$$

where n is the number of moles of gas and R is the universal gas constant, which is 8.3 J.K^{-1}.mol^{-1}. In this equation, **SI units** must be used. Volume (m^3), pressure (Pa) and temperature (K).

- The **volume** of one mole of gas under STP is 22.4 dm^3. This is called the **molar gas volume**.

Chapter 5 End of Chapter Exercises

1. For each of the following, say whether the statement is **true** or **false**. If the statement is false, rewrite the statement correctly.
   (a) Real gases behave like ideal gases, except at low pressures and low temperatures.
   (b) The volume of a given mass of gas is inversely proportional to the pressure it exerts.
   (c) The temperature of a fixed mass of gas is directly proportional to its pressure, regardless of the volume of the gas.
2. Which one of the following properties of a fixed quantity of a gas must be kept constant during an investigation of Boyle's law?
   (a) density
   (b) pressure
   (c) temperature
   (d) volume

   (*IEB 2003 Paper 2*)
3. Three containers of *equal volume* are filled with *equal masses* of helium, nitrogen and carbon dioxide gas respectively. The gases in the three containers are all at the same *temperature*. Which one of the following statements is correct regarding the pressure of the gases?
   (a) All three gases will be at the same pressure
   (b) The helium will be at the greatest pressure
   (c) The nitrogen will be at the greatest pressure
   (d) The carbon dioxide will be at the greatest pressure

   (*IEB 2004 Paper 2*)
4. One mole of an ideal gas is stored at a temperature T (in Kelvin) in a rigid gas tank. If the average speed of the gas particles is doubled, what is the new Kelvin temperature of the gas?
   (a) 4T
   (b) 2T
   (c) $\sqrt{2}$T
   (d) 0.5 T

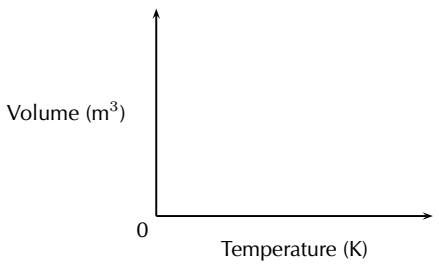
   (*IEB 2002 Paper 2*)

5. The ideal gas equation is given by **pV = nRT**. Which one of the following conditions is true according to Avogadro's hypothesis?

a	$p \propto 1/V$	(T = constant)
b	$V \propto T$	(p = constant)
c	$V \propto n$	(p, T = constant)
d	$p \propto T$	(n = constant)

(*DoE Exemplar paper 2, 2007*)

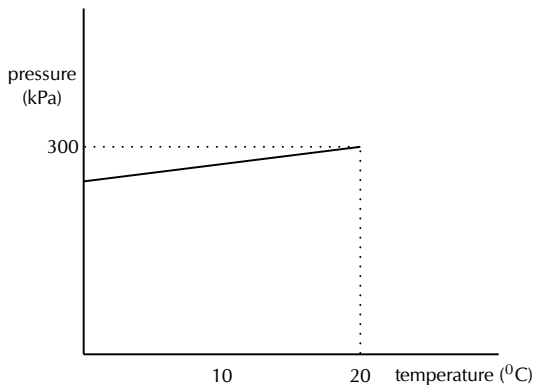
6. Use your knowledge of the gas laws to explain the following statements.
   (a) It is dangerous to put an aerosol can near heat.
   (b) A pressure vessel that is poorly designed and made can be a serious safety hazard (a pressure vessel is a closed, rigid container that is used to hold gases at a pressure that is higher than the normal air pressure).
   (c) The volume of a car tyre increases after a trip on a hot road.
7. Copy the following set of labelled axes and answer the questions that follow:



   (a) On the axes, **using a solid line**, draw the graph that would be obtained for a fixed mass of an ideal gas if the pressure is kept constant.
   (b) If the gradient of the above graph is measured to be 0.008 m^3.K^{-1}, calculate the pressure that 0.3 mol of this gas would exert.

   (**IEB 2002 Paper 2**)
8. Two gas cylinders, A and B, have a volume of 0.15 m^3 and 0.20 m^3 respectively. Cylinder A contains 1.25 mol He gas at pressure p and cylinder B contains 2.45 mol He gas at standard pressure. The ratio of the Kelvin temperatures A:B is 1.80:1.00. Calculate the pressure of the gas (in kPa) in cylinder A.

   (*IEB 2002 Paper 2*)
9. A learner investigates the relationship between the Celsius temperature and the pressure of a fixed amount of helium gas in a 500 cm^3 closed container. From the results of the investigation, she draws the graph below:



   (a) Under the conditions of this investigation, helium gas behaves like an ideal gas. Explain briefly why this is so.

(b) From the shape of the graph, the learner concludes that the pressure of the helium gas is directly proportional to the Celsius temperature. Is her conclusion correct? Briefly explain your answer.

(c) Calculate the pressure of the helium gas at 0 °C.

(d) Calculate the mass of helium gas in the container.

(*IEB 2003 Paper 2*)

10. One of the cylinders of a motor car engine, before compression contains 450 cm^3 of a mixture of air and petrol in the gaseous phase, at a temperature of 30°C and a pressure of 100 kPa. If the volume of the cylinder after compression decreases to one tenth of the original volume, and the temperature of the gas mixture rises to 140°C, calculate the pressure now exerted by the gas mixture.

11. In an experiment to determine the relationship between pressure and temperature of a fixed mass of gas, a group of learners obtained the following results:

Pressure (kPa)	101	120	130.5	138
Temperature (^{0}C)	0	50	80	100
Total gas volume (cm^3)	250	250	250	250

(a) Draw a straight-line graph of pressure (on the dependent, y-axis) versus temperature (on the independent, x-axis) on a piece of graph paper. Plot the points. Give your graph a suitable heading.
A straight-line graph passing through the origin is essential to obtain a mathematical relationship between pressure and temperature.

(b) Extrapolate (extend) your graph and determine the temperature (in ^{0}C) at which the graph will pass through the temperature axis.

(c) Write down, in words, the relationship between pressure and Kelvin temperature.

(d) From your graph, determine the pressure (in kPa) at 173 K. Indicate on your graph how you obtained this value.

(e) How would the gradient of the graph be affected (if at all) if a larger mass of the gas is used? Write down ONLY **increases**, **decreases** or **stays the same**.

(*DoE Exemplar Paper 2, 2007*)

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(1.) 00y3 (2.) 00y4 (3.) 00y5 (4.) 00y6 (5.) 00y7 (6.) 00y8
(7.) 00y9 (8.) 00ya (9.) 01y1 (10.) 01y2 (11.) 01y3

Quantitative Aspects of Chemical Change

6

An equation for a chemical reaction can provide us with a lot of useful information. It tells us what the reactants and the products are in the reaction, and it also tells us the ratio in which the reactants combine to form products. Look at the equation below:

$$Fe + S \rightarrow FeS$$

In this reaction, every atom of iron (Fe) will react with a single atom of sulphur (S) to form one molecule of iron sulphide (FeS). However, what the equation doesn't tell us, is the **quantities** or the **amount** of each substance that is involved. You may for example be given a small sample of iron for the reaction. How will you know how many atoms of iron are in this sample? And how many atoms of sulphur will you need for the reaction to use up all the iron you have? Is there a way of knowing what mass of iron sulphide will be produced at the end of the reaction? These are all very important questions, especially when the reaction is an industrial one, where it is important to know the quantities of reactants that are needed, and the quantity of product that will be formed. This chapter will look at how to quantify the changes that take place in chemical reactions.

See introductory video: VPiwd at www.everythingscience.co.za

6.1 The Mole

ESBBG

Sometimes it is important to know exactly how many particles (e.g. atoms or molecules) are in a sample of a substance, or what quantity of a substance is needed for a chemical reaction to take place.

You will remember from Grade 10 that the **atomic mass** of an element, describes the mass of an atom of that element relative to the mass of an atom of carbon-12. So the mass of an atom of carbon (atomic mass is 12 u) for example, is twelve times greater than the mass of an atom of hydrogen, which has an atomic mass of 1 u. How can this information be used to help us to know what mass of each element will be needed if we want to end up with the same number of *atoms* of carbon and hydrogen?

Let's say for example, that we have a sample of 12 g carbon. What mass of *hydrogen* will contain the same number of atoms as 12 g carbon? We know that each atom of carbon weighs twelve times more than an atom of hydrogen. Surely then, we will only need 1g of hydrogen for the number of atoms in the two samples to be the same? You will notice that the number of particles (in this case, *atoms*) in the two substances is the same when the ratio of their sample masses (12 g carbon: 1g hydrogen $= 12 : 1$) is the same as the ratio of their atomic masses (12 u: 1 u = 12:1).

To take this a step further, if you were to weigh out samples of a number of elements so that the mass of the sample was the same as the atomic mass of that element, you would find that the number of particles in each sample is 6.022×10^{23}. These results are shown in Table 6.1 below for a number of different elements. So, 24.31 g of magnesium (atomic mass $= 24.31$ u) for example, has the same number of atoms as 40.08 g of calcium (atomic mass $= 40.08$ u).

Element	Atomic mass (u)	Sample mass (g)	Atoms in sample
Hydrogen (H)	1	1	6.022×10^{23}
Carbon (C)	12	12	6.022×10^{23}
Magnesium (Mg)	24.31	24.31	6.022×10^{23}
Sulphur (S)	32.07	32.07	6.022×10^{23}
Calcium (Ca)	40.08	40.08	6.022×10^{23}

Table 6.1: Table showing the relationship between the sample mass, the atomic mass and the number of atoms in a sample, for a number of elements.

This result is so important that scientists decided to use a special unit of measurement to define this quantity: the **mole** or 'mol'. A **mole** is defined as being an amount of a substance which contains the same number of particles as there are atoms in 12 g of carbon. In the examples that were used earlier, 24.31 g magnesium is *one mole* of magnesium, while 40.08 g of calcium is *one mole* of calcium. A mole of any substance always contains the same number of particles.

DEFINITION: Mole

The mole (abbreviation 'mol') is the SI (Standard International) unit for 'amount of substance'.

In one mole of any substance, there are 6.022×10^{23} particles. This is known as **Avogadro's number**.

DEFINITION: Avogadro's number

The number of particles in a mole, equal to 6.022×10^{23}.

FACT

The original hypothesis that was proposed by Amadeo Avogadro was that *'equal volumes of gases, at the same temperature and pressure, contain the same number of molecules'*. His ideas were not accepted by the scientific community and it was only four years after his death, that his original hypothesis was accepted and that it became known as 'Avogadro's Law'. In honour of his contribution to science, the number of particles in one mole was named *Avogadro's number*.

Exercise 6 - 1

1. Complete the following table:

Element	Atomic mass (u)	Sample mass (g)	Number of moles in the sample
Hydrogen	1.01	1.01	
Magnesium	24.31	24.31	
Carbon	12.01	24.02	
Chlorine	35.45	70.9	
Nitrogen		42.08	

2. How many atoms are there in:
   (a) 1 mole of a substance
   (b) 2 moles of calcium
   (c) 5 moles of phosphorus
   (d) 24.31 g of magnesium
   (e) 24.02 g of carbon

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(1.) 00yb (2.) 00yc

6.2 Molar Mass

ESBBH

DEFINITION: Molar mass

Molar mass (M) is the mass of 1 mole of a chemical substance. The unit for molar mass is **grams per mole** or $g \cdot mol^{-1}$.

Refer to Table 6.1. You will remember that when the mass, in grams, of an element is equal to its atomic mass, the sample contains one mole of that element. This mass is called the **molar mass** of that element.

Element	**Atomic mass (u)**	**Molar mass ($g.mol^{-1}$)**	**Mass of one mole of the element (g)**
Magnesium	24.31	24.31	24.31
Lithium	6.94	6.94	6.94
Oxygen	16	16	16
Nitrogen	14.01	14.01	14.01
Iron	55.85	55.85	55.85

Table 6.2: The relationship between atomic mass, molar mass and the mass of one mole for a number of elements.

It is worth remembering the following: On the periodic table, the atomic mass that is shown can be interpreted in three ways.

1. The mass of a *single, average atom* of that element relative to the mass of an atom of carbon.
2. The average atomic mass of all the isotopes of that element. This use is the relative atomic mass.
3. The mass of *one mole of the element*. This third use is the molar mass of the element.

Example 1: *Calculating the number of moles from mass*

QUESTION

Calculate the number of moles of iron (Fe) in a 111.7 g sample.

SOLUTION

Step 1 : ***Find the molar mass of iron***
If we look at the periodic table, we see that the molar mass of iron is 55.85 g.mol^{-1}. This means that 1 mole of iron will have a mass of 55.85 g.

Step 2 : ***Use the molar mass and sample mass to calculate the number of moles of iron***
If 1 mole of iron has a mass of 55.85 g, then: the number of moles of iron in 111.7 g must be:

$$\frac{111.7 \text{ g}}{55.85\text{g} \cdot \text{mol}^{-1}} = 2\text{mol}$$

There are 2 moles of iron in the sample.

Example 2: *Calculating mass from moles*

QUESTION

You have a sample that contains 5 moles of zinc.

1. *What is the mass of the zinc in the sample?*
2. *How many atoms of zinc are in the sample?*

SOLUTION

Step 1 : ***Find the molar mass of zinc***
Molar mass of zinc is $65.38 \text{ g} \cdot \text{mol}^{-1}$, meaning that 1 mole of zinc has a mass of 65.38 g.

Step 2 : ***Calculate the mass of zinc, using moles and molar mass.***
If 1 mole of zinc has a mass of 65.38 g, then 5 moles of zinc has a mass of:

$$65.38 \text{ g} \times 5 \text{ mol} = 326.9 \text{ g (answer to a)}$$

Step 3 : ***Use the number of moles of zinc and Avogadro's number to calculate the number of zinc atoms in the sample.***

$$5 \times 6.022 \times 10^{23} = 30.115 \times 10^{23}$$

(answer to b)

Exercise 6 - 2

1. Give the molar mass of each of the following elements:
   (a) hydrogen
   (b) nitrogen
   (c) bromine
2. Calculate the number of moles in each of the following samples:
   (a) 21.62 g of boron (B)
   (b) 54.94 g of manganese (Mn)
   (c) 100.3 g of mercury (Hg)
   (d) 50 g of barium (Ba)
   (e) 40 g of lead (Pb)

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(1.) 00yd (2.) 00ye

6.3 An equation to calculate moles and mass in chemical reactions

ESBBI

The calculations that have been used so far, can be made much simpler by using the following equation:

Tip

Remember that when you use the equation $n = \frac{m}{M}$, the mass is always in grams (g) and molar mass is in grams per mol (g.mol^{-1}).

$$\textbf{n} \text{ (number of moles)} = \frac{\textbf{m} \text{ (mass of substance in g)}}{\textbf{M} \text{ (molar mass of substance in } \mathrm{g \cdot mol^{-1}})}$$

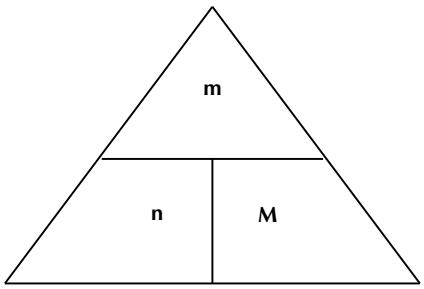
The equation can also be used to calculate mass and molar mass, using the following equations:

$$m = n \times M$$

and

$$M = \frac{m}{n}$$

The following diagram may help to remember the relationship between these three variables. You need to imagine that the horizontal line is like a 'division' sign and that the vertical line is like a 'multiplication' sign. So, for example, if you want to calculate 'M', then the remaining two letters in the triangle are 'm' and 'n' and 'm' is above 'n' with a division sign between them. In your calculation then, 'm' will be the numerator and 'n' will be the denominator.



Example 3: *Calculating moles from mass*

QUESTION

Calculate the number of moles of copper there are in a sample that weighs 127 g.

SOLUTION

Step 1 : ***Write the equation to calculate the number of moles***

$$n = \frac{m}{M}$$

Step 2 : ***Substitute numbers into the equation***

$$n = \frac{127}{63.55} = 2$$

There are 2 moles of copper in the sample.

Example 4: *Calculating mass from moles*

QUESTION

You are given a 5 mol sample of sodium. What mass of sodium is in the sample?

SOLUTION

Step 1 : ***Write the equation to calculate the sample mass.***

$$m = n \times M$$

Step 2 : ***Substitute values into the equation.***
$M_{\text{Na}} = 22.99 \text{ g} \cdot \text{mol}^{-1}$

Therefore,

$$m = 5 \times 22.99 = 114.95 \text{ g}$$

The sample of sodium has a mass of 114.95 g.

Example 5: *Calculating atoms from mass*

QUESTION

Calculate the number of atoms there are in a sample of aluminium that weighs 80.94 g.

SOLUTION

Step 1 : ***Calculate the number of moles of aluminium in the sample.***

$$n = \frac{m}{M} = \frac{80.94}{26.98} = 3 \text{ mol}$$

Step 2 : ***Use Avogadro's number to calculate the number of atoms in the sample.***

Number of atoms in 3 mol aluminium $= 3 \times 6.022 \times 10^{23}$
There are 18.069×10^{23} aluminium atoms in a sample of 80.94 g.

Exercise 6 - 3

1. Calculate the number of moles in each of the following samples:
   (a) 5.6 g of calcium
   (b) 0.02 g of manganese

(c) 40 g of aluminium

2. A lead sinker has a mass of 5 g.
   (a) Calculate the number of moles of lead the sinker contains.
   (b) How many lead atoms are in the sinker?
3. Calculate the mass of each of the following samples:
   (a) 2.5 mol magnesium
   (b) 12 mol lithium
   (c) 4.5×10^{25} atoms of silica

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(1.) 00yf (2.) 00yg (3.) 00yh

6.4 Molecules and compounds

ESBBJ

So far, we have only discussed moles, mass and molar mass in relation to *elements*. But what happens if we are dealing with a molecule or some other chemical compound? Do the same concepts and rules apply? The answer is 'yes'. However, you need to remember that all your calculations will apply to the *whole molecule*. So, when you calculate the molar mass of a molecule, you will need to add the molar mass of each atom in that compound. Also, the number of moles will also apply to the whole molecule. For example, if you have one mole of nitric acid (HNO_3), it means you have 6.022×10^{23} **molecules** of nitric acid in the sample. This also means that there are 6.022×10^{23} **atoms** of hydrogen, 6.022×10^{23} **atoms** of nitrogen and ($3 \times 6.022 \times 10^{23}$) **atoms** of oxygen in the sample.

In a balanced chemical equation, the number that is written in front of the element or compound, shows the **mole ratio** in which the reactants combine to form a product. If there are no numbers in front of the element symbol, this means the number is '1'.

$$\text{e.g. } N_2 + 3H_2 \rightarrow 2NH_3$$

In this reaction, 1 mole of nitrogen reacts with 3 moles of hydrogen to produce 2 moles of ammonia.

Example 6: *Calculating molar mass*

QUESTION

Calculate the molar mass of H_2SO_4.

SOLUTION

Step 1 : ***Use the periodic table to find the molar mass for each element in the molecule.***
Hydrogen $= 1.008$ g·mol^{-1}; Sulphur $= 32{,}07$ g·mol^{-1}; Oxygen $= 16$ g·mol^{-1}

Step 2 : ***Add the molar masses of each atom in the molecule***

$$M_{(H_2SO_4)} = (2 \times 1.008) + (32.07) + (4 \times 16) = 98.09 \text{ g} \cdot \text{mol}^{-1}$$

Example 7: *Calculating moles from mass*

QUESTION

Calculate the number of moles there are in 1 kg of $MgCl_2$.

SOLUTION

Step 1 : ***Write the equation for calculating the number of moles in the sample.***

$$n = \frac{m}{M}$$

Step 2 : ***Calculate the values that you will need, to substitute into the equation***

1. Convert mass into grams
$$m = 1kg \times 1000 = 1000g$$
2. Calculate the molar mass of $MgCl_2$.
$$M_{(MgCl_2)} = 24.31 + (2 \times 35.45) = 95.21 \text{ g} \cdot \text{mol}^{-1}$$

Step 3 : ***Substitute values into the equation***

$$n = \frac{1000}{95.21} = 10.5 \text{ mol}$$

There are 10.5 moles of magnesium chloride in a 1 kg sample.

Example 8: *Calculating the mass of reactants and products*

QUESTION

Barium chloride and sulphuric acid react according to the following equation to produce barium sulphate and hydrochloric acid.

$$BaCl_2 + H_2SO_4 \rightarrow BaSO_4 + 2HCl$$

If you have 2 g of $BaCl_2$:

1. *What quantity (in g) of H_2SO_4 will you need for the reaction so that all the barium chloride is used up?*
2. *What mass of HCl is produced during the reaction?*

SOLUTION

Step 1 : ***Calculate the number of moles of $BaCl_2$ that react.***

$$n = \frac{m}{M} = \frac{2}{208.24} = 0.0096 \text{ mol}$$

Step 2 : ***Determine how many moles of H_2SO_4 are needed for the reaction***
According to the balanced equation, 1 mole of $BaCl_2$ will react with 1 mole of H_2SO_4. Therefore, if 0.0096 moles of $BaCl_2$ react, then there must be the same number of moles of H_2SO_4 that react because their mole ratio is 1:1.

Step 3 : ***Calculate the mass of H_2SO_4 that is needed.***

$$m = n \times M = 0.0096 \times 98.086 = 0.94 \text{ g}$$

(answer to 1)

Step 4 : ***Determine the number of moles of HCl produced.***
According to the balanced equation, 2 moles of HCl are produced for every 1 mole of the two reactants. Therefore the number of moles of HCl produced is (2×0.0096), which equals 0.0192 moles.

Step 5 : ***Calculate the mass of HCl.***

$$m = n \times M = 0.0192 \times 35.73 = 0.69 \text{ g}$$

(answer to 2)

Activity: *Understanding moles and Avogadro's number*

Divide into groups of three and spend about 20 minutes answering the following questions together:

1. What are the units of the mole? Hint: Check the definition of the mole.
2. You have a 56 g sample of iron sulphide (FeS)

(a) How many **moles** of FeS are there in the sample?
(b) How many **molecules** of FeS are there in the sample?
(c) What is the difference between a mole and a molecule?

3. The exact size of **Avogadro's number** is sometimes difficult to imagine.
   (a) Write down Avogadro's number without using scientific notation.
   (b) How long would it take to count to Avogadro's number? You can assume that you can count two numbers in each second.

See video: VPjdj at www.everythingscience.co.za

Exercise 6 - 4

1. Calculate the molar mass of the following chemical compounds:
   (a) KOH
   (b) $FeCl_3$
   (c) $Mg(OH)_2$
2. How many moles are present in:
   (a) 10 g of Na_2SO_4
   (b) 34 g of $Ca(OH)_2$
   (c) 2.45×10^{23} molecules of CH_4?
3. For a sample of 0.2 moles of potassium bromide (KBr), calculate:
   (a) the number of moles of K^+ ions
   (b) the number of moles of Br^- ions
4. You have a sample containing 3 moles of calcium chloride.
   (a) What is the chemical formula of calcium chloride?
   (b) How many calcium atoms are in the sample?
5. Calculate the mass of:
   (a) 3 moles of NH_4OH
   (b) 4.2 moles of $Ca(NO_3)_2$
6. 96.2 g sulphur reacts with an unknown quantity of zinc according to the following equation:

$$Zn + S \rightarrow ZnS$$

   (a) What mass of zinc will you need for the reaction, if all the sulphur is to be used up?
   (b) What mass of zinc sulphide will this reaction produce?
7. Calcium chloride reacts with carbonic acid to produce calcium carbonate and hydrochloric acid according to the following equation:

$$CaCl_2 + H_2CO_3 \rightarrow CaCO_3 + 2HCl$$

   If you want to produce 10 g of calcium carbonate through this chemical reaction, what quantity (in g) of calcium chloride will you need at the start of the reaction?

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(1.) 00yi (2.) 00yj (3.) 00yk (4.) 00ym (5.) 00yn (6.) 00yp
(7.) 00yq

6.5 The Composition of Substances

ESBBK

The **empirical formula** of a chemical compound is a simple expression of the relative number of each type of atom in that compound. In contrast, the **molecular formula** of a chemical compound gives the actual number of atoms of each element found in a molecule of that compound.

DEFINITION: Empirical formula

The empirical formula of a chemical compound gives the relative number of each type of atom in that compound.

DEFINITION: Molecular formula

The molecular formula of a chemical compound gives the exact number of atoms of each element in one molecule of that compound.

The compound *ethanoic acid* for example, has the molecular formula CH_3COOH or simply $C_2H_4O_2$. In one molecule of this acid, there are two carbon atoms, four hydrogen atoms and two oxygen atoms. The ratio of atoms in the compound is 2:4:2, which can be simplified to 1:2:1. Therefore, the empirical formula for this compound is CH_2O. The empirical formula contains the smallest whole number ratio of the elements that make up a compound.

Knowing either the empirical or molecular formula of a compound, can help to determine its composition in more detail. The opposite is also true. Knowing the *composition* of a substance can help you to determine its formula. There are three different types of composition problems that you might come across:

1. Problems where you will be given the formula of the substance and asked to calculate the percentage by mass of each element in the substance.
2. Problems where you will be given the percentage composition and asked to calculate the formula.
3. Problems where you will be given the products of a chemical reaction and asked to calculate the formula of one of the reactants. These are often referred to as combustion analysis problems.

See video: VPjdp at www.everythingscience.co.za

Example 9: *Calculating the percentage by mass of elements in a compound*

QUESTION

Calculate the percentage that each element contributes to the overall mass of sulphuric acid (H_2SO_4).

SOLUTION

Step 1 : ***Write down the atomic mass of each element in the compound.***

Hydrogen $= 1.008 \times 2 = 2.016$ u
Sulphur $= 32.07$ u
Oxygen $= 4 \times 16 = 64$ u

Step 2 : ***Calculate the molecular mass of sulphuric acid.***
Use the calculations in the previous step to calculate the molecular mass of sulphuric acid.

$$\text{Mass} = 2.016 + 32.07 + 64 = 98.09 \text{ u}$$

Step 3 : ***Convert the mass of each element to a percentage of the total mass of the compound***
Use the equation:

$$\text{Percentage by mass} = \frac{\text{atomic mass}}{\text{molecular mass of } H_2SO_4} \times 100\%$$

Hydrogen

$$\frac{2.016}{98.09} \times 100\% = 2.06\%$$

Sulphur

$$\frac{32.07}{98.09} \times 100\% = 32.69\%$$

Oxygen

$$\frac{64}{98.09} \times 100\% = 65.25\%$$

(You should check at the end that these percentages add up to 100%!)
In other words, in one molecule of sulphuric acid, hydrogen makes up 2.06% of the mass of the compound, sulphur makes up 32.69% and oxygen makes up 65.25%.

Example 10: *Determining the empirical formula of a compound*

QUESTION

A compound contains 52.2% carbon (C), 13.0% hydrogen (H) and 34.8% oxygen (O). Determine its empirical formula.

SOLUTION

Step 1 : ***If we assume that we have 100 g of this substance, then we can convert each element percentage into a mass in grams.***

Carbon $= 52.2$ g, hydrogen $= 13.0$ g and oxygen $= 34.8$ g

Step 2 : ***Convert the mass of each element into number of moles***

$$n = \frac{m}{M}$$

Therefore,

$$n(carbon) = \frac{52.2}{12.01} = 4.35 \text{ mol}$$

$$n(hydrogen) = \frac{13.0}{1.008} = 12.90 \text{ mol}$$

$$n(oxygen) = \frac{34.8}{16} = 2.18 \text{ mol}$$

Step 3 : ***Convert these numbers to the simplest mole ratio by dividing by the smallest number of moles***

In this case, the smallest number of moles is 2.18. Therefore:

Carbon

$$\frac{4.35}{2.18} = 2$$

Hydrogen

$$\frac{12.90}{2.18} = 6$$

Oxygen

$$\frac{2.18}{2.18} = 1$$

Therefore the empirical formula of this substance is: C_2H_6O.

Example 11: *Determining the formula of a compound*

QUESTION

207 g of lead combines with oxygen to form 239 g of a lead oxide. Use this information to work out the formula of the lead oxide (atomic masses: Pb = 207 u and O = 16 u).

SOLUTION

Step 1 : ***Calculate the mass of oxygen in the reactants***

$$239 - 207 = 32 \text{ g}$$

Step 2 : ***Calculate the number of moles of lead and oxygen in the reactants.***

$$n = \frac{m}{M}$$

Lead

$$\frac{207}{207} = 1 \text{ mol}$$

Oxygen

$$\frac{32}{16} = 2 \text{ mol}$$

Step 3 : ***Deduce the formula of the compound***

The mole ratio of Pb:O in the product is 1:2, which means that for every atom of lead, there will be two atoms of oxygen. The formula of the compound is PbO_2.

Example 12: *Empirical and molecular formula*

QUESTION

Vinegar, which is used in our homes, is a dilute form of acetic acid. A sample of acetic acid has the following percentage composition: 39.9% carbon, 6.7% hydrogen and 53.4% oxygen.

1. *Determine the empirical formula of acetic acid.*
2. *Determine the molecular formula of acetic acid if the molar mass of acetic acid is* $60 \text{ g} \cdot \text{mol}^{-1}$.

SOLUTION

Step 1 : ***Calculate the mass of each element in 100 g of acetic acid.***

In 100 g of acetic acid, there is 39.9 g C, 6.7 g H and 53.4 g O

Step 2 : ***Calculate the number of moles of each element in 100 g of acetic acid.***

$n = \frac{m}{M}$

$$\begin{aligned} n_C &= \frac{39.9}{12} = 3.33 \text{ mol} \\ n_H &= \frac{6.7}{1} = 6.7 \text{ mol} \\ n_O &= \frac{53.4}{16} = 3.34 \text{ mol} \end{aligned}$$

Step 3 : ***Divide the number of moles of each element by the lowest number to get the simplest mole ratio of the elements (i.e. the empirical formula) in acetic acid.***

Empirical formula is CH_2O

Step 4 : ***Calculate the molecular formula, using the molar mass of acetic acid.***

The molar mass of acetic acid using the empirical formula is $30 \text{ g} \cdot \text{mol}^{-1}$. Therefore the actual number of moles of each element must be double what it is in the empirical formula.

The molecular formula is therefore $C_2H_4O_2$ or CH_3COOH

Exercise 6 - 5

1. Calcium chloride is produced as the product of a chemical reaction.
   (a) What is the formula of calcium chloride?
   (b) What percentage does each of the elements contribute to the mass of a molecule of calcium chloride?
   (c) If the sample contains 5 g of calcium chloride, what is the mass of calcium in the sample?
   (d) How many moles of calcium chloride are in the sample?
2. 13g of zinc combines with 6.4g of sulphur. What is the empirical formula of zinc sulphide?
   (a) What mass of zinc sulphide will be produced?
   (b) What percentage does each of the elements in zinc sulphide contribute to its mass?
   (c) Determine the formula of zinc sulphide.

3. A calcium mineral consisted of 29.4% calcium, 23.5% sulphur and 47.1% oxygen by mass. Calculate the empirical formula of the mineral.
4. A chlorinated hydrocarbon compound was analysed and found to consist of 24.24% carbon, 4.04% hydrogen and 71.72% chlorine. From another experiment the molecular mass was found to be 99 g · mol^{-1}. Deduce the empirical and molecular formula.

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(1.) 00yr (2.) 00ys (3.) 00yt (4.) 00yu

6.6 Molar Volumes of Gases

ESBBL

It is possible to calculate the volume of one mole of gas at STP using what we now know about gases.

1. *Write down the ideal gas equation*

$$pV = nRT, \text{ therefore } V = \frac{nRT}{p}$$

2. *Record the values that you know, making sure that they are in SI units*

   You know that the gas is under STP conditions. These are as follows:

   p = 101.3 kPa = 101 300 Pa

   n = 1 mole

   $R = 8.31$ J · K^{-1} · mol^{-1}

   T = 273 K

3. *Substitute these values into the original equation.*

$$V = \frac{nRT}{p}$$

$$V = \frac{1 \text{ mol} \times 8.31 \text{ J} \cdot \text{K}^{-1} \cdot \text{mol}^{-1} \times 273K}{101\ 300 \text{ Pa}}$$

4. *Calculate the volume of 1 mole of gas under these conditions* The volume of 1 mole of gas at STP is 22.4×10^{-3} m^3 = 22.4 dm^3.

Tip

The standard units used for this equation are P in Pa, V in m^3 and T in K. Remember also that 1 000 cm^3 = 1 dm^3 and 1 000 dm^3 = 1 m^3.

Example 13: *Ideal Gas*

QUESTION

A sample of gas occupies a volume of 20 dm^3, has a temperature of 280 K and has a pressure

of 105 Pa. Calculate the number of moles of gas that are present in the sample.

SOLUTION

Step 1 : ***Convert all values into SI units***

The only value that is not in SI units is volume. V $= 0.02$ m^3.

Step 2 : ***Write the equation for calculating the number of moles in a gas.***

We know that $pV = nRT$
Therefore,

$$n = \frac{pV}{RT}$$

Step 3 : ***Substitute values into the equation to calculate the number of moles of the gas.***

$$n = \frac{105 \times 0.02}{8.31 \times 280} = \frac{2.1}{2326.8} = 0.0009 \text{ mol}$$

Exercise 6 - 6

1. An enclosed gas(i.e. one in a sealed container) has a volume of 300 cm^3 and a temperature of 300 K. The pressure of the gas is 50 kPa. Calculate the number of moles of gas that are present in the container.

2. What pressure will 3 mol of gaseous nitrogen exert if it is pumped into a container that has a volume of 25 dm^3 at a temperature of 29 °C?

3. The volume of air inside a tyre is 19 litres and the temperature is 290 K. You check the pressure of your tyres and find that the pressure is 190 kPa. How many moles of air are present in the tyre?

4. Compressed carbon dioxide is contained within a gas cylinder at a pressure of 700 kPa. The temperature of the gas in the cylinder is 310 K and the number of moles of gas is 13 moles of carbon dioxide. What is the volume of the gas inside the cylinder?

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(1.) 00yv (2.) 00yw (3.) 00yx (4.) 00yy

6.7 Molar concentrations of liquids

ESBBM

A typical solution is made by dissolving some solid substance in a liquid. The amount of substance that is dissolved in a given volume of liquid is known as the **concentration** of the liquid. Mathematically, concentration (C) is defined as moles of solute (n) per unit volume (V) of solution.

Tip

Do not confuse molarity (M) with molar mass (M). Look carefully at the question in which the M appears to determine whether it is concentration or molar mass. Sometimes you will see molar mass written as M_m.

$$C = \frac{n}{V}$$

For this equation, the units for volume are dm^3. Therefore, the unit of concentration is mol.dm^{-3}. When concentration is expressed in mol.dm^{-3} it is known as the **molarity** (M) of the solution. Molarity is the most common expression for concentration.

DEFINITION: Concentration

Concentration is a measure of the amount of solute that is dissolved in a given volume of liquid. It is measured in mol.dm^{-3}. Another term that is used for concentration is **molarity (M)**

Example 14: *Concentration Calculations 1*

QUESTION

If 3.5 g of sodium hydroxide (NaOH) is dissolved in 2.5 dm^3 of water, what is the concentration of the solution in mol.dm^{-3}?

SOLUTION

Step 1 : ***Convert the mass of NaOH into moles***

$$n = \frac{m}{M} = \frac{3.5}{40} = 0.0875 \text{ mol}$$

Step 2 : ***Calculate the concentration of the solution.***

$$C = \frac{n}{V} = \frac{0.0875}{2.5} = 0.035 \text{ M}$$

The concentration of the solution is 0.035 mol $\cdot$ dm^{-3} or 0.035 M

Example 15: *Concentration Calculations 2*

QUESTION

You have a 1 dm^3 container in which to prepare a solution of potassium permanganate ($KMnO_4$). What mass of $KMnO_4$ is needed to make a solution with a concentration of 0.2 M?

SOLUTION

Step 1 : ***Calculate the number of moles of $KMnO_4$ needed.***

$$C = \frac{n}{V}$$

therefore

$$n = C \times V = 0.2 \times 1 = 0.2 \text{ mol}$$

Step 2 : ***Convert the number of moles of $KMnO_4$ to mass.***

$$m = n \times M = 0.2 \times 158.04 = 31.61 \text{ g}$$

The mass of $KMnO_4$ that is needed is 31.61 g.

Example 16: *Concentration Calculations 3*

QUESTION

How much sodium chloride (in g) will one need to prepare 500 cm^3 of solution with a concentration of 0.01 M?

SOLUTION

Step 1 : ***Convert all quantities into the correct units for this equation.***

$$V = \frac{500}{1000} = 0.5 \text{ dm}^3$$

Step 2 : ***Calculate the number of moles of sodium chloride needed.***

$$n = C \times V = 0.01 \times 0.5 = 0.005 \text{ mol}$$

Step 3 : ***Convert moles of $KMnO_4$ to mass.***

$$m = n \times M = 0.005 \times 58.45 = 0.29 \text{ g}$$

The mass of sodium chloride needed is 0.29 g

Exercise 6 - 7

1. 5.95 g of potassium bromide was dissolved in 400 cm^3 of water. Calculate its molarity.
2. 100 g of sodium chloride (NaCl) is dissolved in 450 cm^3 of water.
   (a) How many moles of NaCl are present in solution?
   (b) What is the volume of water (in dm^3)?
   (c) Calculate the concentration of the solution.
   (d) What mass of sodium chloride would need to be added for the concentration to become 5.7 $mol.dm^{-3}$?
3. What is the molarity of the solution formed by dissolving 80 g of sodium hydroxide (NaOH) in 500 cm^3 of water?
4. What mass (g) of hydrogen chloride (HCl) is needed to make up 1000 cm^3 of a solution of concentration 1 $mol.dm^{-3}$?
5. How many moles of H_2SO_4 are there in 250 cm^3 of a 0.8M sulphuric acid solution? What mass of acid is in this solution?

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(1.) 00yz (2.) 00z0 (3.) 00z1 (4.) 00z2 (5.) 00z3

6.8 Stoichiometric calculations

ESBBN

Stoichiometry is the calculation of the quantities of reactants and products in chemical reactions. It is also the numerical relationship between reactants and products. In grade 10 you learnt how to write balanced chemical equations. By knowing the ratios of substances in a reaction, it is possible to use stoichiometry to calculate the amount of either reactants or products that are involved in the reaction. The examples shown below will make this concept clearer.
See video: VPjgn at www.everythingscience.co.za

Example 17: Stoichiometric calculation 1

QUESTION

What volume of oxygen at S.T.P. is needed for the complete combustion of 2dm^3 of propane (C_3H_8)? (Hint: CO_2 and H_2O are the products in this reaction (and in all combustion reactions))

SOLUTION

Step 1 : ***Write a balanced equation for the reaction.***

$$C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4H_2O(g)$$

Step 2 : ***Determine the ratio of oxygen to propane that is needed for the reaction.***
From the balanced equation, the ratio of oxygen to propane in the reactants is 5:1.

Step 3 : ***Determine the volume of oxygen needed for the reaction.***
1 volume of propane needs 5 volumes of oxygen, therefore 2 dm^3 of propane will need 10 dm^3 of oxygen for the reaction to proceed to completion.

Example 18: Stoichiometric calculation 2

QUESTION

What mass of iron (II) sulphide is formed when 5.6 g of iron is completely reacted with sulphur?

SOLUTION

Step 1 : ***Write a balanced chemical equation for the reaction.***

$$Fe(s) + S(s) \rightarrow FeS(s)$$

Step 2 : ***Calculate the number of moles of iron that react.***

$$n = \frac{m}{M} = \frac{5.6}{55.85} = 0.1 \text{ mol}$$

Step 3 : ***Determine the number of moles of FeS produced.***
From the equation 1 mole of Fe gives 1 mole of FeS. Therefore, 0.1 moles of iron in the reactants will give 0.1 moles of iron sulphide in the product.

Step 4 : ***Calculate the mass of iron sulphide formed***

Tip

A closer look at the worked example (stoichiometric calculation 2) shows that 5.6 g of iron is needed to produce 8.79 g of iron (II) sulphide. The amount of sulphur that is needed in the reactants is 3.2 g. What would happen if the amount of sulphur in the reactants was increased to 6.4 g but the amount of iron was still 5.6 g? Would more FeS be produced? In fact, the amount of iron(II) sulphide produced remains the same. No matter how much sulphur is added to the system, the amount of iron (II) sulphide will not increase because there is not enough iron to react with the additional sulphur in the reactants to produce more FeS. When all the iron is used up the reaction stops. In this example, the iron is called the **limiting reagent**. Because there is more sulphur than can be used up in the reaction, it is called the **excess reagent**.

$$m = n \times M = 0.1 \times 87.911 = 8.79 \text{ g}$$

The mass of iron (II) sulphide that is produced during this reaction is 8.79 g.

Example 19: *Industrial reaction to produce fertiliser*

QUESTION

Sulphuric acid (H_2SO_4) reacts with ammonia (NH_3) to produce the fertiliser ammonium sulfate ($(NH_4)_2SO_4$) according to the following equation:

$$H_2SO_4(aq) + 2NH_3(g) \rightarrow (NH_4)_2SO_4(aq)$$

What is the maximum mass of ammonium sulphate that can be obtained from 2.0 kg of sulphuric acid and 1.0 kg of ammonia?

SOLUTION

Step 1 : ***Convert the mass of sulphuric acid and ammonia into moles***

$$n(H_2SO_4) = \frac{m}{M} = \frac{2000 \text{ g}}{98.078 \text{ g} \cdot \text{mol}^{-1}} = 20.39 \text{ mol}$$

$$n(NH_3) = \frac{1000 \text{ g}}{17.03 \text{ g} \cdot \text{mol}^{-1}} = 58.72 \text{ mol}$$

Step 2 : ***Use the balanced equation to determine which of the reactants is limiting.***
From the balanced chemical equation, 1 mole of H_2SO_4 reacts with 2 moles of NH_3 to give 1 mole of $(NH_4)_2SO_4$. Therefore 20.39 moles of H_2SO_4 need to react with 40.78 moles of NH_3. In this example, NH_3 is in excess and H_2SO_4 is the limiting reagent.

Step 3 : ***Calculate the maximum amount of ammonium sulphate that can be produced***
Again from the equation, the mole ratio of H_2SO_4 in the reactants to $(NH_4)_2SO_4$ in the product is 1:1. Therefore, 20.39 moles of H_2SO_4 will produce 20.39 moles of $(NH_4)_2SO_4$.

The maximum mass of ammonium sulphate that can be produced is calculated as follows:

$$m = n \times M = 20.41 \text{ mol} \times 132 \text{ g} \cdot \text{mol}^{-1} = 2694 \text{ g}$$

The maximum amount of ammonium sulphate that can be produced is 2.694 kg.

Exercise 6 - 8

1. Diborane, B_2H_6, was once considered for use as a rocket fuel. The combustion reaction for diborane is:

$$B_2H_6(g) + 3O_2(g) \rightarrow 2HBO_2(g) + 2H_2O(\ell)$$

   If we react 2.37 grams of diborane, how many grams of water would we expect to produce?

2. Sodium azide is a commonly used compound in airbags. When triggered, it has the following reaction:

$$2NaN_3(s) \rightarrow 2Na(s) + 3N_2(g)$$

   If 23.4 grams of sodium azide is used, how many moles of nitrogen gas would we expect to produce?

3. Photosynthesis is a chemical reaction that is vital to the existence of life on Earth. During photosynthesis, plants and bacteria convert carbon dioxide gas, liquid water, and light into glucose ($C_6H_{12}O_6$) and oxygen gas.
   (a) Write down the equation for the photosynthesis reaction.
   (b) Balance the equation.
   (c) If 3 moles of carbon dioxide are used up in the photosynthesis reaction, what mass of glucose will be produced?

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(1.) 00z4 (2.) 00z5 (3.) 00z6

Chapter 6 — Summary

See the summary presentation (Presentation: VPjgr at www.everythingscience.co.za)

- It is important to be able to quantify the changes that take place during a chemical reaction.
- The **mole (n)** is a SI unit that is used to describe an amount of substance that contains the same number of particles as there are atoms in 12 g of carbon.
- The number of particles in a mole is called the **Avogadro constant** and its value is 6.022×10^{23}. These particles could be atoms, molecules or other particle units, depending on the substance.
- The **molar mass (M)** is the mass of one mole of a substance and is measured in grams per mole or $g.mol^{-1}$. The numerical value of an element's molar mass is the same as its atomic mass. For a compound, the molar mass has the same numerical value as the molecular mass of that compound.
- The relationship between moles (n), mass in grams (m) and molar mass (M) is defined by the following equation:

$$n = \frac{m}{M}$$

- In a balanced chemical equation, the number in front of the chemical symbols describes the **mole ratio** of the reactants and products.

- The **empirical formula** of a compound is an expression of the relative number of each type of atom in the compound.

- The **molecular formula** of a compound describes the actual number of atoms of each element in a molecule of the compound.

- The formula of a substance can be used to calculate the **percentage by mass** that each element contributes to the compound.

- The **percentage composition** of a substance can be used to deduce its chemical formula.

- One mole of gas occupies a volume of 22.4 dm^3.

- The **concentration** of a solution can be calculated using the following equation,

$$C = \frac{n}{V}$$

  where C is the concentration (in $mol.dm^{-3}$), n is the number of moles of solute dissolved in the solution and V is the volume of the solution (in dm^3).

- **Molarity** is a measure of the concentration of a solution, and its units are $mol.dm^{-3}$.

- **Stoichiometry** is the calculation of the quantities of reactants and products in chemical reactions. It is also the numerical relationship between reactants and products.

- A **limiting reagent** is the chemical that is used up first in a reaction, and which therefore determines how far the reaction will go before it has to stop.

- An **excess reagent** is a chemical that is in greater quantity than the limiting reagent in the reaction. Once the reaction is complete, there will still be some of this chemical that has not been used up.

Chapter 6 End of Chapter Exercises

1. Write only the word/term for each of the following descriptions:
   (a) the mass of one mole of a substance
   (b) the number of particles in one mole of a substance
2. 5 g of magnesium chloride is formed as the product of a chemical reaction. Select the **true** statement from the answers below:
   (a) 0.08 moles of magnesium chloride are formed in the reaction
   (b) the number of atoms of Cl in the product is 0.6022×10^{23}
   (c) the number of atoms of Mg is 0.05
   (d) the atomic ratio of Mg atoms to Cl atoms in the product is 1:1
3. 2 moles of oxygen gas react with hydrogen. What is the mass of oxygen in the reactants?
   (a) 32 g
   (b) 0.125 g
   (c) 64 g
   (d) 0.063 g
4. In the compound potassium sulphate (K_2SO_4), oxygen makes up x% of the mass of the compound. $x =$:
   (a) 36.8
   (b) 9.2
   (c) 4
   (d) 18.3
5. The molarity of a 150 cm^3 solution, containing 5 g of NaCl is...
   (a) 0.09 M
   (b) 5.7×10^{-4} M
   (c) 0.57 M
   (d) 0.03 M
6. 300 cm^3 of a 0.1 $mol.dm^{-3}$ solution of sulphuric acid is added to 200 cm^3 of a 0.5 $mol.dm^{-3}$ solution of sodium hydroxide.
   (a) Write down a balanced equation for the reaction which takes place when these two solutions are mixed.
   (b) Calculate the number of moles of sulphuric acid which were added to the sodium hydroxide solution.
   (c) Is the number of moles of sulphuric acid enough to fully neutralise the sodium hydroxide solution? Support your answer by showing all relevant calculations. (IEB Paper 2 2004)
7. Ozone (O_3) reacts with nitrogen monoxide gas (NO) to produce NO_2 gas. The NO gas forms largely as a result of emissions from the exhausts of motor vehicles and from certain jet planes. The NO_2 gas also contributes to the brown smog (smoke and fog), which is seen over most urban areas. This gas is also harmful to humans, as it causes breathing (respiratory) problems. The following equation indicates the reaction between ozone and nitrogen monoxide:

$$O_3(g) + NO(g) \rightarrow O_2(g) + NO_2(g)$$

In one such reaction 0.74 g of O_3 reacts with 0.67 g NO.

(a) Calculate the number of moles of O_3 and of NO present at the start of the reaction.

(b) Identify the limiting reagent in the reaction and justify your answer.

(c) Calculate the mass of NO_2 produced from the reaction.

(DoE Exemplar Paper 2, 2007)

8. A learner is asked to make 200 cm^3 of sodium hydroxide (NaOH) solution of concentration 0.5 $mol.dm^{-3}$.

(a) Determine the mass of sodium hydroxide pellets he needs to use to do this.

(b) Using an accurate balance the learner accurately measures the correct mass of the NaOH pellets. To the pellets he now adds exactly 200 cm^3 of pure water. Will his solution have the correct concentration? Explain your answer.
The learner then takes 300 cm^3 of a 0.1 $mol.dm^{-3}$ solution of sulphuric acid (H_2SO_4) and adds it to 200 cm^3 of a 0.5 $mol.dm^{-3}$ solution of NaOH at 25^0C.

(c) Write down a balanced equation for the reaction which takes place when these two solutions are mixed.

(d) Calculate the number of moles of H_2SO_4 which were added to the NaOH solution.

(e) Is the number of moles of H_2SO_4 calculated in the previous question enough to fully neutralise the NaOH solution? Support your answer by showing all the relevant calculations.
(IEB Paper 2, 2004)

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(1.) 00z7 (2.) 00z8 (3.) 00z9 (4.) 00za (5.) 00zb (6.) 01y4
(7.) 01y5 (8.) 01y6

Energy Changes In Chemical Reactions 7

All chemical reactions involve energy changes. In some reactions, we are able to observe these energy changes as either an increase or a decrease in the overall energy of the system.

See introductory video: VPjkd at www.everythingscience.co.za

7.1 What causes the energy changes in chemical reactions? ESBBO

When a chemical reaction occurs, bonds in the reactants *break*, while new bonds *form* in the product. The following example explains this. Hydrogen reacts with oxygen to form water, according to the following equation:

$$2H_2 + O_2 \rightarrow 2H_2O$$

In this reaction, the bond between the two hydrogen atoms in the H_2 molecule will *break*, as will the bond between the oxygen atoms in the O_2 molecule. New bonds will *form* between the two hydrogen atoms and the single oxygen atom in the water molecule that is formed as the product.

For bonds to *break*, energy must be *absorbed*. When new bonds *form*, energy is *released*. The energy that is needed to break a bond is called the **bond energy** or **bond dissociation energy**. Bond energies are measured in units of kJ.mol^{-1}.

> *DEFINITION: Bond energy*
>
> Bond energy is a measure of bond strength in a chemical bond. It is the amount of energy (in kJ.mol^{-1}) that is needed to break the chemical bond between two atoms.

7.2 Exothermic and endothermic reactions ESBBP

In some reactions, the energy that must be *absorbed* to break the bonds in the reactants, is less than the total energy that is *released* when new bonds are formed. This means that in the overall reaction, energy is *released* as either heat or light. This type of reaction is called an **exothermic** reaction. Another way of describing an exothermic reaction is that it is one in which the energy of the product is less than the energy of the reactants, because energy has been released during the reaction. We can represent this using the following general formula:

$$\text{Reactants} \rightarrow \text{Product} + \text{Energy}$$

DEFINITION: Exothermic reaction

An exothermic reaction is one that releases energy in the form of heat or light.

In other reactions,the energy that must be *absorbed* to break the bonds in the reactants, is more than the total energy that is *released* when new bonds are formed. This means that in the overall reaction, energy must be *absorbed* from the surroundings. This type of reaction is known as an **endothermic** reaction. Another way of describing an endothermic reaction is that it is one in which the energy of the product is greater than the energy of the reactants, because energy has been absorbed during the reaction. This can be represented by the following formula:

$$\text{Reactants} + \text{Energy} \rightarrow \text{Product}$$

DEFINITION: Endothermic reaction

An endothermic reaction is one that absorbs energy in the form of heat or light.

The difference in energy (E) between the reactants and the products is known as the **heat of the reaction**. It is also sometimes referred to as the **enthalpy change** of the system.

General experiment: *Endothermic and exothermic reactions 1*

Apparatus and materials: You will need citric acid, sodium bicarbonate, a glass beaker, the lid of a margarine container, thermometer, glass stirring rod and a pair of scissors. Note that citric acid is found in citrus fruits such as lemons. Sodium bicarbonate is actually bicarbonate of soda (baking soda), the baking ingredient that helps cakes to rise.
Method:

1. Cut a piece of plastic from the margarine container lid that will be big enough to cover the top of the beaker. Cut a small hole in the centre of this piece of plastic and place the thermometer through it.
2. Pour some citric acid ($H_3C_6H_5O_7$) into the glass beaker, cover the beaker with its 'lid' and record the temperature of the solution.
3. Stir in the sodium bicarbonate ($NaHCO_3$), then cover the beaker again.
4. Immediately record the temperature, and then take a temperature reading every two minutes after that. Record your results in a table like the one below.

Time (mins)	0	2	4	6
Temperature (^{0}C)				

The equation for the reaction that takes place is:

$$H_3C_6H_5O_7(aq) + 3NaHCO_3(s) \rightarrow 3CO_2(g) + 3H_2O(\ell) + Na_3C_6H_5O_7(aq)$$

Results:

- Plot your temperature results on a graph of temperature against time. What happens to the temperature during this reaction?
- Is this an exothermic or an endothermic reaction?
- Why was it important to keep the beaker covered with a lid?

- Do you think a glass beaker is the best thing to use for this experiment? Explain your answer.
- Suggest another container that could have been used and give reasons for your choice. It might help you to look back to Grade 10 for some ideas!

General experiment: *Endothermic and exothermic reactions 2*

Apparatus and materials: Vinegar, steel wool, thermometer, glass beaker and plastic lid (from previous demonstration).
Method:

1. Put the thermometer through the plastic lid, cover the beaker and record the temperature in the empty beaker. You will need to leave the thermometer in the beaker for about 5 minutes in order to get an accurate reading.
2. Take the thermometer out of the jar.
3. Soak a piece of steel wool in vinegar for about a minute. The vinegar removes the protective coating from the steel wool so that the metal is exposed to oxygen.
4. After the steel wool has been in the vinegar, remove it and squeeze out any vinegar that is still on the wool. Wrap the steel wool around the thermometer and place it (still wrapped round the thermometer) back into the jar. The jar is automatically sealed when you do this because the thermometer is through the top of the lid.
5. Leave the steel wool in the beaker for about 5 minutes and then record the temperature. Record your observations.

Results: You should notice that the temperature *increases* when the steel wool is wrapped around the thermometer.
Conclusion: The reaction between oxygen and the exposed metal in the steel wool, is **exothermic**, which means that energy is released and the temperature increases.

7.3 The heat of reaction

ESBBQ

The **heat of the reaction** is represented by the symbol ΔH, where:

$$\Delta H = E_{prod} - E_{react}$$

- In an *exothermic* reaction, ΔH is less than zero because the energy of the reactants is greater than the energy of the product. For example,

  $H_2 + Cl_2 \rightarrow 2HCl \qquad \Delta H = -183$ kJ

- In an *endothermic* reaction, ΔH is greater than zero because the energy of the reactants is less than the energy of the product. For example,

$$C + H_2O \rightarrow CO + H_2 \qquad \Delta H = +131 \text{ kJ}$$

Some of the information relating to exothermic and endothermic reactions is summarised in Table 7.1.

DEFINITION: Enthalpy

Enthalpy is the heat content of a chemical system for a given pressure, and is given the symbol 'H'.

Type of reaction	**Exothermic**	**Endothermic**
Energy absorbed or released	Released	Absorbed
Relative energy of reactants and products	Energy of reactants greater than energy of product	Energy of reactants less than energy of product
Sign of ΔH	Negative	Positive

Table 7.1: A comparison of exothermic and endothermic reactions

Writing equations using ΔH
There are two ways to write the heat of the reaction in an equation. For the exothermic reaction $C(s) + O_2(g) \rightarrow CO_2(g)$, we can write:
$C(s) + O_2(g) \rightarrow CO_2(g) \qquad \Delta H = -393 \text{ kJ} \cdot \text{mol}^{-1}$ or
$C(s) + O_2(g) \rightarrow CO_2(g) + 393 \text{ kJ} \cdot \text{mol}^{-1}$
For the endothermic reaction, $C(s) + H_2O(g) \rightarrow H_2(g) + CO(g)$, we can write:
$C(s) + H_2O(g) \rightarrow H_2(g) + CO(g) \qquad \Delta H = +131 \text{ kJ} \cdot \text{mol}^{-1}$ or
$C(s) + H_2O(g) + 131\text{kJ} \cdot \text{mol}^{-1} \rightarrow CO + H_2$
The **units** for ΔH are $\text{kJ} \cdot \text{mol}^{-1}$. In other words, the ΔH value gives the amount of energy that is absorbed or released per mole of product that is formed. Units can also be written as kJ, which then gives the total amount of energy that is released or absorbed when the product forms.

Activity: *Endothermic and exothermic reactions*

Apparatus and materials:

Approximately 2 g each of calcium chloride ($CaCl_2$), sodium hydroxide (NaOH), potassium nitrate (KNO_3) and barium chloride ($BaCl_2$); concentrated sulphuric acid (H_2SO_4) (Be Careful, this can cause serious burns) ; 5 test tubes; thermometer.

Method:

1. Dissolve about 1 g of each of the following substances in 5-10 cm^3 of water in a test tube: $CaCl_2$, NaOH, KNO_3 and $BaCl_2$.
2. Observe whether the reaction is endothermic or exothermic, either by feeling whether the side of the test tube gets hot or cold, or using a thermometer.
3. Dilute 3 cm^3 of concentrated H_2SO_4 in 10 cm^3 of water in the fifth test tube and observe whether the temperature changes.
4. Wait a few minutes and then carefully add NaOH to the H_2SO_4. Observe any energy changes.
5. Record which of the above reactions are endothermic and which are exothermic.

Results:

- When $BaCl_2$ and KNO_3 dissolve in water, they take in heat from the surroundings. The dissolution of these salts is **endothermic**.
- When $CaCl_2$ and NaOH dissolve in water, heat is released. The process is **exothermic**.
- The reaction of H_2SO_4 and NaOH is also **exothermic**.

7.4 Examples of endothermic and exothermic reactions

ESBBR

There are many examples of endothermic and exothermic reactions that occur around us all the time. The following are just a few examples.

1. **Endothermic reactions**

   - **Photosynthesis**
     Photosynthesis is the chemical reaction that takes place in plants, which uses energy from the sun to change carbon dioxide and water into food that the plant needs to survive, and which other organisms (such as humans and other animals) can eat so that they too can survive. The equation for this reaction is:

     $$6CO_2 + 12H_2O + \text{energy} \rightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O$$

     Photosynthesis is an endothermic reaction because it will not happen without an external source of energy, which in this case is sunlight.

   - **The thermal decomposition of limestone**
     In industry, the breakdown of limestone into quicklime and carbon dioxide is very important. Quicklime can be used to make steel from iron and also to neutralise soils that are too acid. However, the limestone must be heated in a kiln at a temperature of over $900°C$ before the decomposition reaction will take place. The equation for the reaction is shown below:

     $$CaCO_3 \rightarrow CaO + CO_2$$

2. **Exothermic reactions**

   - **Combustion reactions** - The burning of fuel is an example of a combustion reaction, and we as humans rely heavily on this process for our energy requirements. The following equations describe the combustion of a hydrocarbon such as *methane* (CH_4):

     $$\text{Fuel} + \text{Oxygen} \rightarrow \text{Heat} + \text{Water} + \text{Carbon Dioxide}$$
     $$CH_4 + 2O_2 \rightarrow \text{Heat} + 2H_2O + CO_2$$

     This is why we burn fuels for energy, because the chemical changes that take place during the reaction release huge amounts of energy, which we then use for things like power and electricity. You should also note that *carbon dioxide* is produced during this reaction. Later we will discuss some of the negative impacts of CO_2 on the environment. The chemical reaction that takes place when fuels burn therefore has both positive and negative consequences.

   - **Respiration**
     Respiration is the chemical reaction that happens in our bodies to produce energy for our cells. The equation below describes what happens during this reaction:

     $$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$$

FACT

Lightsticks or glowsticks are used by divers, campers, and for decoration and fun. A lightstick is a plastic tube with a glass vial inside it. To activate a lightstick, you bend the plastic stick, which breaks the glass vial. This allows the chemicals that are inside the glass to mix with the chemicals in the plastic tube. These two chemicals react and release energy. Another part of a lightstick is a fluorescent dye which changes this energy into light, causing the lightstick to glow!

In the reaction above, glucose (a type of carbohydrate in the food we eat) reacts with oxygen from the air that we breathe in, to form carbon dioxide (which we breathe out), water and energy. The energy that is produced allows the cell to carry out its functions efficiently. Can you see now why you are always told that you must eat food to get energy? It is not the food itself that provides you with energy, but the exothermic reaction that takes place when compounds within the food react with the oxygen you have breathed in!

Exercise 7 - 1

1. In each of the following reactions, say whether the reaction is endothermic or exothermic, and give a reason for your answer.
   (a) $H_2 + I_2 \rightarrow 2HI + 21\ kJ \cdot mol^{-1}$
   (b) $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad \Delta H = -802\ kJ \cdot mol^{-1}$
   (c) The following reaction takes place in a flask:
   $Ba(OH)_2.8H_2O + 2NH_4NO_3 \rightarrow Ba(NO_3)_2 + 2NH_3 + 10H_2O$
   Within a few minutes, the temperature of the flask drops by approximately $20°C$.
   (d) $2Na + Cl_2 \rightarrow 2NaCl \quad \Delta H = -411\ kJ \cdot mol^{-1}$
   (e) $C + O_2 \rightarrow CO_2$
2. For each of the following descriptions, say whether the process is endothermic or exothermic and give a reason for your answer.
   (a) evaporation
   (b) the combustion reaction in a car engine
   (c) bomb explosions
   (d) melting ice
   (e) digestion of food
   (f) condensation

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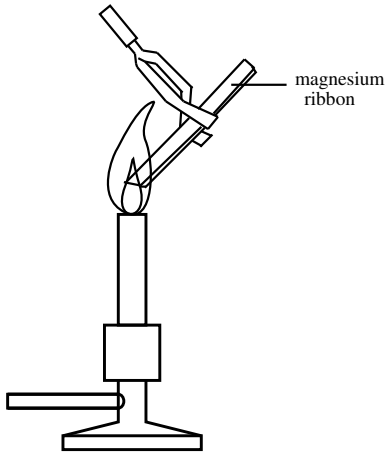
7.5 Spontaneous and non-spontaneous reactions

ESBBS

Activity: *Spontaneous and non-spontaneous reactions*

Apparatus and materials:
A length of magnesium ribbon, thick copper wire and a Bunsen burner.



Method:

1. Scrape the length of magnesium ribbon and copper wire clean.
2. Heat each piece of metal over the Bunsen burner, in a non-luminous flame. Do Not look directly at the flame. Observe whether any chemical reaction takes place.
3. Remove the metals from the flame and observe whether the reaction stops. If the reaction stops, return the metal to the Bunsen flame and continue to heat it.

Results:

- Did any reaction take place before the metals were heated?
- Did either of the reactions continue after they were removed from the flame?
- Write a balanced equation for each of the chemical reactions that takes place.

In the demonstration above, the reaction between magnesium and oxygen, and the reaction between copper and oxygen are both **non-spontaneous**. Before the metals were held over the Bunsen burner, no reaction was observed. They need energy to *initiate* the reaction. After the reaction has started, it may then carry on spontaneously. This is what happened when the magnesium reacted with oxygen. Even after the magnesium was removed from the flame, the reaction continued. Other reactions will not carry on unless there is a constant addition of energy. This was the case when copper reacted with oxygen. As soon as the copper was removed from the flame, the reaction stopped.

Now try carefully adding a solution of dilute sulphuric acid to a solution of sodium hydroxide. What do you observe? This is an example of a **spontaneous reaction** because the reaction takes place without any energy being added.

DEFINITION: Spontaneous reaction

A spontaneous reaction is a physical or chemical change that occurs without the addition of energy.

7.6 Activation energy and the activated complex

ESBBT

From the demonstrations of spontaneous and non-spontaneous reactions, it should be clear that most reactions will not take place until the system has some minimum amount of energy added to it. This energy is called the **activation energy**. **Activation energy** is the 'threshold energy' or the energy that must be overcome in order for a chemical reaction to occur.

> *DEFINITION: Activation energy*
>
> Activation energy or 'threshold energy' is the energy that must be overcome in order for a chemical reaction to occur.

It is possible to draw an energy diagram to show the energy changes that take place during a particular reaction. Let's consider an example:

$$H_2(g) + F_2(g) \rightarrow 2HF(g)$$

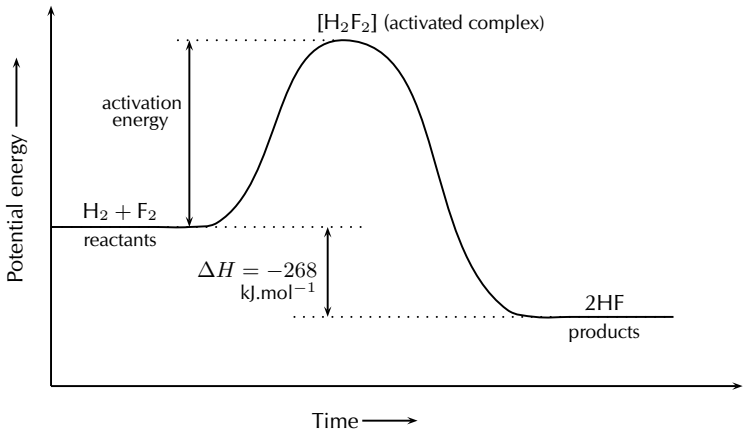


Figure 7.1: The energy changes that take place during an exothermic reaction

The reaction between $H_2(g)$ and $F_2(g)$ (Figure 7.1) needs energy in order to proceed, and this is the activation energy. Once the reaction has started, an in-between, temporary state is reached where the two reactants combine to give H_2F_2. This state is sometimes called a **transition state** and the energy that is needed to reach this state is equal to the activation energy for the reaction. The compound that is formed in this transition state is called the **activated complex**. The transition state lasts for only a very short time, after which either the original bonds reform, or the bonds are broken and a new product forms. In this example, the final product is HF and it has a lower energy than the reactants. The reaction is exothermic and ΔH is negative.

DEFINITION: Activated complex

The activated complex is a transitional structure in a chemical reaction that results from the effective collisions between reactant molecules, and which remains while old bonds break and new bonds form.

In endothermic reactions, the final products have a higher energy than the reactants. An energy diagram is shown below (Figure 7.2) for the endothermic reaction $XY + Z \rightarrow X + YZ$. In this example, the activated complex has the formula XYZ. Notice that the activation energy for the endothermic reaction is much greater than for the exothermic reaction.

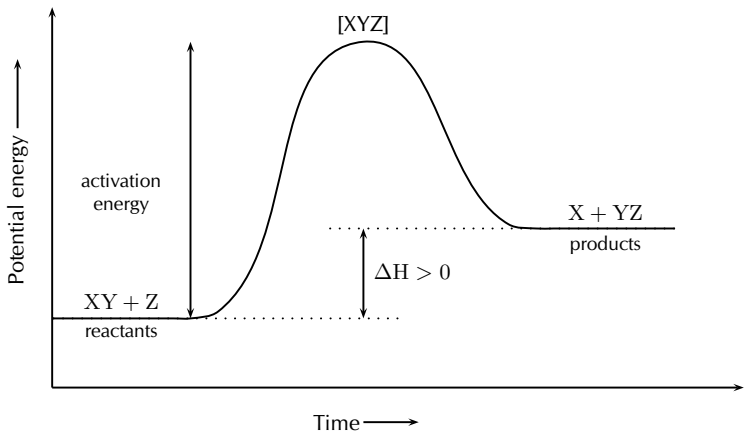


Figure 7.2: The energy changes that take place during an endothermic reaction

Tip

Enzymes and activation energy

An enzyme is a catalyst that helps to speed up the rate of a reaction by lowering the activation energy of a reaction. There are many enzymes in the human body, without which lots of important reactions would never take place. Cellular respiration is one example of a reaction that is catalysed by enzymes. You will learn more about catalysts in Grade 12.

FACT

The reaction between H and F was considered by NASA (National Aeronautics and Space Administration) as a fuel system for rocket boosters because of the energy that is released during this exothermic reaction.

Exercise 7 - 2

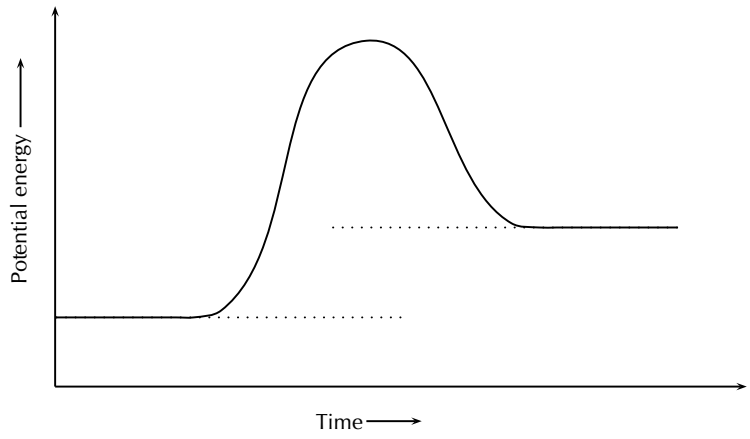
1. Carbon reacts with water according to the following equation:

$$C + H_2O \rightarrow CO + H_2 \quad \Delta H > 0$$

   (a) Is this reaction endothermic or exothermic?

   (b) Give a reason for your answer.

2. Refer to the graph below and then answer the questions that follow:



(a) What is the energy of the reactants?
(b) What is the energy of the products?
(c) Calculate ΔH.
(d) What is the activation energy for this reaction?

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Chapter 7 — Summary

See the summary presentation (Presentation: VPjlm at www.everythingscience.co.za)

- When a reaction occurs, some bonds break and new bonds form. These changes involve **energy**.
- When bonds break, energy is **absorbed** and when new bonds form, energy is **released**.
- The **bond energy** is the amount of energy that is needed to break the chemical bond between two atoms.
- If the energy that is needed to *break* the bonds is greater than the energy that is released when new bonds *form*, then the reaction is **endothermic**. The energy of the product is greater than the energy of the reactants.
- If the energy that is needed to *break* the bonds is less than the energy that is released when new bonds *form*, then the reaction is **exothermic**. The energy of the product is less than the energy of the reactants.
- An endothermic reaction is one that **absorbs** energy in the form of heat, while an exothermic reaction is one that **releases** energy in the form of heat and light.
- The difference in energy between the reactants and the product is called the **heat of reaction** and has the symbol ΔH.

- In an endothermic reaction, ΔH is a positive number, and in an exothermic reaction, ΔH will be negative.
- Photosynthesis, evaporation and the thermal decomposition of limestone, are all examples of endothermic reactions.
- Combustion reactions and respiration are both examples of exothermic reactions.
- A reaction which proceeds without additional energy being added, is called a **spontaneous reaction**.
- Reactions where energy must be *continuously supplied* for the reaction to continue, are called **non-spontaneous** reactions.
- In any reaction, some minimum energy must be overcome before the reaction will proceed. This is called the **activation energy** of the reaction.
- The **activated complex** is the transitional product that is formed during a chemical reaction while old bonds break and new bonds form.

Chapter 7 End of Chapter Exercises

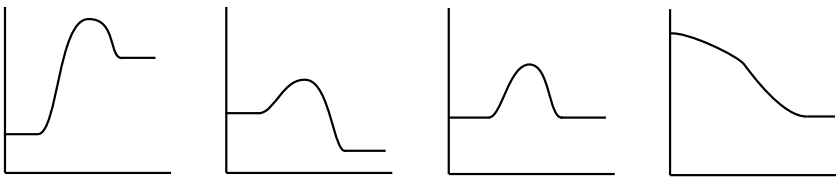
1. For each of the following, say whether the statement is **true** or **false**. If it is false, give a reason for your answer.
   (a) Energy is released in all chemical reactions.
   (b) The condensation of water vapour is an example of an endothermic reaction.
   (c) In an exothermic reaction ΔH is less than zero.
   (d) All non-spontaneous reactions are endothermic.
2. For the following reaction:

$$\text{A} + \text{B} \rightarrow \text{AB} \ \Delta H = -129 \text{ kJ.mol}^{-1}$$

   (a) The energy of the reactants is less than the energy of the product.
   (b) The energy of the product is less than the energy of the reactants.
   (c) The reaction is non-spontaneous.
   (d) The overall energy of the system increases during the reaction.
3. Consider the following chemical equilibrium:

$$2\text{NO}_2 \rightleftharpoons \text{N}_2\text{O}_4 \ \Delta H < 0$$

   Which one of the following graphs best represents the changes in potential energy that take place during the production of N_2O_4?

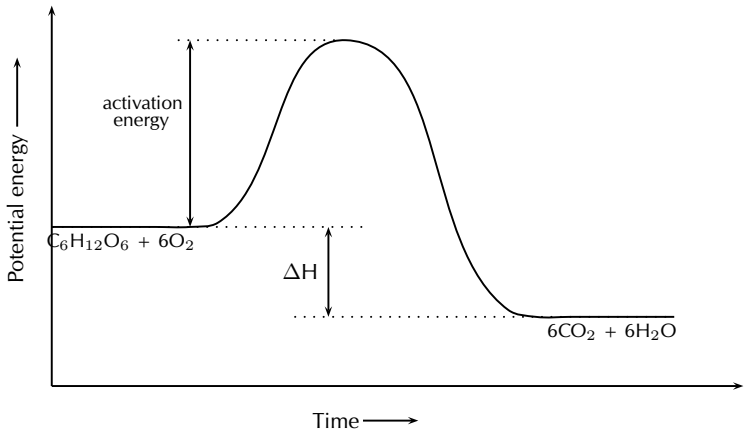


(i) (ii) (iii) (iv)

4. The cellular respiration reaction is catalysed by enzymes. The equation for the reaction is:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

The change in potential energy during this reaction is shown below:



(a) Will the value of ΔH be positive or negative? Give a reason for your answer.
(b) Explain what is meant by 'activation energy'.
(c) What role do enzymes play in this reaction?
(d) Glucose is one of the reactants in cellular respiration. What important chemical reaction produces glucose?
(e) Is the reaction in your answer above an endothermic or an exothermic one? Explain your answer.
(f) Explain why proper nutrition and regular exercise are important in maintaining a healthy body.

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Types of Reactions 8

There are many different types of chemical reactions that can take place. In this chapter, we will be looking at a few of the more common reaction types: acid-base and acid-carbonate reactions, redox reactions and addition, elimination and substitution reactions.

See introductory video: VPjmz at www.everythingscience.co.za

8.1 Acid-base reactions ESBBU

What are acids and bases? ESBBV

In our daily lives, we encounter many examples of acids and bases. In the home, vinegar (acetic acid), lemon juice (citric acid) and tartaric acid (the main acid found in wine) are common, while hydrochloric acid, sulphuric acid and nitric acid are examples of acids that are more likely to be found in laboratories and industry. Hydrochloric acid is also found in the gastric juices in the stomach. Even fizzy drinks contain acid (carbonic acid), as do tea and wine (tannic acid)! Bases that you may know about include sodium hydroxide (caustic soda), ammonium hydroxide and ammonia. Some of these are found in household cleaning products. Acids and bases are also important commercial products in the fertiliser, plastics and petroleum refining industries. Some common acids and bases, and their chemical formulae, are shown in Table 8.1.

Table 8.1: Some common acids and bases and their chemical formulae

Acid	**Formula**	**Base**	**Formula**
Hydrochloric acid	HCl	Sodium hydroxide	$NaOH$
Sulphuric acid	H_2SO_4	Potassium hydroxide	KOH
Nitric acid	HNO_3	Sodium carbonate	Na_2CO_3
Acetic (ethanoic) acid	CH_3COOH	Calcium hydroxide	$Ca(OH)_2$
Carbonic acid	H_2CO_3	Magnesium hydroxide	$Mg(OH)_2$
Sulphurous acid	H_2SO_3	Ammonia	NH_3
Phosphoric acid	H_3PO_4	Sodium bicarbonate	$NaHCO_3$

Most acids share certain characteristics, and most bases also share similar characteristics. It is important to be able to have a definition for acids and bases so that they can be correctly identified in reactions.

Defining acids and bases ESBBW

A number of definitions for acids and bases have developed over the years. One of the earliest was the **Arrhenius** definition. Arrhenius (1887) noticed that water dissociates (splits up) into hydronium (H_3O^+) and hydroxide (OH^-) ions according to the following equation:

Tip

For more information on *dissociation*, refer to Grade 10.

$$H_2O \leftrightharpoons H_3O^+ + OH^-$$

Arrhenius described an acid as a compound that increases the concentration of H_3O^+ ions in solution, and a base as a compound that increases the concentration of OH^- ions in a solution. Look at the following examples showing the dissociation of hydrochloric acid and sodium hydroxide (a base) respectively:

1. $HCl + H_2O \rightarrow H_3O^+ + Cl^-$

   Hydrochloric acid in water increases the concentration of H_3O^+ ions and is therefore an *acid*.

2. $NaOH + H_2O \rightarrow Na^+ + OH^-$

   Sodium hydroxide in water increases the concentration of OH^- ions and is therefore a *base*.

However, this definition could only be used for acids and bases *in water*. Since there are many reactions which do not occur in water it was important to come up with a much broader definition for acids and bases.

In 1923, Lowry and Bronsted took the work of Arrhenius further to develop a broader definition for acids and bases. The **Bronsted-Lowry model** defines acids and bases in terms of their ability to donate or accept protons.

DEFINITION: Acids and bases

According to the Bronsted-Lowry theory of acids and bases, an **acid** is a substance that gives away protons (H^+), and is therefore called a **proton donor**. A **base** is a substance that takes up protons, and is therefore called a **proton acceptor**.

Below are some examples:

1. $HCl(g) + NH_3(g) \rightarrow NH_4^+ + Cl^-$

   In order to decide which substance is a proton donor and which is a proton acceptor, we need to look at what happens to each reactant. The reaction can be broken down as follows:

   $HCl \rightarrow Cl^- + H^+$ and
   $NH_3 + H^+ \rightarrow NH_4^+$

   From these reactions, it is clear that HCl is a *proton donor* and is therefore an **acid**, and that NH_3 is a *proton acceptor* and is therefore a **base**.

2. $CH_3COOH + H_2O \rightarrow H_3O^+ + CH_3COO^-$

   The reaction can be broken down as follows:

   $CH_3COOH \rightarrow CH_3COO^- + H^+$ and
   $H_2O + H^+ \rightarrow H_3O^+$

   In this reaction, CH_3COOH (acetic acid) is a proton donor and is therefore the **acid**. In this case, water acts as a **base** because it accepts a proton to form H_3O^+.

3. $NH_3 + H_2O \rightarrow NH_4^+ + OH^-$

   The reaction can be broken down as follows:

   $H_2O \rightarrow OH^- + H^+$ and

$NH_3 + H^+ \rightarrow NH_4^+$

In this reaction, water donates a proton and is therefore an **acid** in this reaction. Ammonia accepts the proton and is therefore the **base**. Notice that in the previous equation, water acted as a base and that in this equation it acts as an acid. Water can act as both an acid and a base depending on the reaction. This is also true of other substances. These substances are called **ampholytes** and are said to be **amphoteric**.

> *DEFINITION: Amphoteric*
>
> An amphoteric substance is one that can react as either an acid or base. Examples of amphoteric substances include water, ammonia, zinc oxide and beryllium hydroxide.

Conjugate acid-base pairs

ESBBX

Look at the reaction between hydrochloric acid and ammonia to form ammonium and chloride ions:

$$HCl + NH_3 \leftrightharpoons NH_4^+ + Cl^-$$

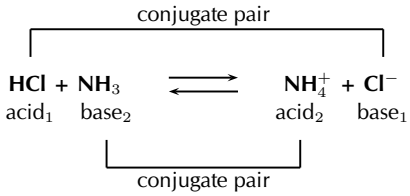
Looking firstly at the *forward reaction* (i.e. the reaction that proceeds from *left* to *right*), the changes that take place can be shown as follows:

$HCl \rightarrow Cl^- + H^+$ and
$NH_3 + H^+ \rightarrow NH_4^+$

Looking at the *reverse reaction* (i.e. the reaction that proceeds from *right* to *left*), the changes that take place are as follows:

$NH_4^+ \rightarrow NH_3 + H^+$ and
$Cl^- + H^+ \rightarrow HCl$

In the **forward reaction**, HCl is a proton donor (acid) and NH_3 is a proton acceptor (base). In the **reverse reaction**, the chloride ion is the proton acceptor (base) and NH_4^+ is the proton donor (acid). A **conjugate acid-base pair** is two compounds in a reaction that change into each other through the loss or gain of a proton. The conjugate acid-base pairs for the above reaction are shown below.



The reaction between ammonia and water is another example:

conjugate pair

$$\mathbf{H_2O} + \mathbf{NH_3} \rightleftharpoons \mathbf{NH_4^+} + \mathbf{OH^-}$$

acid$_1$ base$_2$ acid$_2$ base$_1$

conjugate pair

> *DEFINITION: Conjugate acid-base pair*
>
> The term refers to two compounds that transform into each other by the gain or loss of a proton.

See video: VPjpw at www.everythingscience.co.za

Exercise 8 - 1

In each of the following reactions, label the conjugate acid-base pairs.

1. $H_2SO_4 + H_2O \leftrightharpoons H_3O^+ + HSO_4^-$
2. $NH_4^+ + F^- \leftrightharpoons HF + NH_3$
3. $H_2O + CH_3COO^- \leftrightharpoons CH_3COOH + OH^-$
4. $H_2SO_4 + Cl^- \leftrightharpoons HCl + HSO_4^-$

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Acid-base reactions

ESBBY

When an acid and a base react, they neutralise each other to form a **salt**. If the base contains hydroxide (OH^-) ions, then *water* will also be formed. The word *salt* is a general term which applies to the products of all acid-base reactions. A salt is a product that is made up of the cation from a base and the anion from an acid. When an acid reacts with a base, they **neutralise** each other. In other words, the acid becomes less acidic and the base becomes less basic. Look at the following examples:

1. Hydrochloric acid reacts with sodium hydroxide to form sodium chloride (the salt) and water. Sodium chloride is made up of Na^+ cations from the base (NaOH) and Cl^- anions from the acid (HCl).

   $$\mathrm{HCl + NaOH \rightarrow H_2O + NaCl}$$

2. Hydrogen bromide reacts with potassium hydroxide to form potassium bromide (the salt) and water. Potassium bromide is made up of K^+ cations from the base (KOH) and Br^- anions from the acid (HBr).

   $$\mathrm{HBr + KOH \rightarrow H_2O + KBr}$$

3. Hydrochloric acid reacts with sodium hydrocarbonate to form sodium chloride (the salt) and hydrogen carbonate. Sodium chloride is made up of Na^+ cations from the base ($NaHCO_3$) and Cl^- anions from the acid (HCl).

   $$\mathrm{HCl + NaHCO_3 \rightarrow H_2CO_3 + NaCl}$$

You should notice that in the first two examples, the base contained OH^- ions, and therefore the products were a *salt* and *water*. NaCl (table salt) and KBr are both salts. In the third example, $NaHCO_3$ also acts as a base, despite not having OH^- ions. A salt is still formed as one of the products, but no water is produced.

It is important to realise how important these neutralisation reactions are. Below are some examples:

- **Domestic uses**

  Calcium oxide (CaO) is put on soil that is too acid. Powdered limestone ($CaCO_3$) can also be used but its action is much slower and less effective. These substances can also be used on a larger scale in farming and also in rivers.

- **Biological uses**

  Acids in the stomach (e.g. hydrochloric acid) play an important role in helping to digest food. However, when a person has a stomach ulcer, or when there is too much acid in the stomach, these acids can cause a lot of pain. **Antacids** are taken to neutralise the acids so that they don't burn as much. Antacids are bases which neutralise the acid. Examples of antacids are aluminium hydroxide, magnesium hydroxide ('milk of magnesia') and sodium bicarbonate ('bicarbonate of soda'). Antacids can also be used to relieve heartburn.

- **Industrial uses**

  Alkaline calcium hydroxide (limewater) can be used to absorb harmful acidic SO_2 gas that is released from power stations and from the burning of fossil fuels.

FACT

Bee stings are acidic and have a pH between 5 and 5.5. They can be soothed by using substances such as calomine lotion, which is a mild alkali based on zinc oxide. Bicarbonate of soda can also be used. Both alkalis help to neutralise the acidic bee sting and relieve some of the itchiness!

Acid-base titrations

The neutralisation reaction between an acid and a base can be very useful. If an acidic solution of known concentration (a standard solution) is added to an alkaline solution until the solution is exactly neutralised (i.e. it has neither acidic nor basic properties), it is possible to calculate the exact concentration of the unknown solution. It is possible to do this because, at the exact point where the solution is neutralised, chemically equivalent amounts of acid and base have reacted with each other. This type of calculation is called **volumetric analysis**. The process where an acid solution and a basic solution are added to each other for this purpose, is called a **titration**, and the point of neutralisation is called the **end point** of the reaction. So how exactly can a titration be carried out to determine an unknown concentration? Look at the following steps to help you to understand the process.

Step 1: A measured volume of the solution with unknown concentration is put into a flask.

Step 2: A suitable indicator is added to this solution (bromothymol blue and phenolpthalein are common indicators).

Step 3: A volume of the standard solution is put into a burette (a measuring device) and is slowly added to the solution in the flask, drop by drop.

Step 4: At some point, adding one more drop will change the colour of the unknown solution. For example, if the solution is basic and bromothymol blue is being used as the indicator in the titration, the bromothymol blue would originally have coloured the solution blue. At the end point of the reaction, adding one more drop of acid will change the colour of the basic solution from blue to yellow. Yellow shows that the solution is now acidic.

Tip

When you are busy with these calculations, you will need to remember the following:
1dm^3 = 1 litre = 1 000 ml = 1 000 cm^3, therefore dividing cm^3 by 1 000 will give you an answer in dm^3.

Some other terms and equations which will be useful to remember are shown below:

- Molarity is a term used to describe the concentration of a solution, and is measured in mol.dm^{-3}. The symbol for molarity is M. Refer to Chapter 6 for more information on molarity.
- Moles = molarity (mol · dm^{-3}) × volume (dm^3)
- Molarity (mol · dm^{-3}) = $\frac{\text{moles}}{\text{volume}}$

Step 5: Record the volume of standard solution that has been added up to this point.

Step 6: Use the information you have gathered to calculate the exact concentration of the unknown solution. A worked example is shown below.

Example 1: Titration calculation I

QUESTION

Given the equation:

$$\text{NaOH} + \text{HCl} \rightarrow \text{NaCl} + \text{H}_2\text{O}$$

25 cm^3 of a sodium hydroxide solution was pipetted into a conical flask and titrated with 0.2 M hydrochloric acid. Using a suitable indicator, it was found that 15 cm^3 of acid was needed to neutralise the alkali. Calculate the molarity of the sodium hydroxide.

SOLUTION

Step 1 : ***Write down all the information you know about the reaction, and make sure that the equation is balanced.***

NaOH: V = 25 cm^3
HCl: V = 15 cm^3; C = 0.2 M
The equation is already balanced.

Step 2 : ***Calculate the number of moles of HCl that react according to this equation.***

$$M = \frac{n}{V}$$

Therefore, n(HCl) = M × V (make sure that all the units are correct!)

M = 0.2 mol·dm^{-3}
V = 15 cm^3 = 0.015 dm^3

Therefore

$$n(HCl) = 0.2 \times 0.015 = 0.003$$

There are 0.003 moles of HCl that react

Step 3 : ***Calculate the number of moles of sodium hydroxide in the reaction***

Look at the equation for the reaction. For every mole of HCl there is one mole of NaOH that is involved in the reaction. Therefore, if 0.003 moles of HCl react, we can conclude that the same quantity of NaOH is needed for the reaction. The number of moles of NaOH in the reaction is 0.003.

Step 4 : ***Calculate the molarity of the sodium hydroxide***

First convert the volume into dm^3. V = 0.025 dm^3. Then continue with the calculation.

$$M = \frac{n}{V} = \frac{0.003}{0.025} = 0.12$$

The molarity of the NaOH solution is 0.12 mol.dm^3 or 0.12 M

Example 2: *Titration calculation II*

QUESTION

4.9 g of sulphuric acid is dissolved in water and the final solution has a volume of 220 cm^3. Using titration, it was found that 20 cm^3 of this solution was able to completely neutralise 10 cm^3 of a sodium hydroxide solution. Calculate the concentration of the sodium hydroxide in mol.dm^{-3}.

SOLUTION

Step 1 : ***Write a balanced equation for the titration reaction.***

$$\mathrm{H_2SO_4 + 2NaOH \rightarrow Na_2SO_4 + 2H_2O}$$

Step 2 : ***Calculate the molarity of the sulphuric acid solution.***

$M = \frac{n}{V}$
V = 220 cm^3 = 0.22 dm^3

$$n = \frac{m}{M} = \frac{4.9g}{98 \text{ g} \cdot \text{mol}^{-1}} = 0.05\text{mol}$$

Therefore,

$$M = \frac{0.05}{0.22} = 0.23 \text{ mol} \cdot \text{dm}^{-3}$$

Step 3 : ***Calculate the moles of sulphuric acid that were used in the neutralisation reaction.***

Remember that only 20 cm^3 of the sulphuric acid solution is used.

$M = \frac{n}{V}$, therefore $n = M \times V$

$$n = 0.23 \times 0.02 = 0.0046 \text{ mol}$$

Step 4 : ***Calculate the number of moles of sodium hydroxide that were neutralised.***
According to the balanced chemical equation, the mole ratio of H_2SO_4 to NaOH is 1:2. Therefore, the number of moles of NaOH that are neutralised is 0.0046 × 2 = 0.0092 mol.

Step 5 : ***Calculate the concentration of the sodium hydroxide solution.***

$$M = \frac{n}{V} = \frac{0.0092}{0.01} = 0.92 \text{ M}$$

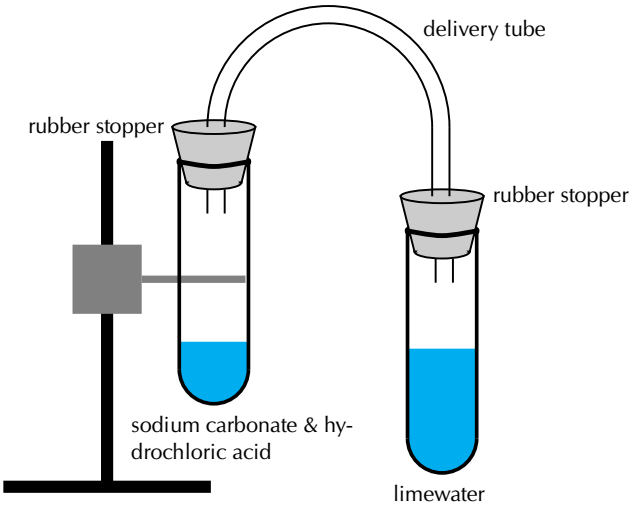
Acid-carbonate reactions

ESBBZ

Activity: *The reaction of acids with carbonates*

Apparatus and materials:

Small amounts of sodium carbonate powder and calcium carbonate powder; hydrochloric acid and sulphuric acid; retort stand; two test tubes; two rubber stoppers for the test tubes; a delivery tube; lime water. The demonstration should be set up as shown below.



Method:

1. Pour limewater into one of the test tubes and seal with a rubber stopper.
2. Carefully pour a small amount of hydrochloric acid into the other test tube.
3. Add a small amount of sodium carbonate to the acid and seal the test tube with the rubber stopper.
4. Connect the two test tubes with a delivery tube.
5. Observe what happens to the colour of the limewater.
6. Repeat the above steps, this time using sulphuric acid and calcium carbonate.

Observations:

The clear lime water turns milky meaning that carbon dioxide has been produced.

When an acid reacts with a carbonate a salt, carbon dioxide and water are formed. Look at the following examples:

- Nitric acid reacts with sodium carbonate to form sodium nitrate, carbon dioxide and water.

$$2HNO_3 + Na_2CO_3 \rightarrow 2NaNO_3 + CO_2 + H_2O$$

- Sulphuric acid reacts with calcium carbonate to form calcium sulfate, carbon dioxide and water.

$$H_2SO_4 + CaCO_3 \rightarrow CaSO_4 + CO_2 + H_2O$$

- Hydrochloric acid reacts with calcium carbonate to form calcium chloride, carbon dioxide and water.

$$2HCl + CaCO_3 \rightarrow CaCl_2 + CO_2 + H_2O$$

Exercise 8 - 2

1. The compound $NaHCO_3$ is commonly known as baking soda. A recipe requires 1.6 g of baking soda, mixed with other ingredients, to bake a cake.
   (a) Calculate the number of moles of $NaHCO_3$ used to bake the cake.
   (b) How many atoms of oxygen are there in the 1.6 g of baking soda?
   During the baking process, baking soda reacts with an acid to produce carbon dioxide and water, as shown by the reaction equation below:
   $$HCO_3^-(aq) + H^+(aq) \rightarrow CO_2(g) + H_2O(l)$$
   (c) Identify the reactant which acts as the Bronsted-Lowry base in this reaction. Give a reason for your answer.
   (d) Use the above equation to explain why the cake rises during this baking process.

   (DoE Grade 11 Paper 2, 2007)

2. Label the acid-base conjugate pairs in the following equation:
   $$HCO_3^- + H_2O \leftrightharpoons CO_3^{2-} + H_3O^+$$

3. A certain antacid tablet contains 22.0 g of baking soda ($NaHCO_3$). It is used to neutralise the excess hydrochloric acid in the stomach. The balanced equation for the reaction is:
   $$NaHCO_3 + HCl \rightarrow NaCl + H_2O + CO_2$$
   The hydrochloric acid in the stomach has a concentration of 1.0 mol.dm^{-3}. Calculate the volume of the hydrochloric acid that can be neutralised by the antacid tablet.

   (DoE Grade 11 Paper 2, 2007)

4. A learner is asked to prepare a *standard solution* of the weak acid, oxalic acid $(COOH)_2 2H_2O$ for use in a titration. The volume of the solution must be 500 cm^3 and the concentration 0.2 mol.dm^{-3}.
   (a) Calculate the mass of oxalic acid which the learner has to dissolve to make up the required standard solution. The leaner titrates this 0.2 mol.dm^{-3} oxalic acid solution against a solution of sodium hydroxide. He finds that 40 cm^3 of the oxalic acid solution exactly neutralises 35 cm^3 of the sodium hydroxide solution.
   (b) Calculate the concentration of the sodium hydroxide solution.

5. A learner finds some sulphuric acid solution in a bottle labelled 'dilute sulphuric acid'. He wants to determine the concentration of the sulphuric acid solution. To do this, he decides to titrate the sulphuric acid against a standard potassium hydroxide (KOH) solution.
   (a) What is a standard solution?

(b) Calculate the mass of KOH which he must use to make 300 cm^3 of a 0.2 $mol.dm^{-3}$ KOH solution.

(c) Calculate the pH of the 0.2 $mol.dm^{-3}$ KOH solution (assume standard temperature).

(d) Write a balanced chemical equation for the reaction between H_2SO_4 and KOH.

(e) During the titration he finds that 15 cm^3 of the KOH solution neutralises 20 cm^3 of the H_2SO_4 solution. Calculate the concentration of the H_2SO_4 solution.

(IEB Paper 2, 2003)

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(1.) 00zm (2.) 00zn (3.) 00zp (4.) 00zq (5.) 00zr

8.2 Redox reactions

ESBCA

A second type of reaction is the **redox** reaction, in which both **oxidation** and **reduction** take place.

Oxidation and reduction

ESBCB

If you look back to Chapter 1, you will remember that we discussed how, during a chemical reaction, an exchange of electrons takes place between the elements that are involved. Using *oxidation numbers* is one way of tracking what is happening to these electrons in a reaction. Refer back to Section 1.11 if you can't remember the rules that are used to give an oxidation number to an element. Below are some examples to refresh your memory before we carry on with this section.

Examples:

1. **CO_2**

   Each oxygen atom has an oxidation number of -2. This means that the charge on *two* oxygen atoms is -4. We know that the molecule of CO_2 is neutral, therefore the carbon atom must have an oxidation number of $+4$.

2. **$KMnO_4$**

   Overall, this molecule has a neutral charge, meaning that the sum of the oxidation numbers of the elements in the molecule must equal zero. Potassium (K) has an oxidation number of $+1$, while oxygen (O) has an oxidation number of -2. If we exclude the atom of manganese (Mn), then the sum of the oxidation numbers equals $+1+(-2x4) = -7$. The atom of manganese must therefore have an oxidation number of $+7$ in order to make the molecule neutral.

By looking at how the oxidation number of an element changes during a reaction, we can easily see whether that element is being **oxidised** or **reduced**.

> *DEFINITION: Oxidation and reduction*
>
> Oxidation is the *loss* of an electron by a molecule, atom or ion. Reduction is the *gain* of an electron by a molecule, atom or ion.

Example:

$$\mathrm{Mg} + \mathrm{Cl_2} \rightarrow \mathrm{MgCl_2}$$

As a *reactant*, magnesium has an oxidation number of zero, but as part of the *product* magnesium chloride, the element has an oxidation number of $+2$. Magnesium has *lost* two electrons and has therefore been *oxidised*. This can be written as a **half-reaction**. The half-reaction for this change is:

$$\mathrm{Mg} \rightarrow \mathrm{Mg^{2+}} + 2\mathrm{e^-}$$

As a *reactant*, chlorine has an oxidation number of zero, but as part of the *product* magnesium chloride, the element has an oxidation number of -1. Each chlorine atom has *gained* an electron and the element has therefore been *reduced*. The half-reaction for this change is:

$$\mathrm{Cl_2} + 2\mathrm{e^-} \rightarrow 2\mathrm{Cl^-}$$

> ***Tip***
>
> Oxidation and reduction made easy!
> An easy way to think about oxidation and reduction is to remember: 'OILRIG' - **O**xidation **I**s **L**oss of electrons, **R**eduction **I**s **G**ain of electrons.

> *DEFINITION: Half-reaction*
>
> A half reaction is either the oxidation or reduction reaction part of a redox reaction. A half reaction is obtained by considering the change in oxidation states of the individual substances that are involved in the redox reaction.

An element that is **oxidised** is called a **reducing agent**, while an element that is **reduced** is called an **oxidising agent**.

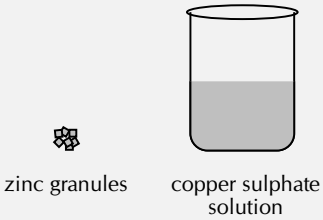
Redox reactions

ESBCC

> *DEFINITION: Redox reaction*
>
> A redox reaction is one involving oxidation and reduction, where there is always a change in the oxidation numbers of the elements involved.

General experiment: *Redox reactions*

Materials: A few granules of zinc; 15 ml copper (II) sulphate solution (blue colour), glass beaker.



Method: Add the zinc granules to the copper sulfate solution and observe what happens. What happens to the zinc granules? What happens to the colour of the solution?
Results:

- Zinc becomes covered in a layer that looks like copper.
- The blue copper sulphate solution becomes clearer.

Cu^{2+} ions from the $CuSO_4$ solution are **reduced** to form copper metal. This is what you saw on the zinc crystals. The reduction of the copper ions (in other words, their removal from the copper sulphate solution), also explains the change in colour of the solution (copper ions in solution are blue). The equation for this reaction is:

$$\mathrm{Cu^{2+} + 2e^- \rightarrow Cu}$$

Zinc is **oxidised** to form Zn^{2+} ions which are clear in the solution. The equation for this reaction is:

$$\mathrm{Zn \rightarrow Zn^{2+} + 2e^-}$$

The overall reaction is:

$$\mathrm{Cu^{2+}(aq) + Zn(s) \rightarrow Cu(s) + Zn^{2+}(aq)}$$

Conclusion: A redox reaction has taken place. Cu^{2+} ions are reduced and the zinc is oxidised.

Below are some further examples of redox reactions:

- $\mathrm{H_2 + F_2 \rightarrow 2HF}$ can be re-written as two half-reactions:

$$\mathrm{H_2 \rightarrow 2H^+ + 2e^-} \text{ (oxidation) and}$$
$$\mathrm{F_2 + 2e^- \rightarrow 2F^-} \text{ (reduction)}$$

- $\mathrm{Cl_2 + 2KI \rightarrow 2KCl + I_2}$ or $\mathrm{Cl_2 + 2I^- \rightarrow 2Cl^- + I_2}$, can be written as two half-reactions:

$$\mathrm{Cl_2 + 2e^- \rightarrow 2Cl^-} \text{ (reduction) and}$$
$$\mathrm{2I^- \rightarrow I_2 + 2e^-} \text{ (oxidation)}$$

In Grade 12, you will go on to look at electrochemical reactions, and the role that electron transfer plays in this type of reaction.
See video: VPjql at www.everythingscience.co.za

Exercise 8 - 3

1. Look at the following reaction:

$$\mathrm{2H_2O_2(\ell) \rightarrow 2H_2O(\ell) + O_2(g)}$$

   (a) What is the oxidation number of the oxygen atom in each of the following compounds?
      i. H_2O_2
      ii. H_2O

iii. O_2

(b) Does the hydrogen peroxide (H_2O_2) act as an oxidising agent or a reducing agent or both, in the above reaction? Give a reason for your answer.

2. Consider the following chemical equations:
   1. $Fe(s) \rightarrow Fe^{2+}(aq) + 2e^-$
   2. $4H^+$ (aq) + O_2 (g) + $4e^- \rightarrow 2H_2O(\ell)$

   Which one of the following statements is correct?

   (a) Fe is oxidised and H^+ is reduced
   (b) Fe is reduced and O_2 is oxidised
   (c) Fe is oxidised and O_2 is reduced
   (d) Fe is reduced and H^+ is oxidised

   (DoE Grade 11 Paper 2, 2007)

3. Which one of the following reactions is a redox reaction?

   (a) $HCl + NaOH \rightarrow NaCl + H_2O$
   (b) $AgNO_3 + NaI \rightarrow AgI + NaNO_3$
   (c) $2FeCl_3 + 2H_2O + SO_2 \rightarrow H_2SO_4 + 2HCl + 2FeCl_2$
   (d) $BaCl_2 + MgSO_4 \rightarrow MgCl_2 + BaSO_4$

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(1.) 00zs (2.) 00zt (3.) 00zu

8.3 Addition, substitution and elimination reactions

ESBCD

Addition reactions

ESBCE

An addition reaction occurs when two or more reactants combine to form a final product. This product will contain *all* the atoms that were present in the reactants. The following is a general equation for this type of reaction:

$$A + B \rightarrow C$$

Notice that C is the final product with no A or B remaining as a residue.

The following are some examples.

1. The reaction between **ethene** and **bromine** to form 1,2-dibromoethane (Figure 8.1).

$$C_2H_4 + Br_2 \rightarrow C_2H_4Br_2$$

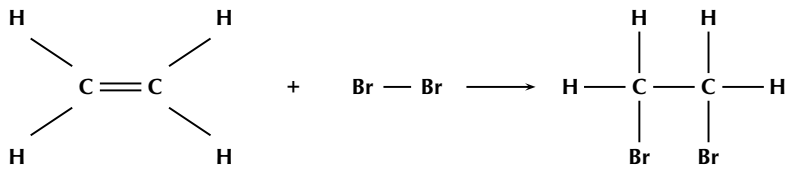


Figure 8.1: The reaction between ethene and bromine is an example of an addition reaction

2. **Polymerisation reactions**

   In industry, making polymers is very important. A polymer is made up of lots of smaller units called *monomers*. When these monomers are added together, they form a polymer. Examples of polymers are polyvinylchloride (PVC) and polystyrene. PVC is often used to make piping, while polystyrene is an important packaging and insulating material. Polystyrene is made up of lots of styrene monomers which are joined through addition reactions (Figure 8.2). 'Polymerisation' refers to the addition reactions that eventually help to form the polystyrene polymer.

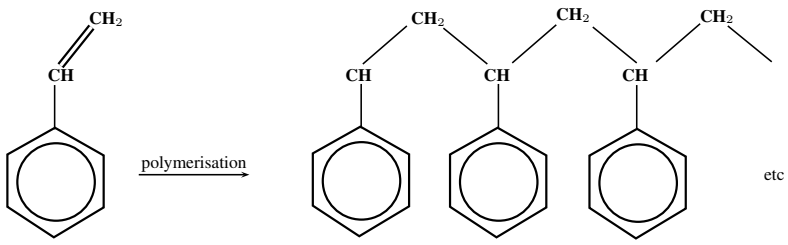


Figure 8.2: The polymerisation of a styrene monomer to form a polystyrene polymer

3. The **hydrogenation** of vegetable oils to form margarine is another example of an addition reaction. Hydrogenation involves adding hydrogen (H_2) to an alkene. An alkene is an organic compound composed of carbon and hydrogen. It contains a double bond between two of the carbon atoms. During hydrogenation, this double bond is broken, and more hydrogen atoms are added to the molecule. The reaction that takes place is shown below. Note that the 'R' represents any side-chain or the rest of the molecule. A side-chain is simply any combination of atoms that are attached to the central part of the molecule.

$$\mathrm{RCHCH_2 + H_2 \rightarrow RCH_2CH_3}$$

4. The production of ethanol (an alcohol) from ethene. Ethanol (CH_3CH_2OH) can be made from alkenes such as ethene (C_2H_4), through a hydration reaction like the one below. A hydration reaction is one where water is added to the reactants.

$$\mathrm{C_2H_4 + H_2O \rightarrow CH_3CH_2OH}$$

   A catalyst is needed for this reaction to take place. The catalyst that is most commonly used is phosphoric acid.

Elimination reactions

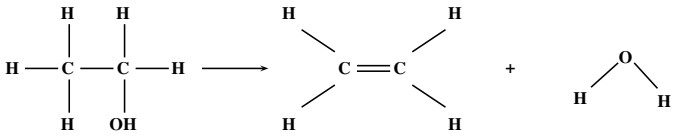
ESBCF

An elimination reaction occurs when a reactant is broken up into two products. The general form of the equation is as follows:

$$A \rightarrow B + C$$

The examples below will help to explain this:

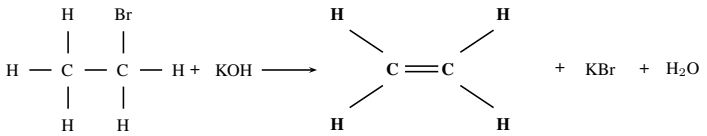
1. The **dehydration of an alcohol** is one example. Two hydrogen atoms and one oxygen atom are eliminated and a molecule of water is formed as a product in the reaction, along with an alkene.



$$\mathrm{CH_3CH_2OH} \rightarrow \mathrm{CH_2CH_2} + \mathrm{H_2O}$$

2. The elimination of **potassium bromide from a bromoalkane**.

$$\mathrm{CH_3CH_2Br} + \mathrm{KOH} \rightarrow \mathrm{CH_2CH_2} + \mathrm{KBr} + \mathrm{H_2O}$$



3. Ethane cracking is an important industrial process used by SASOL and other petrochemical industries. Hydrogen is eliminated from ethane (C_2H_6) to produce an alkene called ethene (C_2H_4). Ethene is then used to produce other products such as polyethylene. You will learn more about these compounds in Grade 12. The equation for the cracking of ethane looks like this:

$$\mathrm{C_2H_6} \rightarrow \mathrm{C_2H_4} + \mathrm{H_2}$$

Substitution reactions

ESBCG

A substitution reaction occurs when an exchange of elements in the reactants takes place. The initial reactants are transformed or 'swopped around' to give a final product. A simple example of a reaction like this is shown below:

$$\mathrm{AB} + \mathrm{CD} \rightarrow \mathrm{AC} + \mathrm{BD}$$

Some simple examples of substitution reactions are shown below:

$$\mathrm{CH_4} + \mathrm{Cl_2} \rightarrow \mathrm{CH_3Cl} + \mathrm{HCl}$$

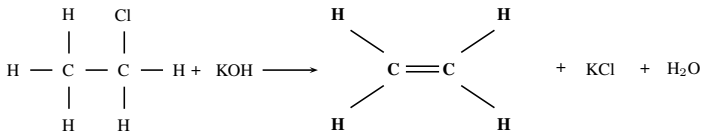
In this example, a chlorine atom and a hydrogen atom are exchanged to create a new product.

$$Cu(H_2O)_4^{2+} + 4Cl^- \rightleftharpoons Cu(Cl)_4^{2-} + 4H_2O$$

In this example, four waters and four chlorines are exchanged to create a new product.

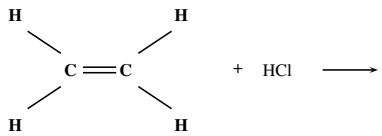
Exercise 8 - 4

1. Refer to the diagram below and then answer the questions that follow:



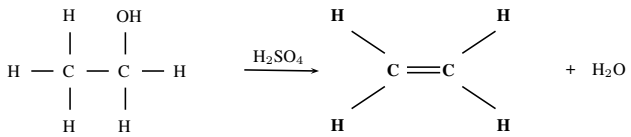
   (a) Is this reaction an example of substitution, elimination or addition?
   (b) Give a reason for your answer above.

2. The following diagram shows the reactants in an addition reaction.



   (a) Draw the final product in this reaction.
   (b) What is the chemical formula of the product?

3. The following reaction takes place:



   Is this reaction a substitution, addition or dehydration reaction? Give a reason for your answer.

4. Consider the following reaction:

$$Ca(OH)_2(s) + 2NH_4Cl(s) \rightarrow CaCl_2(s) + 2NH_3(g) + 2H_2O(g)$$

   Which one of the following best describes the type of reaction which takes place?

   (a) Redox reaction
   (b) Acid-base reaction
   (c) Dehydration reaction

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(1.) 00zv (2.) 00zw (3.) 00zx (4.) 00zy

Chapter 8 — Summary

See the summary presentation (▶ Presentation: VPjvj at www.everythingscience.co.za)

- There are many different **types of reactions** that can take place. These include acid-base, acid-carbonate, redox, addition, substitution and elimination reactions.
- The **Arrhenius** definition of acids and bases defines an acid as a substance that increases the concentration of hydrogen ions (H^+ or H_3O^+) in a solution. A base is a substance that increases the concentration of hydroxide ions (OH^-) in a solution. However this definition only applies to substances that are in water.
- The **Bronsted-Lowry** definition is a much broader one. An **acid** is a substance that **donates protons** and a **base** is a substance that **accepts protons**.
- In different reactions, certain substances can act as both an acid and a base. These substances are called **ampholytes** and are said to be **amphoteric**. Water is an example of an ampholyte.
- A **conjugate acid-base pair** refers to two compounds in a reaction (one reactant and one product) that transform or change into the other through the loss or gain of a proton.
- When an acid and a base react, they form a **salt** and water. The salt is made up of a cation from the base and an anion from the acid. An example of a salt is sodium chloride (NaCl), which is the product of the reaction between sodium hydroxide (NaOH) and hydrochloric acid (HCl).
- The reaction between an acid and a base is a **neutralisation** reaction.
- **Titrations** are reactions between an acid and a base that are used to calculate the concentration of one of the reacting substances. The concentration of the other reacting substance must be known.
- In an **acid-carbonate reaction**, an acid and a carbonate react to form a salt, carbon dioxide and water.
- A **redox reaction** is one where there is always a change in the oxidation numbers of the elements that are involved in the reaction.
- **Oxidation** is the loss of electrons and **reduction** is the gain of electrons.
- When two or more reactants combine to form a product that contains all the atoms that were in the reactants, then this is an **addition reaction**. Examples of addition reactions include the reaction between ethene and bromine, polymerisation reactions and hydrogenation reactions.
- A reaction where the reactant is broken down into one or more product, is called an **elimination reaction**. Alcohol dehydration and ethane cracking are examples of elimination reactions.
- A **substitution reaction** is one where the reactants are transformed or swopped around to form the final product.

Chapter 8 End of Chapter Exercises

1. Give one word/term for each of the following descriptions:
   (a) A chemical reaction during which electrons are transferred
   (b) The addition of hydrogen across a double bond
   (c) The removal of hydrogen and halogen atoms from an alkane to form an alkene

2. For each of the following, say whether the statement is true or false. If the statement is false, re-write the statement correctly.
   (a) The conjugate base of NH_4^+ is NH_3.
   (b) The reactions $C + O_2 \rightarrow CO_2$ and $2KClO_3 \rightarrow 2KCl + 3O_2$ are examples of redox reactions.

   (IEB Paper 2, 2005)
3. When chlorine water (Cl_2 dissolved in water) is added to a solution of potassium bromide, bromine is produced. Which one of the following statements concerning this reaction is correct?
   (a) Br^- is oxidised
   (b) Cl_2 is oxidised
   (c) Br^- is the oxidising agent
   (d) Cl^- is the oxidising agent

   (IEB Paper 2, 2005)
4. The stomach secretes gastric juice, which contains hydrochloric acid. The gastric juice helps with digestion. Sometimes there is an overproduction of acid, leading to heartburn or indigestion. Antacids, such as milk of magnesia, can be taken to neutralise the excess acid. Milk of magnesia is only slightly soluble in water and has the chemical formula $Mg(OH)_2$.
   (a) Write a balanced chemical equation to show how the antacid reacts with the acid.
   (b) The directions on the bottle recommend that children under the age of 12 years take one teaspoon of milk of magnesia, whereas adults can take two teaspoons of the antacid. Briefly explain why the dosages are different.
   (c) Why is it not advisable to take an overdose of the antacid in the stomach? Refer to the hydrochloric acid concentration in the stomach in your answer.
   In an experiment, 25.0 cm^3 of a standard solution of sodium carbonate of concentration 0.1 $mol.dm^{-3}$ was used to neutralise 35.0 cm^3 of a solution of hydrochloric acid.
   (d) Write a balanced chemical equation for the reaction.
   (e) Calculate the concentration of the acid.

   (DoE Grade 11 Exemplar, 2007)

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(1.) 00zz (2.) 0100 (3.) 0101 (4.) 0102

The Lithosphere 9

9.1 Introduction

ESBCH

If we were to cut the Earth in half we would see that our planet is made up of a number of layers, namely the **core** at the centre (separated into the inner and outer core), the **mantle**, the **upper mantle**, the **crust** and the **atmosphere** (Figure 9.1). The core is made up mostly of iron. The mantle, which lies between the core and the crust, consists of molten rock, called **magma** which moves continuously because of convection currents. The crust is the thin, hard outer layer that 'floats' on the magma of the mantle. It is the upper part of the mantle and the crust that make up the **lithosphere** ('lith' means 'types of stone' and 'sphere' refers to the round shape of the earth).
See introductory video: VPjvj at www.everythingscience.co.za

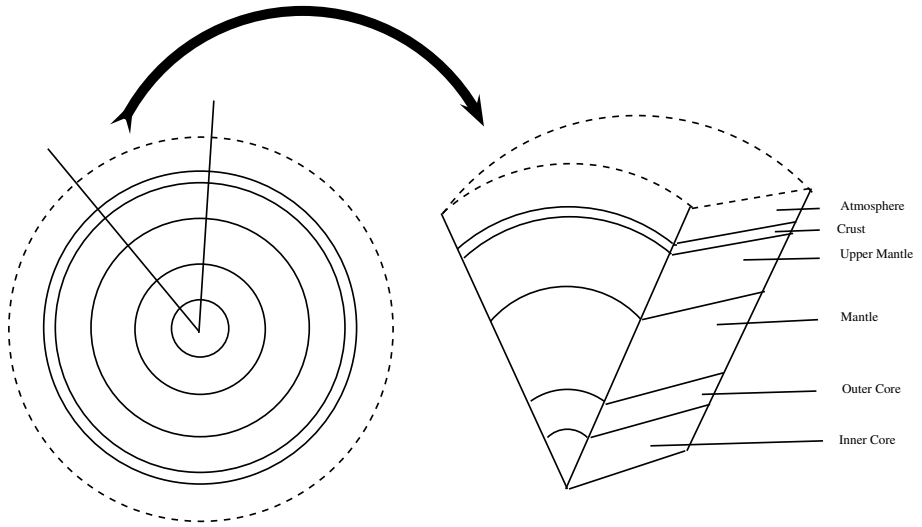

Figure 9.1: A cross-section through the earth to show its different layers

DEFINITION: Lithosphere

The lithosphere is the solid outermost shell of our planet. The lithosphere includes the crust and the upper part of the mantle, and is made up of material from both the continents and the oceans on the Earth's surface.

9.2 The chemistry of the earth's crust

ESBCI

The crust is made up of about 80 elements, which occur in over 2000 different compounds and minerals. However, most of the mass of the material in the crust is made up of only 8 of these elements. These are oxygen (O), silica (Si), aluminium (Al), iron (Fe), calcium (Ca), sodium (Na), potassium (K) and magnesium (Mg). These metal elements are seldom found in their pure form, but are usually part of other more complex **minerals**. A mineral is a compound that is formed through geological processes, which give it a particular structure. A mineral could be a pure element, but more often minerals are made up of many different elements combined. *Quartz* is just one example. It is a mineral that is made up of silicon and oxygen. Some more examples are shown in Table 9.1.

Table 9.1: Table showing examples of minerals and their chemistry

Mineral	**Chemistry**	**Comments**
Quartz	SiO_2 (silicon dioxide)	Quartz is used for glass, in electrical components, optical lenses and in building stone
Gold	Au (pure element) or $AuTe_2$ (Calaverite, a gold mineral)	Gold is often found in a group of minerals called the *tellurides*. Calaverite is a mineral that belongs to this group, and is the most common gold-bearing mineral.
Hematite	Fe_2O_3 (iron oxide)	Iron usually occurs in iron oxide minerals or as an alloy of iron and nickel.
Orthoclase	$KAlSi_3O_8$ (potassium aluminium silicate)	Orthoclase belongs to the *feldspar* group of minerals.
Copper	Cu (pure element) or $Cu_2(CO_3)(OH)_2$ (malachite or copper carbonate hydroxide)	copper can be mined as a pure element or as a mineral such as malachite.

DEFINITION: Mineral

Minerals are natural compounds formed through geological processes. The term 'mineral' includes both the material's chemical composition and its structure. Minerals range in composition from pure elements to complex compounds.

A **rock** is a combination of one or more minerals. *Granite* for example, is a rock that is made up of minerals such as SiO_2, Al_2O_3, CaO, K_2O, Na_2O and others. There are three different types of rocks, **igneous**, **sedimentary** and **metamorphic**. Igneous rocks (e.g. granite, basalt) are formed when magma is brought to the earth's surface as lava, and then solidifies. Sedimentary rocks (e.g. sandstone, limestone) form when rock fragments, organic matter or other sediment particles are deposited and then compacted over time until they solidify. Metamorphic rock is formed when any other rock types are subjected to intense heat and pressure over a period of time. Examples include slate and marble.

Many of the elements that are of interest to us (e.g. gold, iron, copper), are unevenly distributed in the lithosphere. In places where these elements are abundant, it is profitable to extract them (e.g. through mining) for economic purposes. If their concentration is very low, then the cost of extraction becomes more than the money that would be made if they were sold. Rocks that contain valuable minerals are called **ores**. As humans, we are particularly interested in the ores that contain metal elements, and also in those minerals that can be used to produce energy.

DEFINITION: Ore

An ore is a volume of rock that contains minerals which make it valuable for mining.

FACT

A **gemstone** (also sometimes called a **gem** or **semi-precious stone**), is a highly attractive and valuable piece of mineral which, when cut and polished, is used in jewelry and other adornments. Examples of gemstones are amethyst, diamond, cat's eye and sapphire.

Exercise 9 - 1

1. Where are most of the earth's minerals concentrated?
2. Explain the difference between a *mineral*, a *rock* and an *ore*.
3. Carry out your own research to find out which elements are found in the following minerals:
   (a) gypsum
   (b) calcite
   (c) topaz
4. Which minerals are found in the following rocks?
   (a) basalt
   (b) sandstone
   (c) marble

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(1.) 01y8 (2.) 01y9 (3.) 01ya (4.) 01yb

9.3 A brief history of mineral use

ESBCJ

FACT

Originally it was believed that much of Africa's knowledge of metals and their uses was from the Middle East. But this may not be the case. More recent studies have shown that iron was used far earlier than it would have been if knowledge of this metal had started in the Middle East. Many metal technologies may in fact have developed independently in Africa and in many African countries, metals have an extremely important place in society. In Nigeria's Yoruba country for example, iron has divine status because it is used to make instruments for survival. 'Ogun', the God of Iron, is seen as the protector of the kingdom.

Many of the minerals that are important to humans are **metals** such as gold, aluminium, copper and iron. Throughout history, metals have played a very important role in making jewellery, tools, weapons and later machinery and other forms of technology. We have become so used to having metals around us that we seldom stop to think what life might have been like before metals were discovered. During the **Stone Age** for example, **stones** were used to make tools. Slivers of stone were cut from a rock and then sharpened. In Africa, some of the stone tools that have been found date back to 2.5 million years ago!

It was the discovery of *metals* that led to some huge advances in agriculture, warfare, transport and even cookery. One of the first metals to be discovered was **gold**, probably because of its beautiful shiny appearance. Gold was used mostly to make jewellery because it was too soft to make harder tools. Later, **copper** became an important metal because it could be hammered into shape, and it also lasted a lot longer than the stone that had previously been used in knives, cooking utensils and weapons. Copper can also be melted and then put into a mould to re-shape it. This is known as **casting**.

At about the time that copper was in widespread use, it was discovered that if certain kinds of stones are heated to high enough temperatures, liquid metals flow from them. These rocks are **ores**, and contain the metal minerals inside them. The process of heating mineral ores in this way is called **smelting**. It was also found that ores do not only occur at the earth's surface, but also deep *below* it. This discovery led to the beginning of **mining**.

But humans' explorations into the world of metals did not end here! In some areas, the ores of *iron* and *tin* were found close together. The cast alloy of these two metals is **bronze**. Bronze is a very useful metal because it produces a sharper edge than copper. Another important discovery was that of **iron**. Iron is the most abundant metal at the earth's surface but it is more difficult to work with than copper or tin. It is very difficult to extract iron from its ore because it has an extremely high melting point, and only specially designed furnaces are able to produce the temperatures that are needed. An important discovery was that if iron is heated in a furnace with *charcoal*, some of the carbon in the charcoal is transferred to the iron, making the metal even harder. If this hot metal has its temperature reduced very suddenly, it becomes even harder and produces **steel**. Today, steel is a very important part of industry and construction.

9.4 Energy resources and their uses

ESBCK

Apart from minerals and ores, the products of the lithosphere are also important in meeting our energy needs.

Coal is one of the most important fuels that is used in the production of electricity. Coal is formed from organic material when plants and animals decompose, leaving behind organic remains that accumulate and become compacted over millions of years under sedimentary rock. The layers of compact organic material that can be found between sedimentary layers, are coal. When coal is burned, a large amount of heat energy is released, which is used to produce electricity. South Africa is the world's sixth largest coal producer, with Mpumalanga contributing about 83% of our total production. Other areas in which coal is produced, include the Free State, Limpopo and KwaZulu-Natal. One of the problems with coal however, is that it is a non-renewable resource, meaning that once all resources have been used up, it cannot simply be produced again. Burning coal also produces large quantities of greenhouse gases, which may play a role in global warming. At present, ESKOM, the South African government's electric power producer, is the coal industry's main customer.

Another element that is found in the crust, and which helps to meet our energy needs, is **uranium**. Uranium produces energy through the process of *nuclear fission*. Neutrons are aimed at the nuclei of the uranium atoms in order to split them. When the nucleus of a uranium atom is split, a large amount of energy is released as heat. This heat is used to produce steam, which turns turbines to generate electricity. Uranium is produced as a by-product of gold in some mines in the Witwatersrand, and as a by-product in some copper mines, for example in Phalaborwa. This type of nuclear power is relatively environmentally friendly since it produces low gas emissions. However, the process does produce small amounts of radioactive wastes , which must be carefully disposed of in order to prevent contamination.

Oil is another product of the lithosphere which is critical in meeting our fuel needs. While most of South Africa's oil is imported and then processed at a refinery in either Durban, Cape Town or Sasolburg, some is extracted from coal. The technology behind this type of extraction has largely been developed by SASOL (South African Coal, Oil and Gas Corporation). Oil, like coal, is organic in origin and normally forms from organic deposits on the ocean floor. Oil requires unique geological and geochemical conditions in order to be produced. Part of this process involves the burial of organic-rich sediments under extremely high temperatures and pressures. The oil that is produced is then pushed out into nearby sedimentary layers. Oil will then move upwards until it is trapped by an impermeable rock layer. It accumulates here, and can then be accessed by oil rigs and other advanced equipment.

Activity:	*Mining Areas*

Using any reference resources you have available, try to find a map of the mining regions of South Africa.

9.5 Mining and Mineral Processing: Gold

ESBCL

Introduction

ESBCM

Gold was discovered in South Africa in the late 1800's and since then has played a very important role in South Africa's *history* and *economy*. Its discovery brought many foreigners into South Africa, who were lured by the promises of wealth. They set up small mining villages, which later grew into larger settlements, towns and cities. One of the first of these settlements was the beginning of present-day Johannesburg, also known as 'Egoli' or 'Place of Gold'.

Most of South Africa's gold is concentrated in the 'Golden Arc', which stretches from Johannesburg to Welkom. Geologists believe that, millions of years ago, this area was a massive inland lake. Rivers feeding into this lake brought sand, silt, pebbles and fine particles of gold and deposited them over a long period of time. Eventually these deposits accumulated and became compacted to form gold-bearing sedimentary rock or **gold reefs**. It is because of this complex, but unique, set of circumstances that South Africa's gold deposits are so concentrated in that area. In other countries like Zimbabwe, gold occurs in smaller 'pockets', which are scattered over a much greater area.

Mining the Gold

ESBCN

A number of different techniques can be used to mine gold. The three most common methods in South Africa are **panning**, **open cast** and **shaft** mining.

1. **Panning**

   Panning for gold is a manual technique that is used to sort gold from other sediments. Wide, shallow pans are filled with sand and gravel (often from river beds) that may contain gold. Water is added and the pans are shaken so that the gold is sorted from the rock and other materials. Because gold is much more dense, it settles to the bottom of the pan. **Pilgrim's Rest** in Mpumalanga, was the first site for gold panning in South Africa.

2. **Open cast mining**

   This is a form of surface mining. Surface layers of rock and sediments are removed so that the deeper gold rich layers can be reached. This type of mining is not suitable if the gold is buried very deep below the surface.

3. **Shaft mining**

South Africa's thin but extensive gold reefs slope at an angle underneath the ground, and this means that some deposits are very deep and often difficult to reach. Shaft mining is needed to reach the gold ore. After the initial drilling, blasting and equipping of a mine shaft, tunnels are built leading outwards from the main shaft so that the gold reef can be reached. Shaft mining is a dangerous operation, and roof supports are needed so that the rock does not collapse. There are also problems of the intense heat and high pressure below the surface which make shaft mining very complex, dangerous and expensive. A diagram illustrating open cast and shaft mining is shown in Figure 9.2.

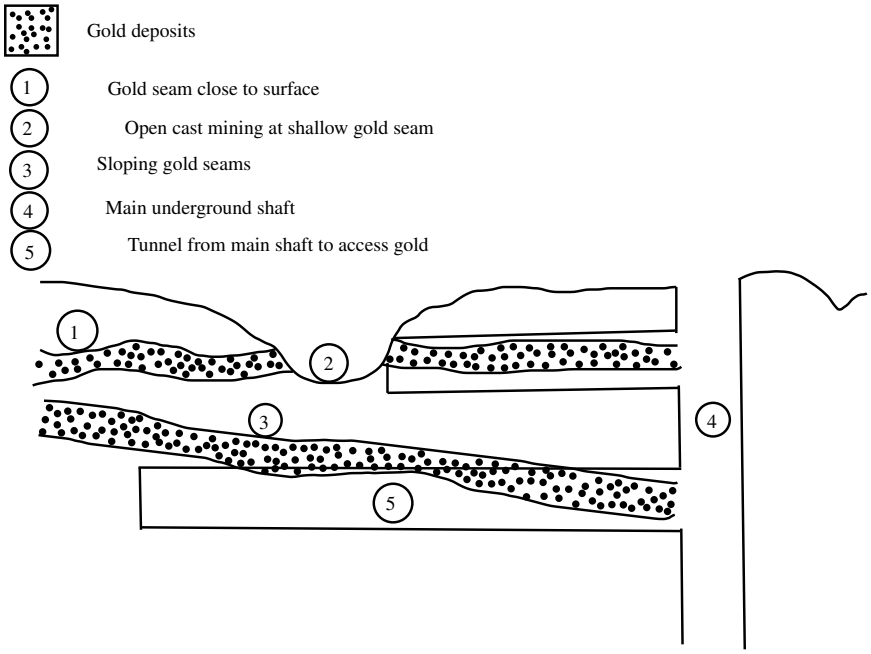


Figure 9.2: Diagram showing open cast and shaft mining

Processing the gold ore

ESBCO

For every ton of ore that is mined, only a very small amount of gold is extracted. A number of different methods can be used to separate gold from its ore, but one of the more common methods is called **gold cyanidation**.

In the process of gold cyanidation, the ore is crushed and then cyanide (CN^-) solution is added so that the gold particles are chemically dissolved from the ore. In this step of the process, gold is oxidised. Zinc dust is then added to the cyanide solution. The zinc takes the place of the gold, so that the gold is precipitated out of the solution. This process is shown in Figure 9.3.

STEP 1 - The ore is crushed until it is in fine pieces

↓

STEP 2 - A sodium cyanide (NaCN) solution is mixed with the finely ground rock

$$4Au + 8NaCN + O_2 + 2H_2O \rightarrow 4NaAu(CN)_2 + 4NaOH$$

Gold is **oxidised**.

↓

STEP 3 - The gold-bearing solution can then be separated from the remaining solid ore through filtration

↓

STEP 4 - Zinc is added. Zinc replaces the gold in the gold-cyanide solution. The gold is precipitated from the solution. This is the **reduction** part of the reaction.

Figure 9.3: Flow diagram showing how gold is processed

Characteristics and uses of gold

ESBCP

Gold has a number of uses because of its varied and unique characteristics. Below is a list of some of these characteristics that have made gold such a valuable metal:

- *Shiny*

  Gold's beautiful appearance has made it one of the favourite metals for use in jewellery.

- *Durable*

  Gold does not tarnish or corrode easily, and therefore does not deteriorate in quality. It is sometimes used in dentistry to make the crowns for teeth.

- *Malleable and ductile*

  Since gold can be bent and twisted into shape, as well as being flattened into very thin sheets, it is very useful in fine wires and to produce sheets of gold.

- *Good conductor*

  Gold is a good conductor of electricity and is therefore used in transistors, computer circuits and telephone exchanges.

- *Heat ray reflector*

  Because gold reflects heat very effectively, it is used in space suits and in vehicles. It is also used in the protective outer coating of artificial satellites. One of the more unusual applications of gold is its use in firefighting, where a thin layer of gold is placed in the masks of the firefighters to protect them from the heat.

Activity: *Dropping like a gold balloon*

Read the article below, which has been adapted from one that appeared in the *Financial Mail* on 15th April 2005 and then answer the questions that follow.

As recently as 1980, South Africa accounted for over 70% of world gold production. In 2004, that figure was a dismal 14%. Chamber of Mines figures showed that SA's annual gold production last year slipped to its lowest level since 1931.

Chamber economist Roger Baxter says the 'precipitous' fall in production was caused by the dual impact of the fall in the rand gold price due to the strong rand, and the continued upward rise in costs. Many of these costs, laments Baxter, are 'costs we do not have control over'. These include water, transport, steel and labour costs, which rose by 13% on average in 2004.

He provides a breakdown of the cost components faced by mines:

- Water prices have risen by 10% per year for the past 3 years
- Steel prices have increased by double-digit rates for each of the past 3 years
- Spoornet's tariffs rose 35% in 2003 and 16.5% in 2004
- Labour costs, which make up 50% of production costs, rose above inflation in 2003 and 2004

At these costs, and at current rand gold prices, about 10 mines, employing 90 000 people, are marginal or loss-making, says Baxter.

1. Refer to the table below showing SA's gold production in tons between 1980 and 2004.

Year	Production (t)
1980	675
1985	660
1990	600
1995	525
2000	425
2004	340

   Draw a line graph to illustrate these statistics.

2. What percentage did South Africa's gold production contribute towards global production in:
   (a) 1980
   (b) 2004
3. Outline two reasons for this drop in gold production.
4. Briefly explain how the increased cost of resources such as water contributes towards declining profitability in gold mines.
5. Suggest a reason why the cost of *steel* might affect gold production.
6. Suggest what impact a decrease in gold production is likely to have on...
   (a) South Africa's economy
   (b) mine employees
7. Find out what the current price of gold is. Discuss why you think gold is so expensive.

Environmental impacts of gold mining

ESBCQ

However, despite the incredible value of gold and its usefulness in a variety of applications, all mining has an environmental cost. The following are just a few of the environmental impacts of gold mining:

- *Resource consumption*

  Gold mining needs large amounts of electricity and water.

- *Poisoned water*

  Acid from gold processing can leach into nearby water systems such as rivers, causing damage to animals and plants, as well as humans that may rely on that water for drinking. The disposal of other toxic waste (e.g. cyanide) can also have a devastating effect on biodiversity.

- *Solid waste*

  This applies particularly to open pit mines, where large amounts of soil and rock must be displaced in order to access the gold reserves. Processing the gold ore also leaves solid waste behind.

- *Air pollution*

  Dust from open pit mines, as well as harmful gases such as sulphur dioxide and nitrogen dioxide which are released from the furnaces, contribute to air pollution.

- *Threaten natural areas*

  Mining activities often encroach on protected areas and threaten biodiversity in their operation areas.

Activity: *Mine rehabilitation*

There is a growing emphasis on the need to rehabilitate old mine sites that are no longer in use. If it is too difficult to restore the site to what it was before, then a new type of land use might be decided for that area. Any mine rehabilitation programme should aim to achieve the following:

- ensure that the site is safe and stable
- remove pollutants that are contaminating the site
- restore the biodiversity that was there before mining started
- restore waterways to what they were before mining

There are different ways to achieve these goals. Plants for example, can be used to remove metals from polluted soils and water, and can also help to stabilise the soil so that other vegetation can grow. Land contouring can help to restore drainage in the area.

Discussion:

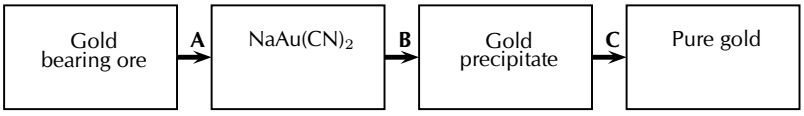
In groups of 3-4, discuss the following questions:

1. What are the main benefits of mine rehabilitation?
2. What are some of the difficulties that may be experienced in trying to rehabilitate a mine site?

3. Suggest some creative ideas that could be used to encourage mining companies to rehabilitate old sites.
4. One rehabilitation project that has received a lot of publicity is the rehabilitation of dunes that were mined for titanium by Richards Bay Minerals (RBM). As a group, carry out your own research to try to find out more about this project.
   - What actions did RBM take to rehabilitate the dunes?
   - Was the project successful?
   - What were some of the challenges faced?

Exercise 9 - 2

Mapungubwe in the Limpopo Province is evidence of gold mining in South Africa as early as 1200. Today, South Africa is a world leader in the technology of gold mining. The following flow diagram illustrates some of the most important steps in the recovery of gold from its ore.



1. Name the process indicated by A.
2. During process A, gold is extracted from the ore. Is gold oxidised or reduced during this process?
3. Use oxidation numbers to explain your answer to the question above.
4. Name the chemical substance that is used in process B.
5. During smelting (illustrated by C in the diagram), gold is sent into a calcining furnace. Briefly explain the importance of this process taking place in the furnace.
6. The recovery of gold can have a negative impact on water in our country, if not managed properly. State at least one negative influence that the recovery of gold can have on water resources and how it will impact on humans and the environment.

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9.6 Mining and mineral processing: Iron

ESBCR

Iron is one of the most abundant metals on Earth. Its concentration is highest in the core, and lower in the crust. It is extracted from **iron ore** and is almost never found in its elemental form. Iron ores are usually rich in **iron oxide** minerals and may vary in colour from dark grey to rusty red. Iron is usually found in minerals such as magnetite (Fe_3O_4) and hematite (Fe_2O_3). Iron ore also contains other elements, which have to be removed in various ways. These include silica (Si), phosphorus (P), aluminium (Al) and sulphur (S).

Iron mining and iron ore processing

ESBCS

One of the more common methods of mining for iron ore is **open cast mining**. Open cast mining is used when the iron ore is found near the surface. Once the ore has been removed, it needs to be crushed into fine particles before it can be processed further.

As mentioned earlier, iron is commonly found in the form of **iron oxides**. To create pure iron, the ore must be **smelted** to remove the oxygen.

> *DEFINITION: Smelting*
>
> Smelting is a method used to extract a metal from its ore and then purify it.

Smelting usually involves heating the ore and also adding a reducing agent (e.g. carbon) so that the metal can be freed from its ore. The bonds between iron and oxygen are very strong, and therefore it is important to use an element that will form stronger bonds with oxygen that the iron. This is why carbon is used. In fact, carbon monoxide is the main ingredient that is needed to strip oxygen from iron. These reactions take place in a **blast furnace**.

A blast furnace is a huge steel container many metres high and lined with heat-resistant material. In the furnace the solid raw materials, i.e. iron ore, carbon (in the form of 'coke', a type of coal) and a flux (e.g. limestone) are fed into the top of the furnace and a blast of heated air is forced into the furnace from the bottom. Temperatures in a blast furnace can reach 2000°C. A simple diagram of a blast furnace is shown in Figure 9.4. The equations for the reactions that take place are shown in the flow diagram below.

STEP 1: Production of carbon monoxide

$$C + O_2 \rightarrow CO_2$$

$$CO_2 + C \rightarrow 2CO$$

STEP 2: Reduction of iron oxides takes place in a number of stages to produce iron.

$$3Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + CO_2$$

$$Fe_3O_4 + CO \rightarrow 3FeO + CO_2$$

$$FeO + CO \rightarrow Fe + CO_2$$

STEP 3: Fluxing

The flux is used to melt impurities in the ore. A common flux is limestone ($CaCO_3$). Common impurities are silica, phosphorus (makes steel brittle), aluminium and sulphur (produces SO_2 gases during smelting and interferes with the smelting process).

$$CaCO_3 \rightarrow CaO + CO_2$$

$$CaO + SiO_2 \rightarrow CaSiO_3$$

In step 3, the calcium carbonate breaks down into calcium oxide and carbon dioxide. The calcium oxide then reacts with silicon dioxide (the impurity) to form a **slag**. In this case the slag is the $CaSiO_3$. The slag melts in the furnace, whereas the silicon dioxide would not have, and floats on the more dense iron. This can then be separated and removed.

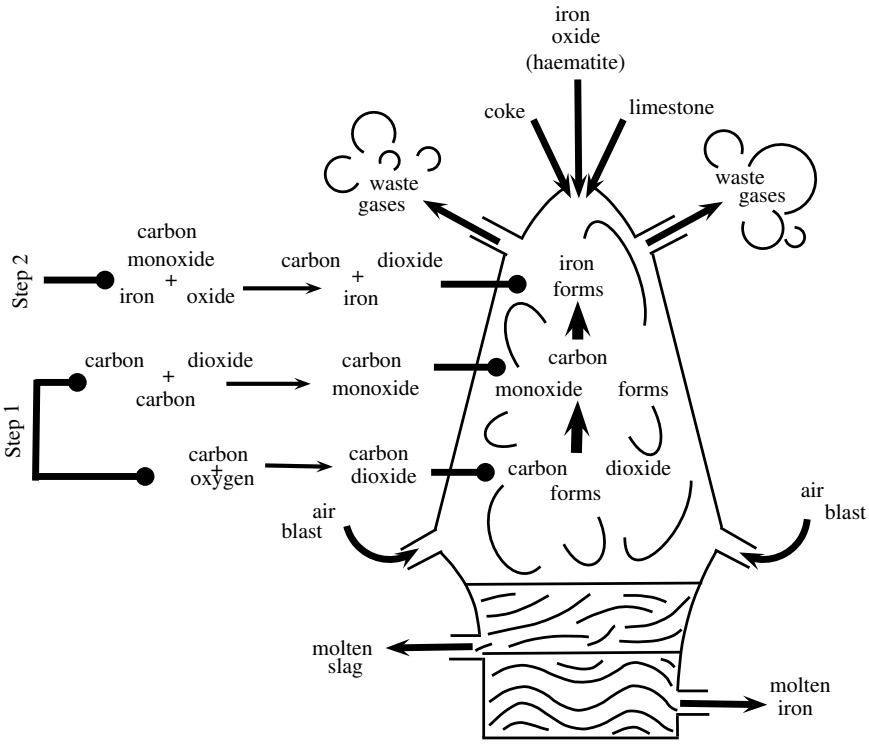

Figure 9.4: A blast furnace, showing the reactions that take place to produce iron

FACT

Iron is also a very important element in all living organisms. One important role that iron plays is that it is a component of the protein **haemoglobin** which is the protein in blood. It is the iron in the haemoglobin that helps to attract and hold oxygen so that this important gas can be transported around the body in the blood, to where it is needed.

Types of iron

ESBCT

Iron is the most used of all the metals. Its combination of low cost and high strength make it very important in applications such as industry, automobiles, the hulls of large ships and in the structural components of buildings. Some of the different forms that iron can take include:

- **Pig iron** is raw iron and is the direct product when iron ore and coke are smelted. It has between 4% and 5% carbon and contains varying amounts of contaminants such as sulphur, silicon and phosphorus. Pig iron is an intermediate step between iron ore, cast iron and steel.
- **Wrought iron** is commercially pure iron and contains less than 0.2% carbon. It is tough, malleable and ductile. Wrought iron does not rust quickly when it is used outdoors. It has mostly been replaced by mild steel for 'wrought iron' gates and blacksmithing. Mild steel does not have the same corrosion resistance as true wrought iron, but is cheaper and more widely available.
- **Steel** is an alloy made mostly of iron, but also containing a small amount of carbon. Elements other than carbon can also be used to make alloy steels. These include manganese and tungsten. By varying the amounts of the alloy elements in the steel, the following characteristics can be altered: hardness, elasticity, ductility and tensile strength.
- **Corrugated iron** is actually sheets of galvanised steel that have been rolled to give them a corrugated pattern. Corrugated iron is a common building material.

One problem with iron and steel is that pure iron and most of its alloys rust. These products therefore need to be protected from water and oxygen, and this is done through painting, galvanisation and plastic coating.

Iron in South Africa

ESBCU

The primary steel industry is an important part of the South African economy and it generates a great deal of foreign exchange.

- About 40 million tons of iron ore is mined annually in South Africa. Approximately 15 million tons are consumed locally, and the remaining 25 million tons are exported.
- South Africa is ranked about 20th in the world in terms of its crude steel production.
- South Africa is the largest steel producer in Africa.
- South Africa exports crude steel and finished steel products, and a lot is also used locally.
- Some of the products that are manufactured in South Africa include reinforcing bars, railway track material, wire rod, plates and steel coils and sheets.

Exercise 9 - 3

Iron is usually extracted from hematite (iron(III)oxide). Iron ore is mixed with limestone and coke in a blast furnace to produce the metal. The following incomplete word equations describe the extraction process:

A coke + oxygen $\rightarrow$ gas X

B gas X + coke $\rightarrow$ gas Y

C iron(III) oxide + gas Y $\rightarrow$ iron + gas X

1. Name the gases X and Y.
2. Write a balanced chemical equation for reaction C.
3. What is the function of gas Y in reaction C?
4. Why is limestone added to the reaction mixture?
5. Briefly describe the impact that the mining of iron has on the economy and the environment in our country.

(DoE Exemplar Paper, Grade 11, 2007)

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(1.) 010d

9.7 Mining and mineral processing: Phosphates

ESBCV

A phosphate is a salt of **phosphoric acid** (H_3PO_4). Phosphates are the naturally occurring form of the element phosphorus. Phosphorus is seldom found in its pure elemental form, and **phosphate** therefore refers to a rock or ore that contains phosphate ions. The chemical formula for the phosphate ion is PO_4^{3-}.

Mining phosphates

ESBCW

Phosphate is found in beds in sedimentary rock, and has to be quarried to access the ore. A quarry is a type of open pit mine that is used to extract ore. In South Africa, the main phosphate producer is at the Phalaborwa alkaline igneous complex, which produces about 3 million tons of ore per year. The ore is crushed into a powder and is then treated with sulphuric acid to form a superphosphate ($Ca(H_2PO_4)_2$), which is then used as a fertiliser. In the equation below, the phosphate mineral is calcium phosphate ($Ca_3(PO_4)_2$.

$$Ca_{10}(PO_4)_6F_2 + 7H_2SO_4 + 3H_2O \rightarrow 3Ca(H_2PO_4)_2H_2O + 7CaSO_4$$

Alternatively, the ore can be treated with concentrated phosphoric acid (which forms a triple superphosphate), in which case the reaction looks like this:

$$Ca_{10}(PO_4)_6F_2 + 14H_3PO_4 + 10H_2O \rightarrow 10Ca(H_2PO_4)_2H_2O + 2HF$$

Uses of phosphates

ESBCX

Phosphates are mostly used in **agriculture**. Phosphates are one of the three main nutrients needed by plants, and they are therefore an important component of **fertilisers** to stimulate plant growth.

Exercise 9 - 4

Rock phosphate [$Ca_{10}(PO_4)_6F_2$], mined from open pit mines at Phalaborwa, is an important raw material in the production of fertilisers. The following two reactions are used to transform rock phosphate into water soluble phosphates:

A: $Ca_{10}(PO_4)_6F_2 + 7X + 3H_2O \rightarrow 3Ca(H_2PO_4)_2H_2O + 2HF + 7CaSO_4$

B: $Ca_{10}(PO_4)_6F_2 + 14Y + 10H_2O \rightarrow 10Ca(H_2PO_4)_2H_2O + 2HF$

1. Identify the acids represented by X and Y.
2. Despite similar molecular formulae, the products $Ca(H_2PO_4)_2$ formed in the two reactions have different common names. Write down the names for each of these products in reactions A and B.

3. Refer to the products in reactions A and B and write down TWO advantages of reaction B over reaction A.
4. Why is rock phosphate unsuitable as fertiliser?
5. State ONE advantage and ONE disadvantage of phosphate mining.

(DoE Exemplar Paper, Grade 11, 2007)

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(1.) 010i

FACT

Exploring the lithosphere for minerals is not a random process! **Geologists** help to piece together a picture of what past environments might have been like, so that predictions can be made about where minerals might have a high concentration. **Geophysicists** measure gravity, magnetics and the electrical properties of rocks to try to make similar predictions, while **geochemists** sample the soils at the earth's surface to get an idea of what lies beneath them. You can see now what an important role scientists play in mineral exploration!

Activity: *Controversy on the Wild Coast - Titanium mining*

Read the extract below, which has been adapted from an article that appeared in the Mail and Guardian *on 4th May 2007, and then answer the questions that follow.*

A potentially violent backlash looms in Pondoland over efforts by an Australian company to persuade villagers to back controversial plans to mine an environmentally sensitive strip of the Wild Coast. The mining will take place in the Xolobeni dunes, south of Port Edward. The application has outraged environmental groups, largely because the proposed mining areas form part of the Pondoland centre of endemism, which has more species than the United Kingdom, some of which are endemic and facing extinction.

Exploratory drilling revealed Xolobeni has the world's 10th largest titanium deposit, worth about R11 billion. The amount of money that will be spent over the mine's 22 years, including a smelter, is estimated at R1.4 billion. The Australian mining company predicts that 570 direct jobs will be created.

But at least two communities fiercely oppose the mining plans. Some opponents are former miners who fear Gauteng's mine dumps and compounds will be replicated on the Wild Coast. Others are employees of failed ecotourism ventures, who blame the mining company for their situation. Many are suspicious of outsiders. The villagers have also complained that some of the structures within the mining company are controlled by business leaders with political connections, who are in it for their own gain. Intimidation of people who oppose the mining has also been alleged. Headman Mandoda Ndovela was shot dead after his outspoken criticism of the mining.

Mzamo Dlamini, a youth living in one of the villages that will be affected by the mining, said 10% of the Amadiba 'who were promised riches by the mining company' support mining. 'The rest say if people bring those machines, we will fight.'

1. Explain what the following words means:
   (a) endemic
   (b) smelter
   (c) ecotourism
2. What kinds of 'riches' do you think the Amadiba people have been promised by the mining company?
3. In two columns, list the potential **advantages** and **disadvantages** of mining in this area.

4. Imagine that you were one of the villagers in this area. Write down *three questions* that you would want the mining company to answer before you made a decision about whether to oppose the mining or not. Share your ideas with the rest of the class.
5. Imagine that you are an environmentalist. What would your main concerns be about the proposed mining project? Again share your answers with the rest of the class.

9.8 Energy resources and their uses: Coal

ESBCY

The products of the lithosphere are also important in meeting our **energy needs**. Coal is one product that is used to produce energy. In South Africa, coal is particularly important because most of our electricity is generated using coal as a fuel. South Africa is the world's sixth largest coal producer, with Mpumalanga contributing about 83% of our total production. Other areas in which coal is produced, include the Free State, Limpopo and KwaZulu-Natal. One of the problems with coal however, is that it is a **non-renewable resource**, meaning that once all resources have been used up, it cannot simply be produced again. Burning coal also produces large quantities of greenhouse gases, which may play a role in global warming. At present, ESKOM, the South African government's electric power producer, is the coal industry's main customer.

The formation of coal

ESBCZ

Coal is what is known as a **fossil fuel**. A fossil fuel is a *hydrocarbon* that has been formed from organic material such as the remains of plants and animals. When plants and animals decompose, they leave behind organic remains that accumulate and become compacted over millions of years under sedimentary rock. Over time, the *heat* and *pressure* in these parts of the earth's crust also increases, and coal is formed. When coal is burned, a large amount of heat energy is released, which is used to produce electricity. **Oil** is also a fossil fuel and is formed in a similar way.

DEFINITION: Fossil Fuel

A fossil fuel is a hydrocarbon that is formed from the fossilised remains of dead plants and animals that have been under conditions of intense heat and pressure for millions of years.

How coal is removed from the ground

ESBDA

Coal can be removed from the crust in a number of different ways. The most common methods used are *strip mining*, *open cast mining* and *underground mining*.

1. **Strip mining**

Strip mining is a form of surface mining that is used when the coal reserves are very shallow. The *overburden* (overlying sediment) is removed so that the coal seams can be reached. These sediments are replaced once the mining is finished, and in many cases, attempts are made to *rehabilitate* the area.

2. **Open cast mining**

   Open cast mining is also a form of surface mining, but here the coal deposits are too deep to be reached using strip mining. One of the environmental impacts of open cast mining is that the overburden is dumped somewhere else away from the mine, and this leaves a huge pit in the ground.

3. **Underground mining**

   Underground mining is normally used when the coal seams are much deeper, usually at a depth greater than 40 m. As with shaft mining for gold, the problem with underground mining is that it is very dangerous, and there is a very real chance that the ground could collapse during the mining if it is not supported. One way to limit the danger is to use *pillar support* methods, where some of the ground is left unmined so that it forms pillars to support the roof. All the other surfaces underground will be mined. Using another method called *longwalling*, the roof is allowed to collapse as the mined-out area moves along. In South Africa, only a small percentage of coal is mined in this way.

The uses of coal

ESBDB

Although in South Africa, the main use of coal is to produce electricity, it can also be used for other purposes.

1. **Electricity**

   In order to generate electricity, solid coal must be crushed and then burned in a furnace with a boiler. A lot of steam is produced and this is used to spin turbines which then generate electricity.

2. **Gasification**

   If coal is broken down and subjected to very high temperatures and pressures, it forms a *synthesis gas*, which is a mix of carbon dioxide and hydrogen gases. This is very important in the *chemical industry* (this will be discussed in Grade 12).

3. **Liquid fuels**

   Coal can also be changed into liquid fuels like petrol and diesel using the **Fischer-Tropsch process**. In fact, South Africa is one of the leaders in this technology (refer to Grade 12). The only problem is that producing liquid fuels from coal, rather than refining petroleum that has been drilled, releases much greater amounts of carbon dioxide into the atmosphere, and this contributes further towards global warming.

Coal and the South African economy

ESBDC

In South Africa, the coal industry is second only to the gold industry. More than this, South Africa is one of the world's top coal *exporters*, and also one of the top *producers*. Of the coal that is produced, most is used locally to produce electricity and the rest is used in industry and domestically.

The problem with coal however, is that it is a **non-renewable resource** which means that once all the coal deposits have been mined, there will be none left. Coal takes such a long time to form, and requires such specific environmental conditions, that it would be impossible for coal to re-form at a rate that would keep up with humankind's current consumption. It is therefore very important that South Africa, and other countries that rely on coal, start to look for alternative energy resources.

The environmental impacts of coal mining ESBDD

There are a number of environmental impacts associated with coal mining.

- *Visual impact and landscape scars*

  Coal mining leaves some very visible scars on the landscape, and destroys biodiversity (e.g. plants, animals). During strip mining and open cast mining, the visual impact is particularly bad, although this is partly reduced by rehabilitation in some cases.

- *Spontaneous combustion and atmospheric pollution*

  Coal that is left in mine dumps may spontaneously combust, producing large amounts of sulphurous smoke which contributes towards atmospheric pollution.

- *Acid formation*

  Waste products from coal mining have a high concentration of sulphur compounds. When these compounds are exposed to water and oxygen, sulphuric acid is formed. If this acid washes into nearby water systems, it can cause a lot of damage to the ecosystem. Acid can also leach into soils and alter its acidity. This in turn affects what will be able to grow there.

- *Global warming*

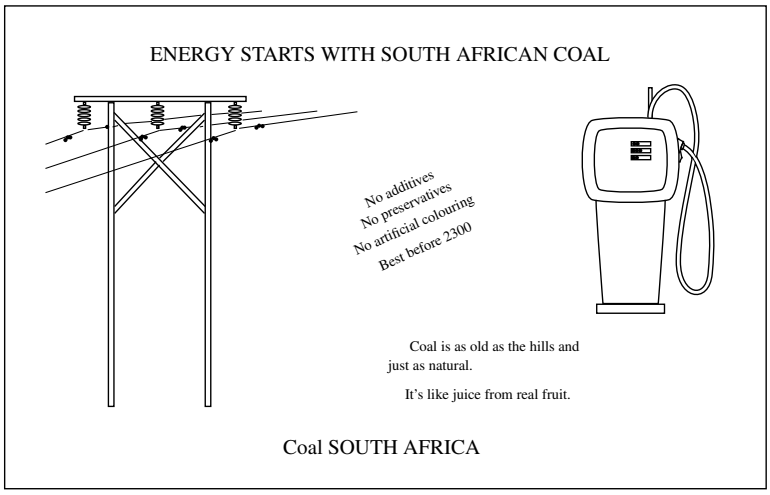
  As was discussed earlier, burning coal to generate electricity produces *carbon dioxide* and *nitrogen oxides* which contribute towards global warming (refer to Chapter 10). Another gas that causes problems is *methane*. All coal contains methane, and coal that is deeper underground contains the most methane. As a greenhouse gas, methane is about twenty times more potent than carbon dioxide.

FACT

It is easy to see how mining, and many other activities including industry and vehicle transport, contribute towards Global Warming. It was for this reason that South Africa joined the **Carbon Sequestration Leadership Forum (CSLF)**. The forum is an international climate change initiative that focuses on developing cost effective technologies to separate and capture carbon dioxide from the atmosphere so that it can be stored in some way. The CSLF also aims to make these technologies as widely available as possible.

Exercise 9 - 5

The following advertisement appeared in a local paper:



1. *"Coal is as old as the hills, and just as natural."* Is this statement TRUE? Motivate your answer by referring to how coal is formed.

2. Coal is a non-renewable energy source. Quote a statement from the advertisement that gives an indication that coal is non-renewable. Give a reason for your choice.

3. Is coal actually a healthy source of energy? Motivate your answer by referring to all influences that coal and coal mining have on both humans and the environment.

4. Why is coal used as a primary energy source in South Africa?

(DoE Exemplar Paper 2, Grade 11, 2007)

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(1.) 010p

9.9 Energy resources and their uses: Oil

ESBDE

Oil is another product of the lithosphere which is very important in meeting our fuel needs.

How oil is formed

ESBDF

Oil is formed in a very similar way to coal, except that the organic material is laid down in **oceans**. Organisms such as zooplankton and algae settle to the ocean floor and become buried under layers of mud. Over time, as these layers of sediment accumulate and the heat and pressure also increase, the organic material changes to a waxy material called *kerogen*. Eventually, with continuing heat and pressure, liquid and gas **hydrocarbons** are formed. These hydrocarbons are lighter than rock and therefore move upwards through the rock layers before being trapped by an impermeable layer. Here the oil will slowly accumulate until there is enough that it can be accessed by oil rigs and other equipment. **Crude oil** or **petroleum**, is actually a mixture of hydrocarbons (mostly alkanes) of different lengths, ranging from 5 carbons to 18 carbons in the hydrocarbon chain. If the mixture contains mostly short hydrocarbons, then it is a gas called **natural gas**. As the hydrocarbon chains in the mixture become longer, the product becomes more and more solid. Coal is made up of the longest hydrocarbons. For more information on hydrocarbons, refer to Grade 12.

Extracting oil

ESBDG

When enough oil has accumulated in a well, it becomes economically viable to try to extract it either through **drilling** or **pumping**. If the pressure in the oil reservoir is high, the oil is forced naturally to the surface. This is known as *primary recovery* of oil. If the pressure is low, then pumps must be used to extract it. This is known as *secondary recovery*. When the oil is very difficult to extract, steam injection into the reservoir can be used to heat the oil, reduce its viscosity and make it easier to extract.

While most of South Africa's oil is imported and then processed at a refinery in either Durban, Cape Town or Sasolburg, some is extracted from coal, as discussed in Section 9.8.

Other oil products

ESBDH

Oil can also be used to make a variety of different products. You will find more information on this in Grade 12.

- *Fractional distillation*

  Fractional distillation is the separation of a mixture into the parts that make it up. In oil refineries, crude oil is separated into useful products such as asphalt, diesel, fuel oil, gasoline, kerosene, liquid petroleum gas (LPG) and tar, to name just a few.

- *Cracking*

  There are two types of cracking, *steam cracking* and *hydrocracking*. Cracking is used to change heavy hydrocarbons such as petroleum into lighter hydrocarbons such as fuels (LPG and gasoline), plastics (ethylene) and other products that are needed to make fuel gas (propylene).

The environmental impacts of oil extraction and use

ESBDI

Some of the key environmental impacts associated with the extraction and use of oil are as follows:

- *Pollution*

  Exploring the oceans for oil, and the actual drilling process, can result in major pollution.

- *Ecosystem impacts*

  Dredging the ocean floors for oil can disrupt seabed ecosystems.

- *Global warming*

  Burning oil as a fuel source produces carbon dioxide, which contributes towards global warming.

9.10 Alternative energy resources

ESBDJ

As the world's population increases, so does the demand for energy. As we have already mentioned, many of our energy resources are **non-renewable** and will soon run out. In addition, many of the fuels that we use produce large amounts of greenhouse gases, which can contribute towards global warming. If we are to maintain the quality and health of our planet, and also meet our growing need for energy, we will need to investigate alternative energy resources. In this next section, we are going to take a closer look at some of these possible alternatives. Many of these options are very controversial, and may have both pros and cons.

- *Nuclear power*

  Another element that is found in the crust, and which helps to meet our energy needs, is **uranium**. Uranium produces energy through the process of *nuclear fission* (Chapter 4). Neutrons are aimed at the nuclei of the uranium atoms in order to split them. When the nucleus of a uranium atom is split, a large amount of energy is released as heat. This heat is used to produce steam, which turns turbines to generate electricity. Uranium is produced as a by-product of gold in some mines in the Witwatersrand, and as a by-product in some copper mines, for example in Phalaborwa. Many people regard this type of nuclear power as relatively environmentally friendly because it doesn't produce a lot of greenhouse gases. However, generating nuclear power does produce radioactive wastes, which must be carefully disposed of in order to prevent contamination. There are also concerns around leaking of nuclear materials.

- *Natural gas*

  Natural gas is formed in a similar way to oil and is often located above oil deposits in the earth's crust. 'Natural gas' refers to a hydrocarbon gas, composed mostly of methane. It is highly combustible and produces low emissions.

  In June 2002, construction began on a pipeline that would stretch for 865 km between Mozambique and South Africa. Mozambique has large sources of under-utilised natural gas and so an agreement was reached between SASOL and the South African and Mozambican governments to build the pipeline, which would transport natural gas from Mozambique to South Africa. The benefits of natural gas include the fact that it is a clean-burning fossil fuel and few by-products are emitted as pollutants. It is also an economical and efficient energy source as the gas can easily be piped directly to a customer's facility.

- *Biofuels*

  In many parts of the world, ethanol is currently being used as a substitute for crude petroleum. Ethanol can be produced through the fermentation of sugar-containing products such as sugar cane. One of the problems with this however, is the vast areas of land that are needed to cultivate the necessary crops. Crops such as maize can also be used in the process. In South Africa, a company called 'Ethanol Africa' has been set up by commercial farmers to convert their surplus maize into environmentally-friendly biofuel, and plans are underway to establish ethanol plants in some of the maize-producing provinces.

- *Hydropower*

  Hydropower produces energy from the action of falling water. As water falls from a height, the energy is used to turn turbines which produce electricity. However, for hydropower to be effective, a large dam is needed to store water. The building of a dam comes with its own set of problems such as the expense of construction, as well as the social and environmental impacts of relocating people (if the area is populated),and disrupting a natural river course.

- *Solar energy*

  Solar energy is energy from the sun. The sun's radiation is trapped in solar panels and is then converted into electricity. While this process is environmentally friendly, and solar energy is a renewable resource, the supply of radiation is not constant (think for example of cloudy days, and nights), and the production of electricity is not efficient. Solar energy can however meet small energy needs such as the direct heating of homes.

- *Geothermal energy*

  This type of energy comes from the natural heat below the Earth's surface. If hot underground steam can be tapped and brought to the surface, it has the potential to produce electricity.

Activity: *Using energy wisely*

The massive power cuts or 'load shedding' that South Africans began to experience at the beginning of 2008, were a dramatic wake-up call to the growing energy crisis that the country faces.

There are alternative energy sources available, but they will take years to become functional, and many of them have their own problems. Another way to look at the problem, is to put the focus on reducing how much energy is *used* rather than focusing only on ways to meet the growing demand.

1. In your groups, discuss ways that each of the following groups of people could save energy.
   (a) industries
   (b) domestic users
   (c) farmers
2. Discuss creative incentives that could be used to encourage each of these groups to reduce their energy consumption.

Chapter 9 — Summary

See the summary presentation (▶ Presentation: VPjxi at www.everythingscience.co.za)

- The **lithosphere** is the solid, outermost part of our planet and contains many important metal elements such as gold and iron, as well as products that are needed to produce energy.
- These elements are seldom found in their pure form, but rather as **minerals** in **rocks**.
- A **mineral** is formed through geological processes. It can either be a pure element (e.g. gold) or may consist of a number of different elements e.g. the gold-bearing mineral calaverite ($AuTe_2$).
- A **rock** is an aggregate of a number of different minerals.
- An **ore** is rock that contains minerals which make it valuable for mining.
- Minerals have been used throughout **history**. As new metals and minerals were discovered, important growth took place in industry, agriculture and technology.
- **Gold** is one of the most important metals in the history of South Africa. It was the discovery of gold that led to an influx of fortune-seeking foreigners, and a growth in mining villages and towns.
- Most of South Africa's gold is concentrated in the 'Golden Arc' in the area between Johannesburg and Welkom.
- Three methods are used to obtain gold from the lithosphere: **panning**, **open cast mining** and **shaft mining**.
- Gold ore must be processed so that the metal can be removed. One way to process the ore after it has been crushed is a method called **gold cyanidation**. A cyanide solution is added to the crushed ore so that a gold-cyanide solution is formed. Zinc is then added to this solution so that the gold is precipitated out.
- Gold has a number of important **characteristics** which make it a useful metal for jewellery and other applications. The metal is shiny, durable, malleable, ductile, is a good conductor of electricity and is also a good heat reflector.
- Gold mining has a number of **environmental impacts**, which include resource consumption, air pollution, poisoned water, solid waste and the destruction of biodiversity in natural areas.
- **Mine rehabilitation** is one way of restoring old mine sites to what they were like before.
- **Iron** is another important metal and is used in industry, furniture and building materials.
- Iron is usually found in minerals such as **iron oxides**. These minerals must be processed to remove the metal.
- When iron ore is **processed**, a blast furnace is used. The iron ore, carbon and a flux are added to the top of the furnace and hot air is blasted into the bottom of the furnace. A number of reactions occur in the furnace to finally remove the iron from its ore. Iron oxides are reduced by carbon monoxide to produce iron.
- Iron can occur in a number of forms, depending on its level of purity and carbon content. It can also occur in an **alloy** e.g. steel.
- **Phosphates** are found in sedimentary rock, which must be quarried to access the ore.
- Phosphates react with phosphoric acid or sulphuric acid to produce a **superphosphate** ($Ca(H_2PO_4)_2$), which is an important component in **fertilisers**.
- The products of the lithosphere are also important in meeting **energy needs**. **Coal** and **oil** can be extracted from the lithosphere for this purpose.
- Coal and oil are both **fossil fuels**. A fossil fuel is a hydrocarbon that has been formed from the fossilised remains of plants and animals that have been under conditions of high heat and pressure over a long period of time.
- Coal and oil are **non-renewable resources**, meaning that once they have been used up, no more can be produced.

- Coal can be removed from the ground using **strip mining**, **open cast mining** or **underground mining**.
- Coal is burned to produce energy, which can be used to generate **electricity**. Coal can also be used to produce **liquid fuels** or a **syngas** which can be converted into other useful products for the chemical industry.
- Some of the **environmental impacts** associated with coal mining include landscape scars, spontaneous combustion, acid formation and global warming.
- Oil is also a fossil fuel but it forms in the **oceans**. It can extracted using either **pumping** or **drilling**, depending on the pressure of the oil.
- **Fractional distillation** of oil can be used to make products such as diesel, gasoline and liquid petroleum gas.
- **Cracking** can be used to convert heavy hydrocarbons to light hydrocarbons.
- The **environmental impacts** of oil extraction and use are similar to those for coal.
- In view of the number of environmental impacts associated with the extraction and use of coal and oil, other **alternative energy sources** should be considered. These include nuclear power, biofuels, hydropower and a number of others. All of these alternatives have their own advantages and disadvantages.

Chapter 9 End of Chapter Exercises

1. Give one word to describe each of the following phrases:
   (a) earth's crust together with the upper layer of the mantle
   (b) a mineral containing silica and oxygen
   (c) an alloy of iron and tin
   (d) a manual technique used to sort gold from other sediments
2. One of the main reasons that South Africa's gold industry has been so economically viable is that:
   (a) gold panning can be used as an additional method to extract gold
   (b) open cast mining can be used to extract gold reserves
   (c) South Africa's geological history is such that its gold reserves are concentrated in large reefs
   (d) South Africa has large amounts of water to use in mining
3. The complete list of reactants in an iron blast furnace is:
   (a) carbon and oxygen
   (b) coal, oxygen, iron ore and limestone
   (c) carbon, oxygen and iron ore
   (d) coal, air, iron ore and slag
4. **More profits, more poisons**

   In the last three decades, gold miners have made use of *cyanidation* to recover gold from the ore. Over 99% of gold from ore can be extracted in this way. It allows miners to obtain gold flakes - too small for the eye to see. Gold can also be extracted from the waste of old operations which sometimes leave as much as a third of the gold behind.

The left-over cyanide can be re-used, but is more often stored in a pond behind a dam or even dumped directly into a local river. A teaspoonful of 2% solution of cyanide can kill a human adult.

Mining companies insist that cyanide breaks down when exposed to sunlight and oxygen which render it harmless. They also point to scientific studies that show that cyanide swallowed by fish will not 'bio-accumulate', which means it does not pose a risk to anyone who eats the fish. In practise, cyanide solution that seeps into the ground will not break down because of the absence of sunlight. If the cyanide solution is very acidic, it could turn into cyanide gas, which is toxic to fish. On the other hand, if the solution is alkaline the cyanide does not break down.

There are no reported cases of human death from cyanide spills. If you don't see corpses, everything is okay.

(a) What is *cyanidation*?
(b) What type of chemical reaction takes place during this process: precipitation, acid-base or redox?
(c) Is the pH of the solution after cyanidation greater than, less than or equal to 7?
(d) How is solid gold recovered from this solution?
(e) Refer to cyanidation and discuss the meaning of the heading of this extract: *More profits, more poisons*.
(DoE Grade 11 Paper 2, 2007)

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(1.) 010t (2.) 010u (3.) 010v (4.) 01yc

The Atmosphere 10

Our Earth is truly an amazing planet! Not only is it exactly the right distance from the sun to have temperatures that will support life, but it is also one of the only planets in our solar system to have liquid water on its surface. In addition, our Earth has an atmosphere that has just the right composition to allow life to exist. The **atmosphere** is the layer of gases that surrounds the Earth. We may not always be aware of them, but without these gases, life on Earth would definitely not be possible. The atmosphere provides the gases that animals and plants need for respiration (breathing) and photosynthesis (the production of food), it helps to keep temperatures on Earth constant and also protects us from the sun's harmful radiation.

In this chapter, we are going to take a closer look at the chemistry of the Earth's atmosphere and at some of the human activities that threaten the delicate balance that exists in this part of our planet.

See introductory video: VPkdh at www.everythingscience.co.za

10.1 The composition of the atmosphere

ESBDK

FACT

The Earth's early atmosphere was very different from what it is today. When the Earth formed around 4.5 billion years ago, there was probably no atmosphere. Some scientists believe that the earliest atmosphere contained gases such as water vapour, carbon dioxide, nitrogen and sulphur which were released from inside the planet as a result of volcanic activity.

Earth's atmosphere is made up of a mixture of gases. Two important gases are nitrogen and oxygen, which make up about 78.1% and 20.9% of the atmosphere respectively. A third gas, argon, contributes about 0.9%, and a number of other gases such as carbon dioxide, methane, water vapour, helium and ozone make up the remaining 0.1%. In an earlier chapter, we discussed the importance of nitrogen as a component of proteins, the building blocks of life. Similarly, oxygen is essential for life because it is the gas we need for respiration. We will discuss the importance of some of the other gases later in this chapter.

If you have ever climbed to a very high altitude (altitude means the 'height' in the atmosphere), you will have noticed that it becomes very difficult to breathe, and many climbers suffer from 'altitude sickness' before they reach their destination. This is because the density of gases becomes less as you move higher in the atmosphere. It is **gravity** that holds the atmosphere close to the Earth. As you move higher, this force weakens slightly and so the gas particles become more spread out. In effect, when you are at a high altitude, the gases in the atmosphere haven't changed, but there are fewer oxygen molecules in the same amount of air that you are able to breathe.

DEFINITION: Earth's atmosphere

The Earth's atmosphere is a layer of gases that surround the planet, and which are held there by the Earth's gravity.

The atmosphere contains roughly 78.1% nitrogen, 20.9% oxygen, 0.9% argon, 0.038% carbon dioxide, trace amounts of other gases, and a variable amount of water vapour. This mixture of gases is commonly known as air. The atmosphere protects life on Earth by absorbing ultraviolet solar radiation and reducing temperature extremes between day and night.

10.2 The structure of the atmosphere

ESBDL

The Earth's atmosphere is divided into different layers, each with its own particular characteristics (Figure 10.1).

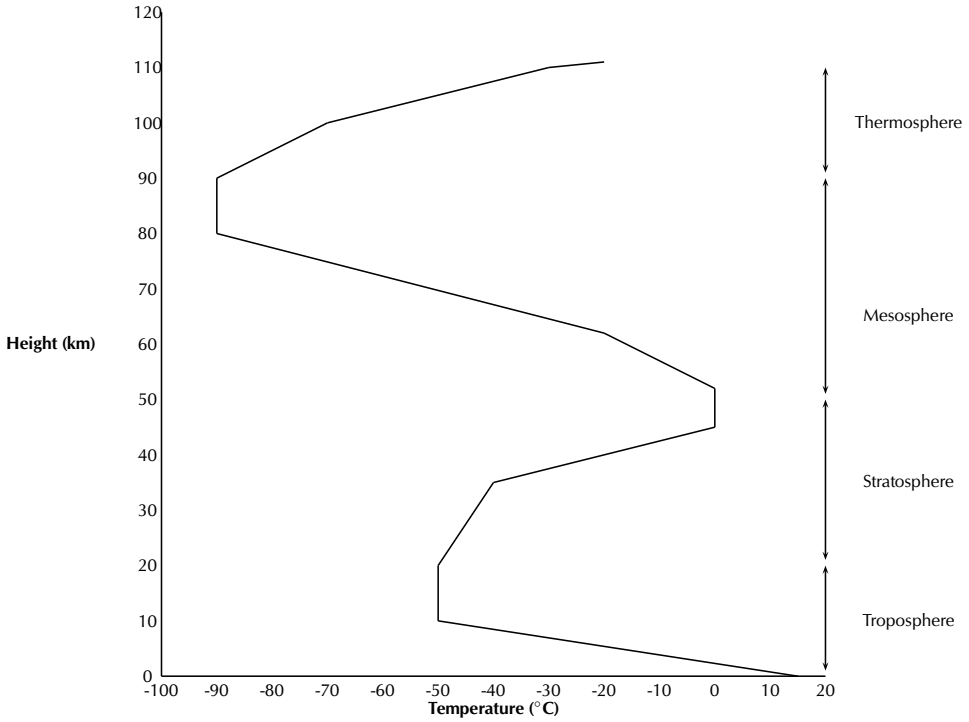

Figure 10.1: A generalised diagram showing the structure of the atmosphere and the changing temperatures up to a height of 110 km

The troposphere

ESBDM

The **troposphere** is the lowest level in the atmosphere, and it is the part in which we live. The troposphere varies in thickness, and extends from the ground to a height of about 7 km at the poles and about 18 km at the equator. An important characteristic of the troposphere is that its temperature *decreases* with an increase in altitude. In other words, as you climb higher, it will get colder. You will have noticed this if you have climbed a mountain, or if you have moved from a city at a high altitude to one which is lower; the average temperature is often lower where the altitude is higher. This is because the troposphere is heated from the 'bottom up'. In other words, places that are closer to sea level will be warmer than those at higher altitudes. The heating of the atmosphere will be discussed in more detail later in this chapter.

FACT

Aeroplanes fly just above the troposphere to avoid all this turbulence. If you have ever been in an aeroplane and have looked out the window once you are well into the flight, you will have noticed that you are actually flying above the level of the clouds. Clouds and weather occur in the troposphere, whereas the stratosphere has very stable atmospheric conditions and very little turbulence.

The word troposphere comes from the Greek *tropos*, meaning *turning* or *mixing*. The troposphere is the most turbulent (or agitated) part of the atmosphere and is the part where our **weather** takes place. Weather is the state of the air at a particular place and time e.g. if it is warm or cold, wet or dry, and how cloudy or windy it is.

The stratosphere

ESBDN

Above the troposphere is another layer called the **stratosphere**. The stratosphere extends from altitudes of 18 to 50 km.

The stratosphere is different from the troposphere because its temperature *increases* as altitude increases. This is because the stratosphere absorbs solar radiation directly, meaning that the upper layers closer to the sun will be warmer. The upper layers of the stratosphere are also warmer because of the presence of the **ozone layer**. Ozone (O_3) is formed when solar radiation splits an oxygen molecule (O_2) into two atoms of oxygen. Each individual atom is then able to combine with an oxygen molecule to form ozone. The two reactions are shown below:

$$O_2 \rightarrow O + O$$

$$O + O_2 \rightarrow O_3$$

The change from one type of molecule to another produces energy, and this contributes to higher temperatures in the upper part of the stratosphere. An important function of the ozone layer is to absorb UV radiation and reduce the amount of harmful radiation that reaches the Earth's surface.

Extension:	*CFCs and the ozone layer*

You may have heard people talking about 'the hole in the ozone layer'. What do they mean by this and do we need to be worried about it?
Most of the Earth's ozone is found in the stratosphere and this limits the amount of UV radiation that reaches the Earth. However, human activities have once again disrupted the chemistry of the atmosphere. Chlorofluorocarbons (CFCs) are compounds found in aerosol cans, fridges and airconditioners. In aerosol cans, it is the CFCs that cause the substance within the can to be sprayed outwards. The negative side of CFCs is that, when they are released into the atmosphere, they break down ozone molecules so that the ozone is no longer able to protect us as much from UV rays. The 'ozone hole' is actually a thinning of the ozone layer approximately above Antarctica. Let's take a closer look at the chemical reactions that are involved in breaking down ozone:

1. When CFCs react with UV radiation, a carbon-chlorine bond in the chlorofluorocarbon breaks and a new compound is formed, with a chlorine atom.

$$CFCl_3 + \text{UV light} \rightarrow CFCl_2^- + Cl^+$$

2. The single chlorine atom reacts with ozone to form a molecule of chlorine monoxide and oxygen gas. In the process, ozone is destroyed.

$$Cl^- + O_3 \rightarrow ClO + O_2$$

3. The chlorine monoxide then reacts with a free oxygen atom (UV radiation breaks O_2 down into single oxygen atoms) to form oxygen gas and a single chlorine atom.

$$ClO + O \rightarrow Cl + O_2$$

4. The chlorine atom is then free to attack more ozone molecules, and the process continues. A single CFC molecule can destroy 100 000 ozone molecules.

One observed consequence of ozone depletion is an increase in the incidence of skin cancer in affected areas because there is more UV radiation reaching Earth's surface. CFC replacements are now being used to reduce emissions, and scientists are trying to find ways to restore ozone levels in the atmosphere.

The mesosphere

ESBDO

The mesosphere is located about 50-80 km above Earth's surface. Within this layer, temperature decreases with increasing altitude. Temperatures in the upper mesosphere can fall as low as -100°C in some areas. Millions of meteors burn up daily in the mesosphere because of collisions with the gas particles that are present in this layer. This leads to a high concentration of iron and other metal atoms.

The thermosphere

ESBDP

The thermosphere exists at altitudes above 80 km. In this part of the atmosphere, UV and shorter X-Ray radiation from the sun cause neutral gas atoms to be *ionised*. At these radiation frequencies, photons from the solar radiation are able to dislodge electrons from neutral atoms and molecules during a collision. A *plasma* is formed, which consists of negative free electrons and positive ions. The part of the atmosphere that is ionised by solar radiation is called the **ionosphere**. At the same time that ionisation takes place however, an opposing process called recombination also begins. Some of the free electrons are drawn to the positive ions, and combine again with them if they are in close enough contact. Since the gas density increases at lower altitudes, the recombination process occurs more often here because the gas molecules and ions are closer together. The ionisation process produces energy which means that the upper parts of the thermosphere, which are dominated by ionisation, have a higher temperature than the lower layers where recombination takes place. Overall, temperature in the thermosphere increases with an increase in altitude.

FACT

The ionosphere is also home to the **aurorae**. Aurorae are caused by the collision of charged particles (e.g. electrons) with atoms in the Earth's upper atmosphere. Charged particles are energised and so, when they collide with atoms, the atoms also become energised. Shortly afterwards, the atoms emit the energy they have gained, as light. Often these emissions are from oxygen atoms, resulting in a greenish glow (wavelength 557.7 nm) and, at lower energy levels or higher altitudes, a dark red glow (wavelength 630 nm). Many other colours can also be observed. For example, emissions from atomic nitrogen are blue, and emissions from molecular nitrogen are purple. Aurorae emit visible light (as described above), and also infra-red, ultraviolet and x-rays, which can be observed with special instruments.

Extension:	*The ionosphere and radio waves*

The ionosphere is of practical importance because it allows **radio waves** to be transmitted. A radio wave is a type of electromagnetic radiation that humans use to transmit information without wires. When using high-frequency bands, the ionosphere is used to reflect the transmitted radio beam. When a radio wave reaches the ionosphere, the electric field in the wave causes the electrons in the ionosphere to start oscillating at the same frequency as the radio wave. Some of the radio wave energy is given up to this mechanical oscillation. The oscillating electron will then either recombine with a positive ion, or will re-radiate the original wave energy back downward again. The beam returns to the Earth's surface, and may then be reflected back into the ionosphere for a second time.

Exercise 10 - 1

1. Complete the following summary table by providing the missing information for each layer in the atmosphere.

Atmospheric layer	Height (km)	Gas composition	General characteristics
Troposphere	0-18		Turbulent; part of atmosphere where weather occurs
			Ozone reduces harmful radiation reaching Earth
Mesosphere			High concentration of metal atoms
	more than 80 km		

2. Use your knowledge of the atmosphere to explain the following statements:
   (a) Athletes who live in coastal areas need to acclimatise (adjust to higher altitude) if they are competing at high altitudes.
   (b) Higher incidences of skin cancer have been recorded in areas where the ozone layer in the atmosphere is thin.
   (c) During a flight, turbulence generally decreases above a certain altitude.

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10.3 Greenhouse gases and global warming

ESBDQ

The heating of the atmosphere

ESBDR

As we mentioned earlier, the distance of the Earth from the sun is not the only reason that temperatures on Earth are within a range that is suitable to support life. The composition of the atmosphere is also critically important.

The Earth receives electromagnetic energy from the sun in the *visible spectrum*. There are also small amounts of infrared and ultraviolet radiation in this incoming solar energy. Most of the radiation is *shortwave* radiation, and it passes easily through the atmosphere towards the Earth's surface, with some being reflected before reaching the surface. At the surface, some of the energy is absorbed, and this heats up the Earth's surface. But the situation is a little more complex than this.

A large amount of the sun's energy is re-radiated from the surface back into the atmosphere as **infrared** radiation, which is invisible to humans. As this radiation passes through the atmosphere, some of it is absorbed by **greenhouse gases** such as carbon dioxide, water vapour and methane. These gases are very important because they re-emit the energy back towards the surface. By doing this, they help to warm the lower layers of the atmosphere even further. It is this 're-emission' of heat by greenhouse

gases, combined with surface heating and other processes (e.g. conduction and convection) that maintain temperatures at exactly the right level to support life. Without the presence of greenhouse gases, most of the sun's energy would be lost and the Earth would be a lot colder than it is! A simplified diagram of the heating of the atmosphere is shown in Figure 10.2.

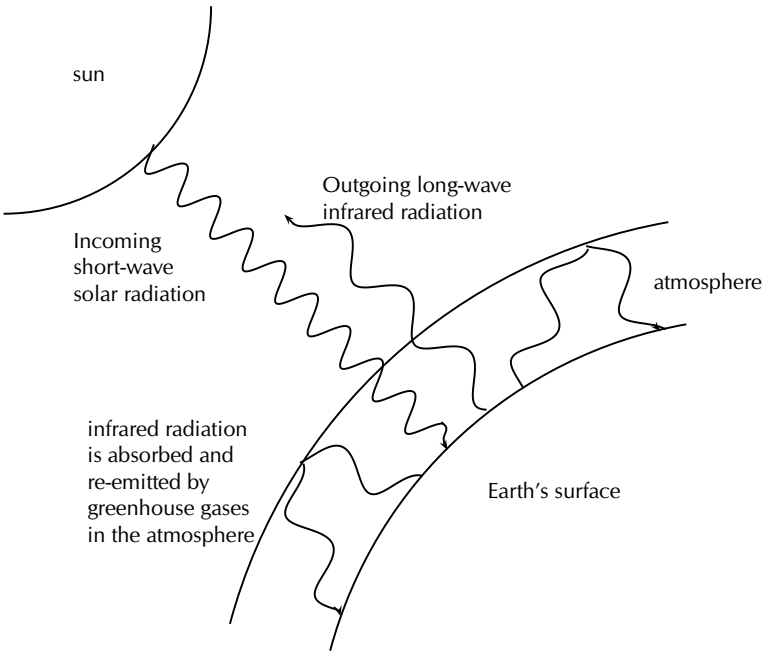


Figure 10.2: The heating of the Earth's atmosphere

The greenhouse gases and global warming *ESBDS*

Many of the greenhouse gases occur naturally in small quantities in the atmosphere. However, human activities have greatly increased their concentration, and this has led to a lot of concern about the impact that this could have in *increasing* global temperatures. This phenomenon is known as **global warming**. Because the natural concentrations of these gases are low, even a small increase in their concentration as a result of human emissions, could have a big effect on temperature. But before we go on, let's look at where some of these human gas emissions come from.

- **Carbon dioxide** (CO_2)

  Carbon dioxide enters the atmosphere through the burning of fossil fuels (oil, natural gas, and coal), solid waste, trees and wood products, and also as a result of other chemical reactions (e.g. the manufacture of cement). Carbon dioxide can also be *removed* from the atmosphere when it is absorbed by plants during photosynthesis.

- **Methane** (CH_4)

  Methane is emitted when coal, natural gas and oil are produced and transported. Methane emissions can also come from livestock and other agricultural practises and from the decay of organic waste.

- **Nitrous oxide** (N_2O)

  Nitrous oxide is emitted by agriculture and industry, and when fossil fuels and solid waste are burned.

- **Fluorinated gases** (e.g. hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride)

  These gases are all *synthetic*, in other words they are man-made. They are emitted from a variety of industrial processes. Fluorinated gases are sometimes used in the place of other ozone-depleting substances (e.g. CFCs). These are very powerful greenhouse gases, and are sometimes referred to as High Global Warming Potential gases ('High GWP gases').

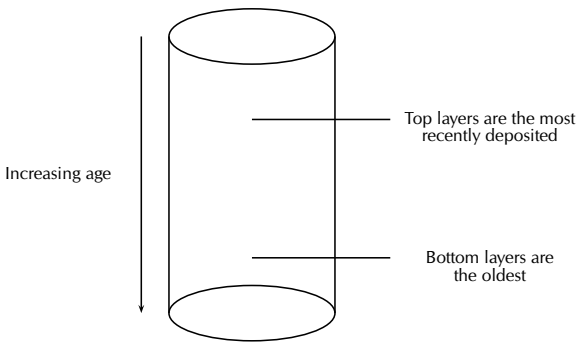
Overpopulation is a major problem in reducing greenhouse gas emissions, and in slowing down global warming. As populations grow, their demands on resources (e.g. energy) increase, and so does their production of greenhouse gases.

Extension:	*Ice core drilling - Taking a look at Earth's past climate*

Global warming is a very controversial issue. While many people are convinced that the increase in average global temperatures is directly related to the increase in atmospheric concentrations of carbon dioxide, others argue that the climatic changes we are seeing are part of a natural pattern. One way in which scientists are able to understand what is happening at present, is to understand the Earth's *past* atmosphere, and the factors that affected its temperature.

So how, you may be asking, do we know what the Earth's *past* climate was like? One method that is used is **ice core drilling**. Antarctica is the coldest continent on Earth, and because of this there is very little melting of ice that takes place. Over thousands of years, ice has accumulated in layers and has become more and more compacted as new ice is added. This is partly why Antarctica is also on average one of the *highest* continents! On average, the ice sheet that covers Antarctica is 2500 m thick, and at its deepest location, is 4700 m thick.

As the snow is deposited on top of the ice sheet each year, it traps different chemicals and impurities which are dissolved in the ice. The ice and impurities hold information about the Earth's environment and climate at the time that the ice was deposited. Drilling an ice core from the surface down, is like taking a journey back in time. The deeper into the ice you venture, the older the layer of ice. By analysing the gases and oxygen isotopes that are present (along with many other techniques) in the ice at various points in the Earth's history, scientists can start to piece together a picture of what the Earth's climate must have been like.



One of the most well known ice cores was the one drilled at a Russian station called **Vostok** in central Antarctica. So far, data has been gathered for dates as far back as 160 000 years!

Activity: Looking at past climatic trends

Make sure that you have read the 'extension box' on ice core drilling before you try this activity.

The values in the table below were extrapolated from data obtained by scientists studying the Vostok ice core. 'Local temperature change' means by how much the temperature at that time was different from what it is today. For example, if the local temperature change 160 000 years ago was -9°C, this means that atmospheric temperatures at that time were 9°C *lower* than what they are today. 'ppm' means 'parts per million' and is a unit of measurement for gas concentrations.

Years before present (× 1000)	**Local temperature change (°C)**	**Carbon dioxide (ppm)**
160	-9	190
150	-10	205
140	-10	240
130	-3	280
120	+1	278
110	-4	240
100	-8	225
90	-5	230
80	-6	220
70	-8	250
60	-9	190
50	-7	220
40	-8	180
30	-7	225
20	-9	200
10	-2	260
0 (1850)	-0.5	280
Present		371

Questions

1. On the same set of axes, draw graphs to show how temperature and carbon dioxide concentrations have changed over the last 160 000 years. Hint: 'Years before present' will go on the x-axis, and should be given *negative* values.
2. Compare the graphs that you have drawn. What do you notice?
3. Is there a relationship between temperature and the atmospheric concentration of carbon dioxide?
4. Do these graphs *prove* that temperature changes are determined by the concentration of gases such as carbon dioxide in the atmosphere? Explain your answer.
5. What other factors might you need to consider when analysing climatic trends?

The consequences of global warming

ESBDT

Activity: *The impacts of global warming*

In groups of 3-4, read the following extracts and then answer the questions that follow.

By 2050 Warming to Doom Million Species, Study Says

By 2050, rising temperatures exacerbated by human-induced belches of carbon dioxide and other greenhouse gases could send more than a million of Earth's land-dwelling plants and animals down the road to extinction, according to a recent study. "Climate change now represents at least as great a threat to the number of species surviving on Earth as habitat-destruction and modification," said Chris Thomas, a conservation biologist at the University of Leeds in the United Kingdom.

The researchers worked independently in six biodiversity-rich regions around the world, from Australia to South Africa, plugging field data on species distribution and regional climate into computer models that simulated the ways species' ranges are expected to move in response to temperature and climate changes. According to the researchers' collective results, the predicted range of climate change by 2050 will place 15 to 35 percent of the 1 103 species studied at risk of extinction.

National Geographic News, 12 July 2004

Global Warming May Dry Up Africa's Rivers, Study Suggests

Many climate scientists already predict that less rain will fall annually in parts of Africa within 50 years due to global warming. Now new research suggests that even a small decrease in rainfall on the continent could cause a drastic reduction in river water, the lifeblood for rural populations in Africa.

A decrease in water availability could occur across about 25 percent of the continent, according to the new study. Hardest hit would be areas in northwestern and southern Africa, with some of the most serious effects striking large areas of Botswana and South Africa.

To predict future rainfall, the scientists compared 21 of what they consider to be the best climate change models developed by research teams around the world. On average, the models forecast a 10 to 20% drop in rainfall in northwestern and southern Africa by 2070. With a 20% decrease, Cape Town would be left with just 42% of its river water, and "Botswana would completely dry up," de Wit said. In parts of northern Africa, river water levels would drop below 50%.

Less river water would have serious implications not just for people but for the many animal species whose habitats rely on regular water supplies.

National Geographic News, 3 March 2006

Discussion questions

1. What is meant by 'biodiversity'?
2. Explain why global warming is likely to cause a *loss of biodiversity*.
3. Why do you think a loss of biodiversity is of such concern to conservationists?
4. Suggest some plant or animal species in South Africa that you think might be particularly vulnerable to extinction if temperatures were to rise significantly. Explain why you chose these species.
5. In what way do people, animals and plants rely on river water?
6. What effect do you think a 50% drop in river water level in some parts of Africa would have on the people living in these countries?

7. Discuss some of the other likely impacts of global warming that we can expect (e.g. sea level rise, melting of polar ice caps, changes in ocean currents).

Taking action to combat global warming

ESBDU

Global warming is a major concern at present. A number of organisations, panels and research bodies have been working to gather accurate and relevant information so that a true picture of our current situation can be painted. One important organisation that you may have heard of is the **Intergovernmental Panel on Climate Change** (IPCC). The IPCC was established in 1988 by two United Nations organisations, the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP), to evaluate the risk of climate change brought on by humans. You may also have heard of the **Kyoto Protocol**, which will be discussed a little later.

Activity: World carbon dioxide emissions

The data in the table below shows carbon dioxide emissions from the consumption of fossil fuels (in million metric tons of carbon dioxide).

Region or Country	1980	1985	1990	1995	2000	2004
United States	4754	4585	5013	5292	5815	5912
Brazil	186	187	222	288	345	336
France	487	394	368	372	399	405
UK	608	588	598	555	551	579
Saudi Arabia	175	179	207	233	288	365
Botswana	1.26	1.45	2.68	3.44	4.16	3.83
South Africa	234	298	295	344	378	429
India	299	439	588	867	1000	1112
World Total	18333	19412	21426	22033	23851	27043

Questions

1. Redraw the table and use a coloured pen to highlight those countries that are 'developed' and those that are 'developing'.
2. Explain why CO_2 emissions are so much higher in developed countries than in developing countries.
3. How does South Africa compare to the other developing countries, and also to the developed countries?

Carbon dioxide emissions are a major problem worldwide. The **Kyoto Protocol** was signed in Kyoto, Japan in December 1997. Its main objective was to reduce global greenhouse gas emissions by encouraging countries to become signatories to the guidelines that had been laid out in the protocol. These guidelines set targets for the world's major producers to reduce their emissions within a certain time. However, some of the worst contributors to greenhouse gas emissions (e.g. USA) were not prepared to sign the protocol, partly because of the potential effect this would have on the country's economy, which relies on industry and other 'high emission' activities.

Panel discussion

Form groups with 5 people in each. Each person in the group must adopt one of the following roles during the discussion:

- the owner of a large industry
- an environmental scientist
- an economist
- a politician
- a chairperson for the discussion

In your group, you are going to discuss some of the economic and environmental implications for a country that decides to sign the Kyoto Protocol. Each person will have the opportunity to express the view of the character they have adopted. You may ask questions of the other people, or challenge their ideas, provided that you ask permission from the chairperson first.

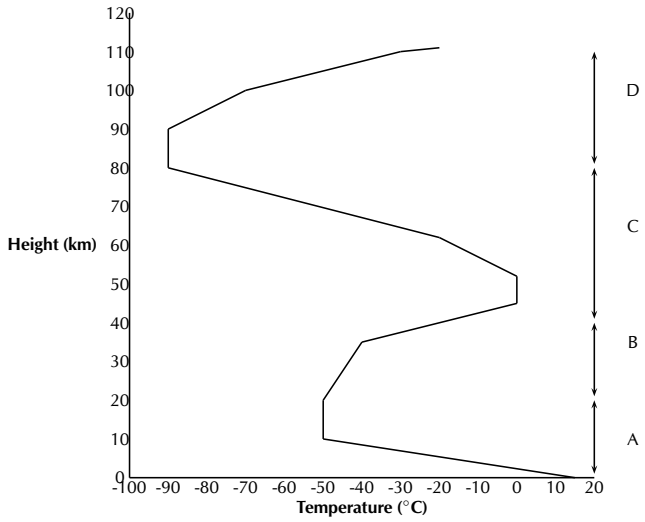
Chapter 10 — Summary

See the summary presentation (▶ Presentation: VPkds at www.everythingscience.co.za)

- The **atmosphere** is the layer of gases that the surrounds Earth. These gases are important in sustaining life, regulating temperature and protecting the Earth from harmful radiation.
- The gases that make up the atmosphere are nitrogen, oxygen, carbon dioxide, argon and others e.g. water vapour, methane.
- There are four layer in the atmosphere, each with their own characteristics.
- The **troposphere** is the lowest layer and here, temperature decreases with an increase in altitude. The troposphere is where weather occurs.
- The next layer is the **stratosphere** where temperature increases with an increase in altitude because of the presence of ozone in this layer, and the direct heating from the sun.
- The depletion of the ozone layer is largely because of CFCs, which break down ozone through a series of chemical reactions.
- The **mesosphere** is characterised by very cold temperatures and meteor collisions. The mesosphere contains high concentrations of metal atoms.
- In the **thermosphere**, neutral atoms are ionised by UV and X-ray radiation from the sun. Temperature increases with an increase in altitude because of the energy that is released during this ionisation process, which occurs mostly in the upper thermosphere.
- The thermosphere is also known as the **ionosphere**, and is the part of the atmosphere where radio waves can be transmitted.
- The **auroras** are bright coloured skies that occur when charged particles collide with atoms in the upper atmosphere. Depending on the type of atom, energy is released as light at different wavelengths.
- The Earth is heated by radiation from the sun. Incoming radiation has a short wavelength and some is absorbed directly by the Earth's surface. However, a large amount of energy is re-radiated as longwave infrared radiation.
- **Greenhouse gases** such as carbon dioxide, water vapour and methane absorb infrared radiation and re-emit it back towards the Earth's surface. In this way, the bottom layers of the atmosphere are kept much warmer than they would be if all the infrared radiation was lost.
- Human activities such as the burning of fossil fuels, increase the concentration of greenhouse gases in the atmosphere and may contribute towards **global warming**.
- Some of the impacts of global warming include changing climate patterns, rising sea levels and a loss of biodiversity, to name a few. Interventions are needed to reduce this phenomenon.

Chapter 10 End of Chapter Exercises

1. The atmosphere is a relatively thin layer of gases which support life and provide protection to living organisms. The force of gravity holds the atmosphere against the Earth. The diagram below shows the temperatures associated with the various layers that make up the atmosphere and the altitude (height) from the Earth's surface.



(a) Write down the names of the layers A, B and D of the atmosphere.

(b) In which one of the layers of the atmosphere is ozone found?

(c) Give an explanation for the decrease in temperature as altitude increases in layer A.

(d) In layer B, there is a steady increase in temperature as the altitude increases. Write down an explanation for this trend.

2. **Planet Earth in Danger**
It is now accepted that greenhouse gases are to blame for Planet Earth getting warmer. The increase in the number of sudden floods in Asia and droughts in Africa; the rising sea level and increasing average temperatures are global concerns. Without natural greenhouse gases,like carbon dioxide and water vapour,life on Earth is not possible. However, the increase in levels of carbon dioxide in the atmosphere since the Industrial Revolution is of great concern. Greater disasters are to come, which will create millions of climate refugees. It is our duty to take action for the sake of future generations who will pay dearly for the wait-and-see attitude of the current generation. Urgent action to reduce waste is needed. Global warming is a global challenge and calls for a global response now, not later.
(Adapted from a speech by the French President, Jacques Chirac)

(a) How do greenhouse gases, such as carbon dioxide, heat up the Earth's surface?

(b) Draw a Lewis structure for the carbon dioxide molecule

(c) The chemical bonds within the carbon dioxide molecule are polar. Support this statement by performing a calculation using the table of electronegativities.

(d) Classify the carbon dioxide molecule as polar or non-polar. Give a reason for your answer.

(e) Suggest ONE way in which YOU can help to reduce the emissions of greenhouse gases.

3. Plants need carbon dioxide (CO_2) to manufacture food. However, the engines of motor vehicles cause too much carbon dioxide to be released into the atmosphere.
   (a) State the possible consequence of having too much carbon dioxide in the atmosphere.
   (b) Explain **two** possible effects on humans if the amount of carbon dioxide in the atmosphere becomes too low.

   (DoE Exemplar Paper Grade 11, 2007)

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Part II

Physics

Vectors 11

11.1 Introduction

ESBDV

This chapter focuses on vectors. We will learn what is a vector and how it differs from everyday numbers. We will also learn how to add, subtract and multiply them and where they appear in Physics.

Are vectors Physics? No, vectors themselves are not Physics. Physics is just a description of the world around us. To describe something we need to use a language. The most common language used to describe Physics is Mathematics. Vectors form a very important part of the mathematical description of Physics, so much so that it is absolutely essential to master the use of vectors.

See introductory video: VPkel at www.everythingscience.co.za

11.2 Scalars and Vectors

ESBDW

In Mathematics, you learned that a number is something that represents a quantity. For example if you have 5 books, 6 apples and 1 bicycle, the 5, 6, and 1 represent how many of each item you have.

These kinds of numbers are known as *scalars*.

> *DEFINITION: Scalar*
>
> A scalar is a quantity that has only magnitude (size).

An extension to a scalar is a vector, which is a scalar with a direction. For example, if you travel 1 km down Main Road to school, the quantity **1 km down Main Road** is a vector. The "**1 km**" is the quantity (or scalar) and the "**down Main Road**" gives a direction.

In Physics we use the word *magnitude* to refer to the scalar part of the vector.

> *DEFINITION: Vectors*
>
> A vector is a quantity that has both magnitude and direction.

A vector should tell you *how much* and *which way*.

For example, a man is driving his car east along a freeway at 100 km·hr^{-1}. What we have given here is a vector – the velocity. The car is moving at 100 km·hr^{-1}(this is the magnitude) and we know where it is going – east (this is the direction). Thus, we know the speed and direction of the car. These two quantities, a magnitude and a direction, form a vector we call velocity.

11.3 Notation

ESBDX

Vectors are different to scalars and therefore have their own notation.

Mathematical Representation

ESBDY

There are many ways of writing the symbol for a vector. Vectors are denoted by symbols with an arrow pointing to the right above it. For example, $\vec{a}$, $\vec{v}$ and $\vec{F}$ represent the vectors acceleration, velocity and force, meaning they have both a magnitude and a direction.

Sometimes just the magnitude of a vector is needed. In this case, the arrow is omitted. In other words, F denotes the magnitude of the vector $\vec{F}$. $|\vec{F}|$ is another way of representing the magnitude of a vector.

Graphical Representation

ESBDZ

Vectors are drawn as arrows. An arrow has both a magnitude (how long it is) and a direction (the direction in which it points). The starting point of a vector is known as the *tail* and the end point is known as the *head*.

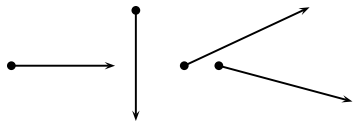


Figure 11.1: Examples of vectors

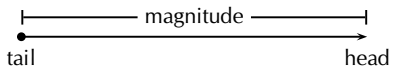


Figure 11.2: Parts of a vector

11.4 Directions

ESBEA

There are many acceptable methods of writing vectors. As long as the vector has a magnitude and a direction, it is most likely acceptable. These different methods come from the different methods of

expressing a direction for a vector.

Relative Directions

ESBEB

The simplest method of expressing direction is with relative directions: to the left, to the right, forward, backward, up and down.

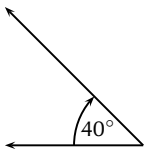
Compass Directions

ESBEC

Another common method of expressing directions is to use the points of a compass: North, South, East, and West.

If a vector does not point exactly in one of the compass directions, then we use an angle. For example, we can have a vector pointing 40° North of West. Start with the vector pointing along the West direction:

Then rotate the vector towards the north until there is a 40° angle between the vector and the West.



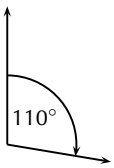
The direction of this vector can also be described as: W 40° N (West 40° North); or N 50° W (North 50° West)

Bearing

ESBED

The final method of expressing direction is to use a *bearing*. A bearing is a direction relative to a fixed point.

Given just an angle, the convention is to define the angle with respect to the North. So, a vector with a direction of 110° has been rotated clockwise 110° relative to the North. A bearing is always written as a three digit number, for example 275° or 080° (for 80°).

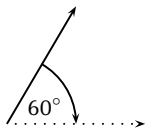


Exercise 11 - 1

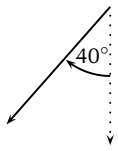
1. Classify the following quantities as scalars or vectors:
   (a) 12 km
   (b) 1 m south
   (c) 2 m·s^{-1}, 45°
   (d) 075°, 2 cm
   (e) 100 km·hr^{-1}, 0°
2. Use two different notations to write down the direction of the vector in each of the following diagrams:

(a)

(b)



(c)



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(1.) 00mz (2.) 00n0

11.5 Drawing Vectors

ESBEE

In order to draw a vector accurately we must specify a scale and include a reference direction in the diagram. A scale allows us to translate the length of the arrow into the vector's magnitude. For instance if one chose a scale of 1 cm = 2 N (1 cm represents 2 N), a force of 20 N towards the East would be represented as an arrow 10 cm long. A reference direction may be a line representing a horizontal surface or the points of a compass.

Method: Drawing Vectors

1. Decide upon a scale and write it down.
2. Determine the length of the arrow representing the vector, by using the scale.
3. Draw the vector as an arrow. Make sure that you fill in the arrow head.
4. Fill in the magnitude of the vector.

Example 1: *Drawing vectors*

QUESTION

Represent the following vector quantities:

1. *6 m·s^{-1}north*
2. *16 m east*

SOLUTION

Step 1 : ***Decide upon a scale and write it down.***

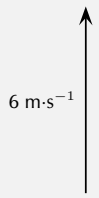
1. 1 cm = 2 m·s^{-1}
2. 1 cm = 4 m

Step 2 : ***Determine the length of the arrow at the specific scale.***

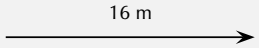
1. If 1 cm = 2 m·s^{-1}, then 6 m·s^{-1} = 3 cm
2. If 1 cm = 4 m, then 16 m = 4 cm

Step 3 : ***Draw the vectors as arrows.***

1. Scale used: 1 cm = 2 m·s^{-1}
   Direction = North



2. Scale used: 1 cm = 4 m
   Direction = East



Exercise 11 - 2

Draw each of the following vectors to scale. Indicate the scale that you have used:

1. 12 km south
2. 1,5 m N 45° W
3. 1 m·s^{-1}, 20° East of North
4. 50 km·hr^{-1}, 085°
5. 5 mm, 225°

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(1.) 00n1

11.6 Mathematical Properties of Vectors

ESBEF

Vectors are mathematical objects and we need to understand the mathematical properties of vectors, like adding and subtracting.

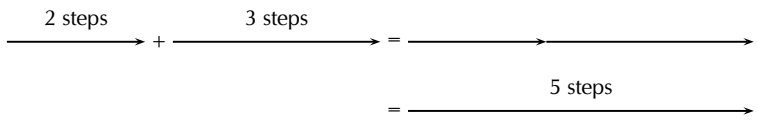
For all the examples in this section, we will use displacement as our vector quantity. Displacement was discussed in Grade 10.Displacement is defined as the distance together with direction of the straight line joining a final point to an initial point.

Remember that displacement is just one example of a vector. We could just as well have decided to use forces or velocities to illustrate the properties of vectors.

Adding Vectors

ESBEG

When vectors are added, we need to add both a magnitude **and** a direction. For example, take 2 steps in the forward direction, stop and then take another 3 steps in the forward direction. The first 2 steps is a displacement vector and the second 3 steps is also a displacement vector. If we did not stop after the first 2 steps, we would have taken 5 steps in the forward direction in total. Therefore, if we add the displacement vectors for 2 steps and 3 steps, we should get a total of 5 steps in the forward direction. Graphically, this can be seen by first following the first vector two steps forward and then following the second one three steps forward (i.e. in the same direction):



We add the second vector at the end of the first vector, since this is where we now are after the first vector has acted. The vector from the tail of the first vector (the starting point) to the head of the last (the end point) is then the sum of the vectors. This is the *head-to-tail* method of vector addition.

As you can convince yourself, the order in which you add vectors does not matter. In the example above, if you decided to first go 3 steps forward and then another 2 steps forward, the end result would still be 5 steps forward.

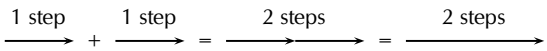
The final answer when adding vectors is called the *resultant*. The resultant displacement in this case will be 5 steps forward.

> *DEFINITION: Resultant of Vectors*
>
> The resultant of a number of vectors is the single vector whose effect is the same as the individual vectors acting together.

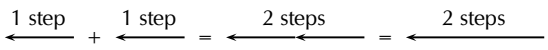
In other words, the individual vectors can be replaced by the resultant – the overall effect is the same. If vectors $\vec{a}$ and $\vec{b}$ have a resultant $\vec{R}$, this can be represented mathematically as,

$$\vec{R} \quad = \quad \vec{a} + \vec{b}.$$

Let us consider some more examples of vector addition using displacements. The arrows tell you how far to move and in what direction. Arrows to the right correspond to steps forward, while arrows to the left correspond to steps backward. Look at all of the examples below and check them.

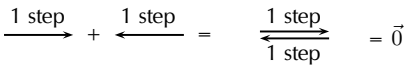


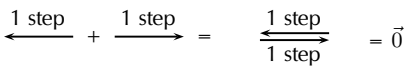
This example says 1 step forward and then another step forward is the same as an arrow twice as long – two steps forward.



This examples says 1 step backward and then another step backward is the same as an arrow twice as long – two steps backward.

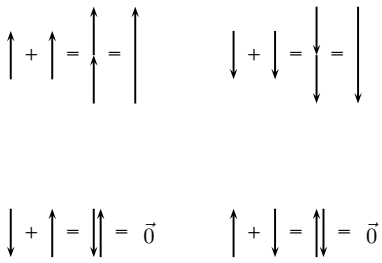
It is sometimes possible that you end up back where you started. In this case the net result of what you have done is that you have gone nowhere (your start and end points are at the same place). In this case, your resultant displacement is a vector with length zero units. We use the symbol $\vec{0}$ to denote such a vector:



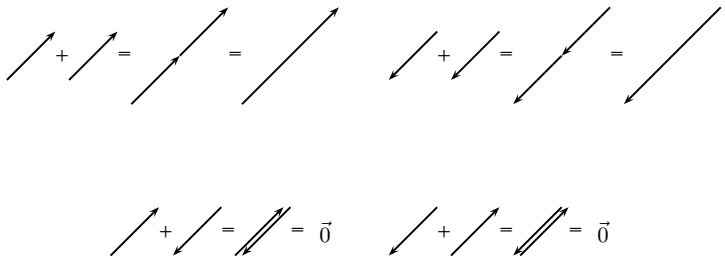


Check the following examples in the same way. Arrows up the page can be seen as steps left and arrows down the page as steps right.

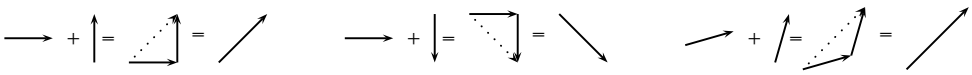
Try a couple to convince yourself!



It is important to realise that the directions are not special– 'forward and backwards' or 'left and right' are treated in the same way. The same is true of any set of parallel directions:



In the above examples the separate displacements were parallel to one another. However the same head-to-tail technique of vector addition can be applied to vectors in any direction.



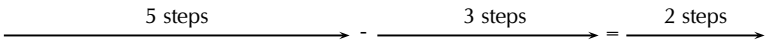
Now you have discovered one use for vectors; describing resultant displacement – how far and in what direction you have travelled after a series of movements.

Although vector addition here has been demonstrated with displacements, all vectors behave in exactly the same way. Thus, if given a number of forces acting on a body you can use the same method to determine the resultant force acting on the body. We will return to vector addition in more detail later.

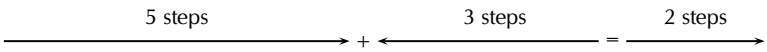
Subtracting Vectors

ESBEH

What does it mean to subtract a vector? Well this is really simple; if we have 5 apples and we subtract 3 apples, we have only 2 apples left. Now lets work in steps; if we take 5 steps forward and then subtract 3 steps forward we are left with only two steps forward:



What have we done? You originally took 5 steps forward but then you took 3 steps back. That backward displacement would be represented by an arrow pointing to the left (backwards) with length 3. The net result of adding these two vectors is 2 steps forward:

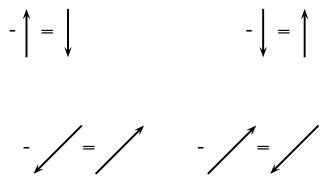


Tip

Subtracting a vector from another is the same as adding a vector in the opposite direction.

Thus, subtracting a vector from another is the same as adding a vector in the opposite direction (i.e. subtracting 3 steps forwards is the same as adding 3 steps backwards).

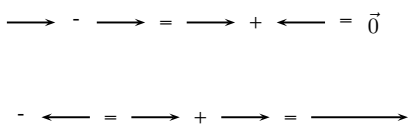
In the problem, motion in the forward direction has been represented by an arrow to the right. Arrows to the right are positive and arrows to the left are negative. More generally, vectors in opposite directions differ in sign (i.e. if we define up as positive, then vectors acting down are negative). Thus, changing the sign of a vector simply reverses its direction:



In mathematical form, subtracting $\vec{a}$ from $\vec{b}$ gives a new vector $\vec{c}$:

$$\begin{aligned}\vec{c} &= \vec{b} - \vec{a} \\ &= \vec{b} + (-\vec{a})\end{aligned}$$

This clearly shows that subtracting vector $\vec{a}$ from $\vec{b}$ is the same as adding $(-\vec{a})$ to $\vec{b}$. Look at the following examples of vector subtraction.

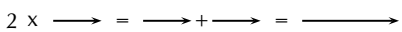


Scalar Multiplication

ESBEI

What happens when you multiply a vector by a scalar (an ordinary number)?

Going back to normal multiplication we know that 2×2 is just 2 groups of 2 added together to give 4. We can adopt a similar approach to understand how vector multiplication works.



11.7 Techniques of Vector Addition

ESBEJ

Now that you have learned about the mathematical properties of vectors, we return to vector addition in more detail. There are a number of techniques of vector addition. These techniques fall into two main categories - graphical and algebraic techniques.

Graphical Techniques

ESBEK

Graphical techniques involve drawing accurate scale diagrams to denote individual vectors and their resultants. We next discuss the two primary graphical techniques, the head-to-tail technique and the parallelogram method.

The Head-to-Tail Method

In describing the mathematical properties of vectors we used displacements and the head-to-tail graphical method of vector addition as an illustration. The head-to-tail method of graphically adding vectors is a standard method that must be understood.

Method: Head-to-Tail Method of Vector Addition

1. Draw a rough sketch of the situation.
2. Choose a scale and include a reference direction.
3. Choose any of the vectors and draw it as an arrow in the correct direction and of the correct length – remember to put an arrowhead on the end to denote its direction.
4. Take the next vector and draw it as an arrow starting from the arrowhead of the first vector in the correct direction and of the correct length.
5. Continue until you have drawn each vector – each time starting from the head of the previous vector. In this way, the vectors to be added are drawn one after the other head-to-tail.
6. The resultant is then the vector drawn from the tail of the first vector to the head of the last. Its magnitude can be determined from the length of its arrow using the scale. Its direction too can be determined from the scale diagram.

Example 2: *Head-to-Tail Addition I*

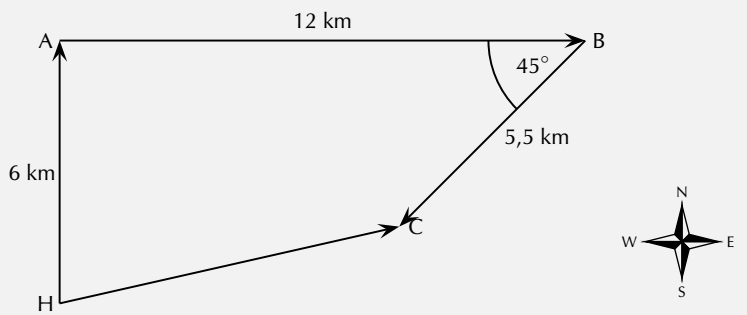
QUESTION

A ship leaves harbour H and sails 6 km north to port A. From here the ship travels 12 km east to port B, before sailing 5,5 km south-west to port C. Determine the ship's resultant displacement using the head-to-tail technique of vector addition.

SOLUTION

Step 1 : ***Draw a rough sketch of the situation***

Its easy to understand the problem if we first draw a quick sketch. The rough sketch should include all of the information given in the problem. All of the magnitudes of the displacements are shown and a compass has been included as a reference direction. In a rough sketch one is interested in the approximate shape of the vector diagram.



Step 2 : ***Choose a scale and include a reference direction.***

The choice of scale depends on the actual question – you should choose a scale such that your vector diagram fits the page.

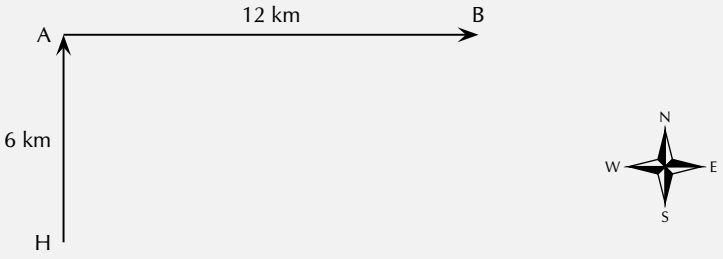
It is clear from the rough sketch that choosing a scale where 1 cm represents 2 km (scale: 1 cm = 2 km) would be a good choice in this problem. The diagram will then take up a good fraction of an A4 page. We now start the accurate construction.

Step 3 : ***Choose any of the vectors to be summed and draw it as an arrow in the correct direction and of the correct length – remember to put an arrowhead on the end to denote its direction.***

Starting at the harbour H we draw the first vector 3 cm long in the direction north.

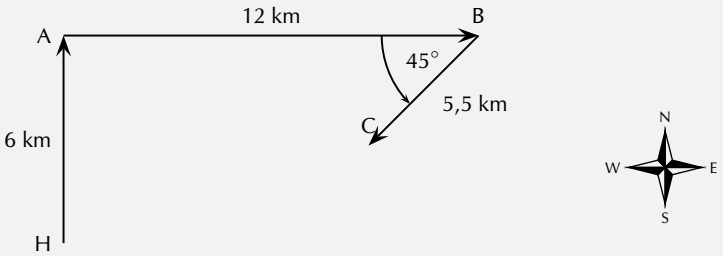
Step 4 : ***Take the next vector and draw it as an arrow starting from the head of the first vector in the correct direction and of the correct length.***

Since the ship is now at port A we draw the second vector 6 cm long starting from point A in the direction east.



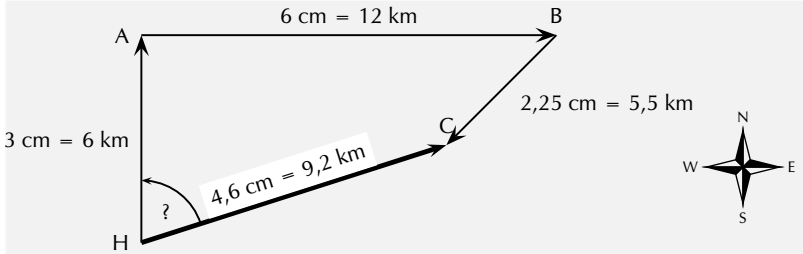
Step 5 : ***Take the next vector and draw it as an arrow starting from the head of the second vector in the correct direction and of the correct length.***

Since the ship is now at port B we draw the third vector 2,25 cm long starting from this point in the direction south-west. A protractor is required to measure the angle of 45°.



Step 6 : ***The resultant is then the vector drawn from the tail of the first vector to the head of the last. Its magnitude can be determined from the length of its arrow using the scale. Its direction too can be determined from the scale diagram.***

As a final step we draw the resultant displacement from the starting point (the harbour H) to the end point (port C). We use a ruler to measure the length of this arrow and a protractor to determine its direction.



Step 7 : ***Apply the scale conversion***
We now use the scale to convert the length of the resultant in the scale diagram to the actual displacement in the problem. Since we have chosen a scale of 1 cm = 2 km in this problem the resultant has a magnitude of 9,2 km. The direction can be specified in terms of the angle measured either as 072,3° east of north or on a bearing of 072,3°.

Step 8 : ***Quote the final answer***
The resultant displacement of the ship is 9,2 km on a bearing of 072,3°.

Example 3: *Head-to-Tail Graphical Addition II*

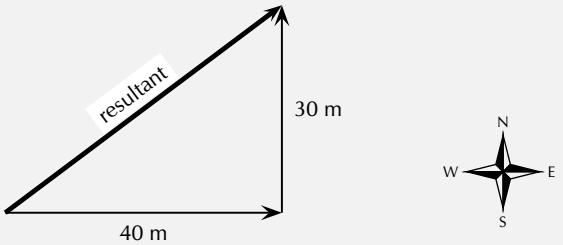
QUESTION

A man walks 40 m East, then 30 m North.

1. *What was the total distance he walked?*
2. *What is his resultant displacement?*

SOLUTION

Step 1 : ***Draw a rough sketch***



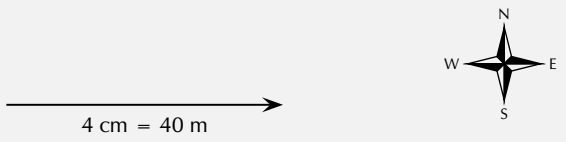
Step 2 : ***Determine the distance that the man travelled***
In the first part of his journey he travelled 40 m and in the second part he travelled 30 m. This gives us a total distance travelled of 40 m + 30 m = 70 m.

Step 3 : ***Determine his resultant displacement***

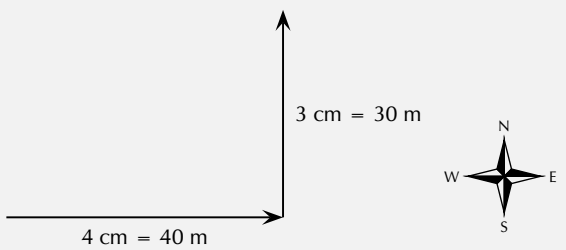
The man's resultant displacement is the **vector** from where he started to where he ended. It is the vector sum of his two separate displacements. We will use the head-to-tail method of accurate construction to find this vector.

Step 4 : ***Choose a suitable scale***
A scale of 1 cm represents 10 m (1 cm = 10 m) is a good choice here. Now we can begin the process of construction.

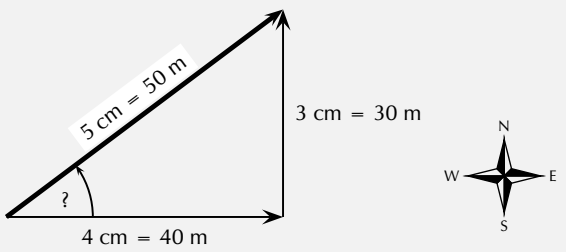
Step 5 : ***Draw the first vector to scale***
We draw the first displacement as an arrow 4 cm long in an eastwards direction.



Step 6 : ***Draw the second vector to scale***
Starting from the head of the first vector we draw the second vector as an arrow 3 cm long in a northerly direction.



Step 7 : ***Determine the resultant vector***
Now we connect the starting point to the end point and measure the length and direction of this arrow (the resultant).



Step 8 : ***Find the direction***
To find the direction you measure the angle between the resultant and the 40 m vector. You should get about 37°.

Step 9 : ***Apply the scale conversion***
Finally we use the scale to convert the length of the resultant in the scale diagram to the actual magnitude of the resultant displacement. According to the chosen scale 1 cm = 10 m. Therefore 5 cm represents 50 m. The resultant displacement is then 50 m 37° north of east.

The Parallelogram Method

The *parallelogram method* is another graphical technique of finding the resultant of two vectors.

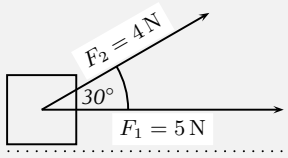
Method: The Parallelogram Method

1. Make a rough sketch of the vector diagram.
2. Choose a scale and a reference direction.
3. Choose either of the vectors to be added and draw it as an arrow of the correct length in the correct direction.
4. Draw the second vector as an arrow of the correct length in the correct direction from the tail of the first vector.
5. Complete the parallelogram formed by these two vectors.
6. The resultant is then the diagonal of the parallelogram. The magnitude can be determined from the length of its arrow using the scale. The direction too can be determined from the scale diagram.

Example 4: *Parallelogram Method of Vector Addition I*

QUESTION

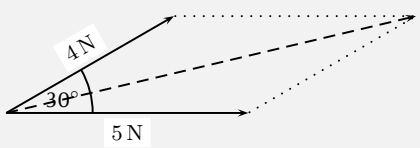
A force of $F_1 = 5\,\mathrm{N}$ is applied to a block in a horizontal direction. A second force $F_2 = 4\,\mathrm{N}$ is applied to the object at an angle of 30° above the horizontal.



Determine the resultant force acting on the block using the parallelogram method of accurate construction.

SOLUTION

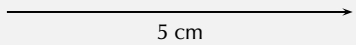
Step 1 : ***Firstly make a rough sketch of the vector diagram***



Step 2 : ***Choose a suitable scale***
In this problem a scale of 1 cm = 1 N would be appropriate, since then the vector diagram would take up a reasonable fraction of the page. We can now begin the accurate scale diagram.

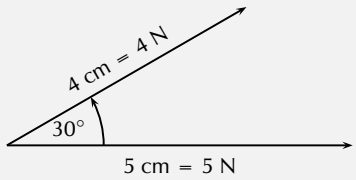
Step 3 : ***Draw the first scaled vector***

Let us draw F_1 first. According to the scale it has length 5 cm.



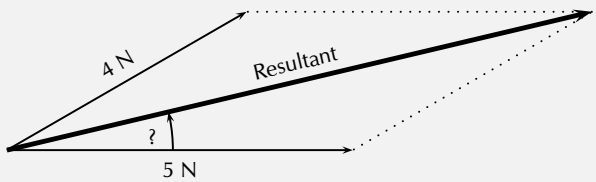
Step 4 : ***Draw the second scaled vector***

Next we draw F_2. According to the scale it has length 4 cm. We make use of a protractor to draw this vector at 30° to the horizontal.



Step 5 : ***Determine the resultant vector***

Next we complete the parallelogram and draw the diagonal.



The resultant has a measured length of 8,7 cm.

Step 6 : ***Find the direction***

We use a protractor to measure the angle between the horizontal and the resultant. We get 13,3°.

Step 7 : ***Apply the scale conversion***

Finally we use the scale to convert the measured length into the actual magnitude. Since 1 cm = 1 N, 8,7 cm represents 8,7 N. Therefore the resultant force is 8,7 N at 13,3° above the horizontal.

The parallelogram method is restricted to the addition of just two vectors. However, it is arguably the most intuitive way of adding two forces acting on a point.

Algebraic Addition and Subtraction of Vectors

ESBEL

Vectors in a Straight Line

Whenever you are faced with adding vectors acting in a straight line (i.e. some directed left and some right, or some acting up and others down) you can use a very simple algebraic technique:

Method: Addition/Subtraction of Vectors in a Straight Line

1. Choose a positive direction. As an example, for situations involving displacements in the directions west and east, you might choose west as your positive direction. In that case, displacements east are negative.
2. Next simply add (or subtract) the magnitude of the vectors using the appropriate signs.
3. As a final step the direction of the resultant should be included in words (positive answers are in the positive direction, while negative resultants are in the negative direction).

Let us consider a few examples.

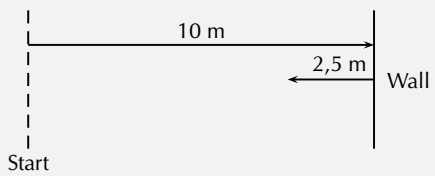
Example 5: *Adding vectors algebraically I*

QUESTION

A tennis ball is rolled towards a wall which is 10 m away from the ball. If after striking the wall the ball rolls a further 2,5 m along the ground away from the wall, calculate algebraically the ball's resultant displacement.

SOLUTION

Step 1 : ***Draw a rough sketch of the situation***



Step 2 : ***Decide which method to use to calculate the resultant***
We know that the resultant displacement of the ball ($\vec{x}_R$) is equal to the sum of the ball's separate displacements ($\vec{x}_1$ and $\vec{x}_2$):

$$\vec{x}_R = \vec{x}_1 + \vec{x}_2$$

Since the motion of the ball is in a straight line (i.e. the ball moves towards and away from the wall), we can use the method of algebraic addition just explained.

Step 3 : ***Choose a positive direction***
Let's choose the **positive** direction to be towards the wall. This means that the **negative** direction is away from the wall.

Step 4 : ***Now define our vectors algebraically***
With right positive:

$$\vec{x}_1 = +10{,}0\,\mathrm{m}$$
$$\vec{x}_2 = -2{,}5\,\mathrm{m}$$

Step 5 : ***Add the vectors***

Next we simply add the two displacements to give the resultant:

$$\begin{aligned}\vec{x}_R &= (+10\,\mathrm{m}) + (-2{,}5\,\mathrm{m}) \\ &= (+7{,}5)\,\mathrm{m}\end{aligned}$$

Step 6 : ***Quote the resultant***

Finally, in this case towards the wall is the positive direction, so: $\vec{x}_R$ = 7,5 m towards the wall.

Example 6: *Subtracting vectors algebraically I*

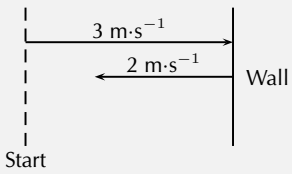
QUESTION

Suppose that a tennis ball is thrown horizontally towards a wall at an initial velocity of 3 m·s^{-1}to the right. After striking the wall, the ball returns to the thrower at 2 m·s^{-1}. Determine the change in velocity of the ball.

SOLUTION

Step 1 : ***Draw a sketch***

A quick sketch will help us understand the problem.



Step 2 : ***Decide which method to use to calculate the resultant***

Remember that velocity is a vector. The change in the velocity of the ball is equal to the difference between the ball's initial and final velocities:

$$\Delta\vec{v} = \vec{v}_f - \vec{v}_i$$

Since the ball moves along a straight line (i.e. left and right), we can use the algebraic technique of vector subtraction just discussed.

Step 3 : ***Choose a positive direction***

Choose the **positive** direction to be towards the wall. This means that the **negative** direction is away from the wall.

Step 4 : ***Now define our vectors algebraically***

$$\begin{aligned}\vec{v}_i &= +3\,\mathrm{m}\cdot\mathrm{s}^{-1} \\ \vec{v}_f &= -2\,\mathrm{m}\cdot\mathrm{s}^{-1}\end{aligned}$$

Step 5 : ***Subtract the vectors***

Thus, the change in velocity of the ball is:

$$\begin{aligned}\Delta\vec{v} &= (-2\,\mathrm{m}\cdot\mathrm{s}^{-1}) - (+3\,\mathrm{m}\cdot\mathrm{s}^{-1}) \\ &= (-5)\,\mathrm{m}\cdot\mathrm{s}^{-1}\end{aligned}$$

Step 6 : ***Quote the resultant***

Remember that in this case towards the wall means a positive velocity, so away from the wall means a negative velocity: $\Delta\vec{v} = 5\,\mathrm{m}\cdot\mathrm{s}^{-1}$ away from the wall.

Exercise 11 - 3

1. Harold walks to school by walking 600 m Northeast and then 500 m N 40° W. Determine his resultant displacement by using accurate scale drawings.
2. A dove flies from her nest, looking for food for her chick. She flies at a velocity of 2 m·s^{-1}on a bearing of 135° and then at a velocity of 1,2 m·s^{-1}on a bearing of 230°. Calculate her resultant velocity by using accurate scale drawings.
3. A squash ball is dropped to the floor with an initial velocity of 2,5 m·s^{-1}. It rebounds (comes back up) with a velocity of 0,5 m·s^{-1}.
   (a) What is the change in velocity of the squash ball?
   (b) What is the resultant velocity of the squash ball?

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(1.) 00n6 (2.) 00n7 (3.) 01vv

Remember that the technique of addition and subtraction just discussed can only be applied to vectors acting along a straight line. When vectors are not in a straight line, i.e. at an angle to each other, the following method can be used:

A More General Algebraic technique

Simple geometric and trigonometric techniques can be used to find resultant vectors.

Example 7: *An Algebraic Solution I*

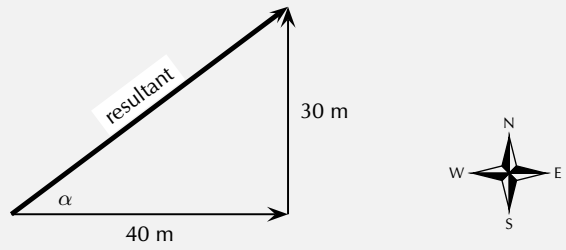
QUESTION

A man walks 40 m East, then 30 m North. Calculate the man's resultant displacement.

SOLUTION

Step 1 : ***Draw a rough sketch***

As before, the rough sketch looks as follows:



Step 2 : ***Determine the length of the resultant***

Note that the triangle formed by his separate displacement vectors and his resultant displacement vector is a right-angle triangle. We can thus use the Theorem of Pythagoras to determine the length of the resultant. Let x_R represent the length of the resultant vector. Then:

$$\begin{aligned} x_R^2 &= (40\,\mathrm{m})^2 + (30\,\mathrm{m})^2 \\ x_R^2 &= 2\,500\,\mathrm{m}^2 \\ x_R &= 50\,\mathrm{m} \end{aligned}$$

Step 3 : ***Determine the direction of the resultant***

Now we have the length of the resultant displacement vector but not yet its direction. To determine its direction we calculate the angle α between the resultant displacement vector and East, by using simple trigonometry:

$$\begin{aligned} \tan\alpha &= \frac{\mathrm{oppositeside}}{\mathrm{adjacentside}} \\ \tan\alpha &= \frac{30}{40} \\ \alpha &= \tan^{-1}(0{,}75) \\ \alpha &= 36{,}9^\circ \end{aligned}$$

Step 4 : ***Quote the resultant***

The resultant displacement is then 50 m at 36,9° North of East.

This is exactly the same answer we arrived at after drawing a scale diagram!

In the previous example we were able to use simple trigonometry to calculate the resultant displacement. This was possible since the directions of motion were perpendicular (north and east). Algebraic techniques, however, are not limited to cases where the vectors to be combined are along the same straight line or at right angles to one another. The following example illustrates this.

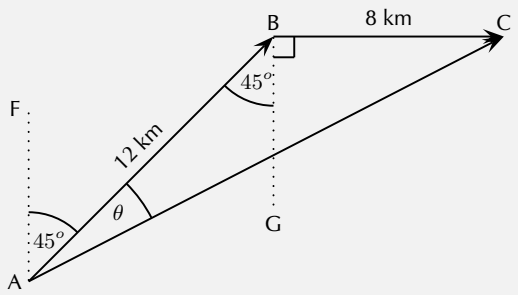
Example 8: *An Algebraic Solution II*

QUESTION

A man walks from point A to point B which is 12 km away on a bearing of 45°. From point B the man walks a further 8 km east to point C. Calculate the resultant displacement.

SOLUTION

Step 1 : ***Draw a rough sketch of the situation***



$B\hat{A}F = 45°$ since the man walks initially on a bearing of 45°. Then, $A\hat{B}G = B\hat{A}F = 45°$ (parallel lines, alternate angles). Both of these angles are included in the rough sketch.

Step 2 : ***Calculate the length of the resultant***
The resultant is the vector AC. Since we know both the lengths of AB and BC and the included angle $A\hat{B}C$, we can use the cosine rule:

$$\begin{aligned} AC^2 &= AB^2 + BC^2 - 2 \cdot AB \cdot BC \cos(A\hat{B}C) \\ &= (12)^2 + (8)^2 - 2 \cdot (12)(8) \cos(135°) \\ &= 343{,}8 \\ AC &= 18{,}5 \text{ km} \end{aligned}$$

Step 3 : ***Determine the direction of the resultant***
Next we use the sine rule to determine the angle θ:

$$\begin{aligned} \frac{\sin\theta}{8} &= \frac{\sin 135°}{18{,}5} \\ \sin\theta &= \frac{8 \times \sin 135°}{18{,}5} \\ \theta &= \sin^{-1}(0{,}3058) \\ \theta &= 17{,}8° \end{aligned}$$

To find $F\hat{A}C$, we add 45°. Thus, $F\hat{A}C = 62{,}8°$.

Step 4 : ***Quote the resultant***
The resultant displacement is therefore 18,5 km on a bearing of 062,8°.

Exercise 11 - 4

1. A frog is trying to cross a river. It swims at 3 m·s^{-1}in a northerly direction towards the opposite bank. The water is flowing in a westerly direction at 5 m·s^{-1}. Find the frog's resultant velocity by using appropriate calculations. Include a rough sketch of the situation in your answer.
2. Sandra walks to the shop by walking 500 m Northwest and then 400 m N 30° E. Determine her resultant displacement by doing appropriate calculations.

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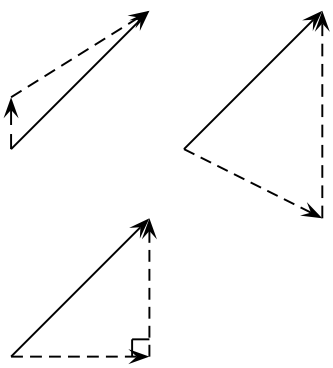
(1.) 00n8 (2.) 00n9

11.8 Components of Vectors

ESBEM

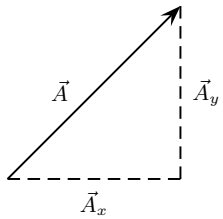
In the discussion of vector addition we saw that a number of vectors acting together can be combined to give a single vector (the resultant). In much the same way a single vector can be broken down into a number of vectors which when added give that original vector. These vectors which sum to the original are called **components** of the original vector. The process of breaking a vector into its components is called **resolving into components**.

While summing a given set of vectors gives just one answer (the resultant), a single vector can be resolved into infinitely many sets of components. In the diagrams below the same black vector is resolved into different pairs of components. These components are shown as dashed lines. When added together the dashed vectors give the original black vector (i.e. the original vector is the resultant of its components).



In practise it is most useful to resolve a vector into components which are at right angles to one another, usually horizontal and vertical.

Any vector can be resolved into a horizontal and a vertical component. If $\vec{A}$ is a vector, then the horizontal component of $\vec{A}$ is $\vec{A}_x$ and the vertical component is $\vec{A}_y$.



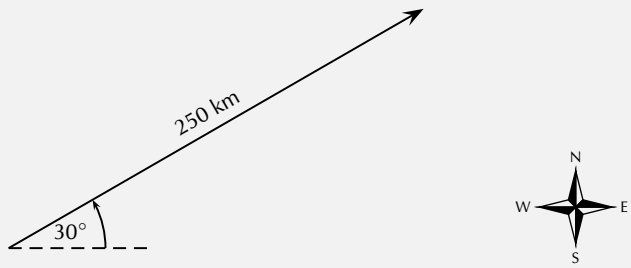
Example 9: *Resolving a vector into components*

QUESTION

A motorist undergoes a displacement of 250 km in a direction 30° north of east. Resolve this displacement into components in the directions north ($\vec{x}_N$) and east ($\vec{x}_E$).

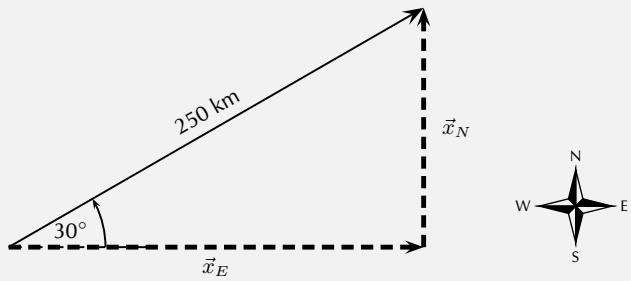
SOLUTION

Step 1 : ***Draw a rough sketch of the original vector***



Step 2 : ***Determine the vector component***

Next we resolve the displacement into its components north and east. Since these directions are perpendicular to one another, the components form a right-angled triangle with the original displacement as its hypotenuse.



Notice how the two components acting together give the original vector as their resultant.

Step 3 : ***Determine the lengths of the component vectors***
Now we can use trigonometry to calculate the magnitudes of the components of the original displacement:

$$\begin{aligned} x_N &= (250)(\sin 30^\circ) \\ &= 125 \text{ km} \end{aligned}$$

and

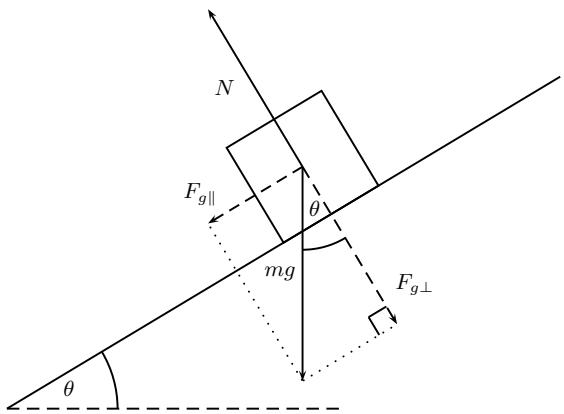
$$\begin{aligned} x_E &= (250)(\cos 30^\circ) \\ &= 216{,}5 \text{ km} \end{aligned}$$

Remember x_N and x_E are the magnitudes of the components – they are in the directions north and east respectively.

Extension:	*Block on an incline*

As a further example of components let us consider a block of mass m placed on a frictionless surface inclined at some angle θ to the horizontal. The block will obviously slide down the incline, but what causes this motion?

The forces acting on the block are its weight mg and the normal force N exerted by the surface on the object. These two forces are shown in the diagram below.



Now the object's weight can be resolved into components parallel and perpendicular to the inclined surface. These components are shown as dashed arrows in the diagram above and are at right angles to each other. The components have been drawn acting from the same point. Applying the parallelogram method, the two components of the block's weight sum to the weight vector.

To find the components in terms of the weight we can use trigonometry:

$$\begin{aligned} F_{g\parallel} &= mg\sin\theta \\ F_{g\perp} &= mg\cos\theta \end{aligned}$$

The component of the weight perpendicular to the slope $F_{g\perp}$ exactly balances the normal force N exerted by the surface. The parallel component, however, $F_{g\parallel}$ is unbalanced and causes the block to slide down the slope.

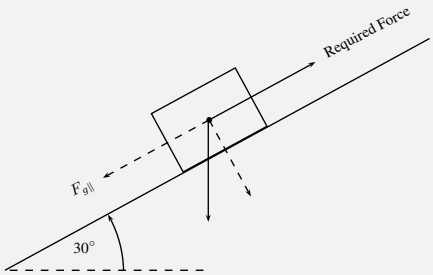
Example 10: *Block on an incline plane*

QUESTION

Determine the force needed to keep a 10 kg block from sliding down a frictionless slope. The slope makes an angle of 30° with the horizontal.

SOLUTION

Step 1 : ***Draw a diagram of the situation***



The force that will keep the block from sliding is equal to the parallel component of the weight, but its direction is up the slope.

Step 2 : ***Calculate*** $F_{g\|}$

$$\begin{aligned} F_{g\|} &= mg\sin\theta \\ &= (10)(9{,}8)(\sin 30^\circ) \\ &= 49\text{N} \end{aligned}$$

Step 3 : ***Write final answer***
The force is 49 N up the slope.

Vector addition using components

ESBEN

Components can also be used to find the resultant of vectors. This technique can be applied to both graphical and algebraic methods of finding the resultant. The method is simple: make a rough sketch of the problem, find the horizontal and vertical components of each vector, find the sum of all horizontal components and the sum of all the vertical components and then use them to find the resultant.

Consider the two vectors, $\vec{A}$ and $\vec{B}$, in Figure 11.3, together with their resultant, $\vec{R}$.

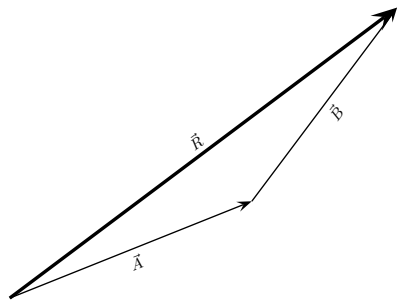


Figure 11.3: An example of two vectors being added to give a resultant

Each vector in Figure 11.3 can be broken down into one component in the x-direction (horizontal) and one in the y-direction (vertical). These components are two vectors which when added give you the original vector as the resultant. This is shown in Figure 11.4 where we can see that:

$$\begin{aligned} \vec{A} &= \vec{A}_x + \vec{A}_y \\ \vec{B} &= \vec{B}_x + \vec{B}_y \\ \vec{R} &= \vec{R}_x + \vec{R}_y \end{aligned} \qquad \begin{aligned} \text{But,} \quad \vec{R}_x &= \vec{A}_x + \vec{B}_x \\ \text{and} \quad \vec{R}_y &= \vec{A}_y + \vec{B}_y \end{aligned}$$

In summary, addition of the x components of the two original vectors gives the x component of the resultant. The same applies to the y components. So if we just added all the components together we would get the same answer! This is another important property of vectors.

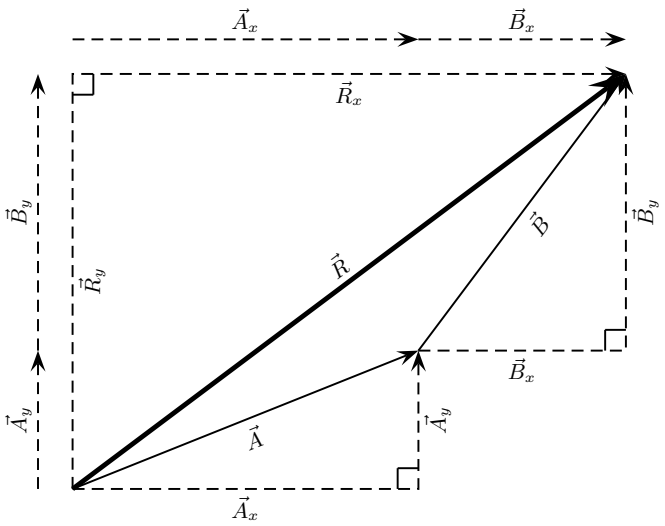


Figure 11.4: Adding vectors using components.

Example 11: *Adding Vectors Using Components*

QUESTION

If in Figure 11.4, $\vec{A} = 5{,}385\,\mathrm{m}$ at an angle of 21.8° to the horizontal and $\vec{B} = 5\,\mathrm{m}$ at an angle of 53,13° to the horizontal, find $\vec{R}$.

SOLUTION

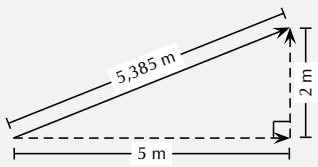
Step 1 : ***Decide how to tackle the problem***
The first thing we must realise is that the order that we add the vectors does not matter. Therefore, we can work through the vectors to be added in any order.

Step 2 : ***Resolve $\vec{A}$ into components***
We find the components of $\vec{A}$ by using known trigonometric ratios. First we find the magnitude of the vertical component, A_y:

$$\begin{aligned}
\sin\theta &= \frac{A_y}{A} \\
\sin 21{,}8^\circ &= \frac{A_y}{5{,}385} \\
A_y &= (5{,}385)(\sin 21{,}8^\circ) \\
&= 2\,\mathrm{m}
\end{aligned}$$

Secondly we find the magnitude of the horizontal component, A_x:

$$\begin{aligned}
\cos\theta &= \frac{A_x}{A} \\
\cos 21.8^\circ &= \frac{A_x}{5{,}385} \\
A_x &= (5{,}385)(\cos 21{,}8^\circ) \\
&= 5\,\mathrm{m}
\end{aligned}$$



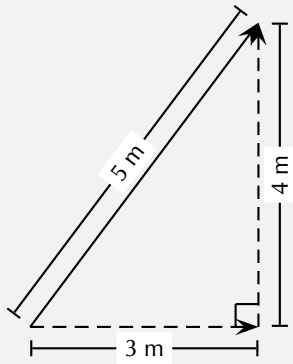
The components give the sides of the right angle triangle, for which the original vector, $\vec{A}$, is the hypotenuse.

Step 3 : ***Resolve $\vec{B}$ into components***
We find the components of $\vec{B}$ by using known trigonometric ratios. First we find the magnitude of the vertical component, B_y:

$$\begin{aligned}
\sin\theta &= \frac{B_y}{B} \\
\sin 53{,}13^\circ &= \frac{B_y}{5} \\
B_y &= (5)(\sin 53{,}13^\circ) \\
&= 4\,\mathrm{m}
\end{aligned}$$

Secondly we find the magnitude of the horizontal component, B_x:

$$\begin{aligned}
\cos\theta &= \frac{B_x}{B} \\
\cos 21{,}8^\circ &= \frac{B_x}{5{,}385} \\
B_x &= (5{,}385)(\cos 53{,}13^\circ) \\
&= 5\,\mathrm{m}
\end{aligned}$$



Step 4 : ***Determine the components of the resultant vector***

Now we have all the components. If we add all the horizontal components then we will have the x-component of the resultant vector, $\vec{R}_x$. Similarly, we add all the vertical components then we will have the y-component of the resultant vector, $\vec{R}_y$.

$$\begin{aligned}
R_x &= A_x + B_x \\
&= 5\,\mathrm{m} + 3\,\mathrm{m} \\
&= 8\,\mathrm{m}
\end{aligned}$$

Therefore, $\vec{R}_x$ is 8 m to the right.

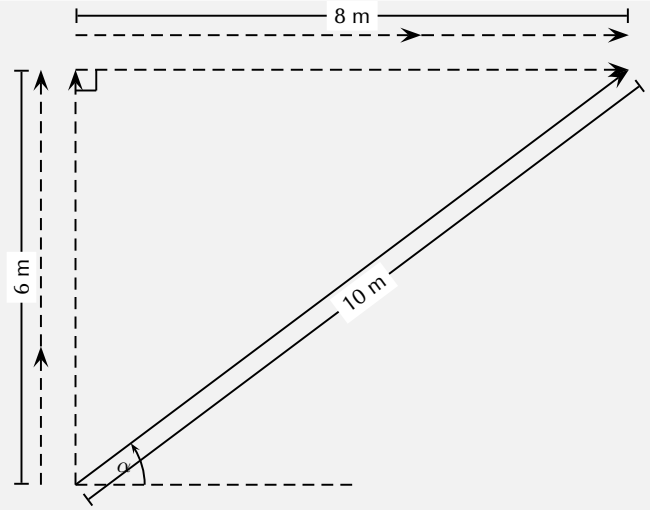
$$\begin{aligned}
R_y &= A_y + B_y \\
&= 2\,\mathrm{m} + 4\,\mathrm{m} \\
&= 6\,\mathrm{m}
\end{aligned}$$

Therefore, $\vec{R}_y$ is 6 m up.

Step 5 : ***Determine the magnitude and direction of the resultant vector***

Now that we have the components of the resultant, we can use the Theorem of Pythagoras to determine the magnitude of the resultant, R.

$$\begin{aligned}
R^2 &= (R_x)^2 + (R_y)^2 \\
R^2 &= (6)^2 + (8)^2 \\
R^2 &= 100 \\
\therefore R &= 10\,\mathrm{m}
\end{aligned}$$



The magnitude of the resultant, R is 10 m. So all we have to do is calculate its direction. We can specify the direction as the angle the vectors makes with a known direction. To do this you only need to visualise the vector as starting at the origin of a coordinate system. We have drawn this explicitly below and the angle we will calculate is labelled α.

Using our known trigonometric ratios we can calculate the value of α;

$$\begin{aligned} \tan\alpha &= \frac{6\,\text{m}}{8\,\text{m}} \\ \alpha &= \tan^{-1}\frac{6\,\text{m}}{8\,\text{m}} \\ \alpha &= 36{,}8^o. \end{aligned}$$

Step 6 : ***Quote the final answer***

$\vec{R}$ is 10 m at an angle of $36{,}8°$ to the positive x-axis.

Exercise 11 - 5

1. Harold walks to school by walking 600 m Northeast and then 500 m N 40° W. Determine his resultant displacement by means of addition of components of vectors.
2. A dove flies from her nest, looking for food for her chick. She flies at a velocity of 2 m·s^{-1}on a bearing of 135° in a wind with a velocity of 1,2 m·s^{-1}on a bearing of 230°. Calculate her resultant velocity by adding the horizontal and vertical components of vectors.

More practice video solutions or help at www.everythingscience.co.za

(1.) 00na (2.) 00nb

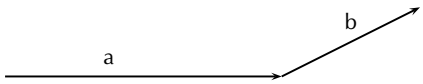
Extension:	*Vector Multiplication*

Vectors are special, they are more than just numbers. This means that multiplying vectors is not necessarily the same as just multiplying their magnitudes. There are two different types of multiplication defined for vectors. You can find the dot product of two vectors or the cross product.

The *dot* product is most similar to regular multiplication between scalars. To take the dot product of two vectors, you just multiply their magnitudes to get out a scalar answer. The mathematical definition of the dot product is:

$$\vec{a} \bullet \vec{b} = |\vec{a}| \cdot |\vec{b}| \cos\theta$$

Take two vectors $\vec{a}$ and $\vec{b}$:



You can draw in the component of $\vec{b}$ that is parallel to $\vec{a}$:

In this way we can arrive at the definition of the dot product. You find how much of $\vec{b}$ is lined up with $\vec{a}$ by finding the component of $\vec{b}$ parallel to $\vec{a}$. Then multiply the magnitude of that component, $|\vec{b}| \cos\theta$, with the magnitude of $\vec{a}$ to get a scalar.

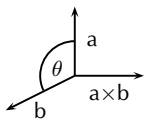
The second type of multiplication, the cross product, is more subtle and uses the directions of the vectors in a more complicated way. The cross product of two vectors, $\vec{a}$ and $\vec{b}$, is written $\vec{a} \times \vec{b}$ and the result of this operation on $\vec{a}$ and $\vec{b}$ is another vector. The magnitude of the cross product of these two vectors is:

$$|\vec{a} \times \vec{b}| = |\vec{a}||\vec{b}| \sin\theta$$

We still need to find the direction of $\vec{a} \times \vec{b}$. We do this by applying the *right hand rule*.

Method: Right Hand Rule

1. Using your right hand:
2. Point your index finger in the direction of $\vec{a}$.
3. Point the middle finger in the direction of $\vec{b}$.
4. Your thumb will show the direction of $\vec{a} \times \vec{b}$.



Chapter 11 — Summary

See the summary presentation (▶ Presentation: VPkfq at www.everythingscience.co.za)

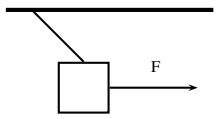
1. A scalar is a physical quantity with magnitude only.
2. A vector is a physical quantity with magnitude and direction.
3. Vectors may be represented as arrows where the length of the arrow indicates the magnitude and the arrowhead indicates the direction of the vector.
4. The direction of a vector can be indicated by referring to another vector or a fixed point (e.g. 30° from the river bank); using a compass (e.g. N 30° W); or bearing (e.g. 053°).

5. Vectors can be added using the head-to-tail method, the parallelogram method or the component method.

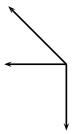
6. The resultant of a number of vectors is the single vector whose effect is the same as the individual vectors acting together.

Chapter 11 End of Chapter Exercises

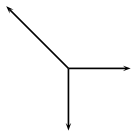
1. An object is suspended by means of a light string. The sketch shows a horizontal force F which pulls the object from the vertical position until it reaches an equilibrium position as shown. Which one of the following vector diagrams best represents all the forces acting on the object?



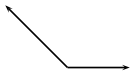
(a.)



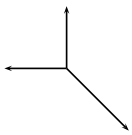
(b.)



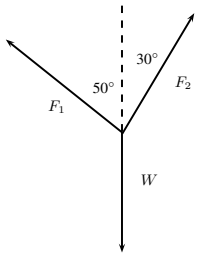
(c.)



(d.)



2. A load of weight W is suspended from two strings. F_1 and F_2 are the forces exerted by the strings on the load in the directions show in the figure above. Which one of the following equations is valid for this situation?



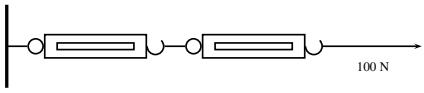
   (a) $W = F_1^2 + F_2^2$

   (b) $F_1 \sin 50° = F_2 \sin 30°$

   (c) $F_1 \cos 50° = F_2 \cos 30°$

   (d) $W = F_1 + F_2$

3. Two spring balances P and Q are connected by means of a piece of string to a wall as shown. A horizontal force of 100 N is exerted on spring balance Q. What will be the readings on spring balances P and Q?



	P	Q
(a.)	100 N	0 N
(b.)	25 N	75 N
(c.)	50 N	50 N
(d.)	100 N	100 N

4. A point is acted on by two forces in equilibrium. The forces

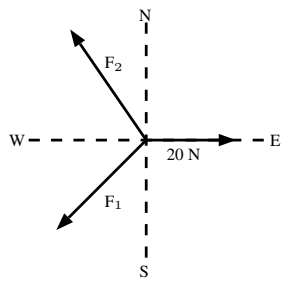
   (a) have equal magnitudes and directions.

   (b) have equal magnitudes but opposite directions.

   (c) act perpendicular to each other.

   (d) act in the same direction.

5. A point in equilibrium is acted on by three forces. Force F_1 has components 15 N due south and 13 N due west. What are the components of force F_2?



   (a) 13 N due north and 20 due west
   (b) 13 N due north and 13 N due west
   (c) 15 N due north and 7 N due west
   (d) 15 N due north and 13 N due east

6. Which of the following contains two vectors and a scalar?
   (a) distance, acceleration, speed
   (b) displacement, velocity, acceleration
   (c) distance, mass, speed
   (d) displacement, speed, velocity

7. Two vectors act on the same point. What should the angle between them be so that a maximum resultant is obtained?

   (a) 0° (b) 90° (c) 180° (d) cannot tell

8. Two forces, 4 N and 11 N, act on a point. Which one of the following cannot be the magnitude of a resultant?

   (a) 4 N (b) 7 N (c) 11 N (d) 15 N

9. A helicopter flies due east with an air speed of 150 km.h^{-1}. It flies through an air current which moves at 200 km.h^{-1} north. Given this information, answer the following questions:
   (a) In which direction does the helicopter fly?
   (b) What is the ground speed of the helicopter?
   (c) Calculate the ground distance covered in 40 minutes by the helicopter.

10. A plane must fly 70 km due north. A cross wind is blowing to the west at 30 km.h^{-1}. In which direction must the pilot steer if the plane flies at a speed of 200 km.h^{-1} in windless conditions?

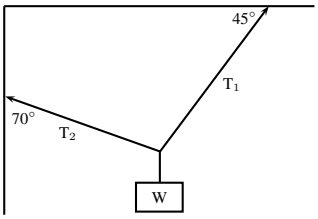
11. A stream that is 280 m wide flows along its banks with a velocity of 1.80m.s^{-1}. A raft can travel at a speed of 2.50 m.s^{-1} across the stream. Answer the following questions:
   (a) What is the shortest time in which the raft can cross the stream?
   (b) How far does the raft drift downstream in that time?
   (c) In what direction must the raft be steered against the current so that it crosses the stream perpendicular to its banks?
   (d) How long does it take to cross the stream in part c?

12. A helicopter is flying from place X to place Y. Y is 1000 km away in a direction $50°$ east of north and the pilot wishes to reach it in two hours. There is a wind of speed 150 km.h^{-1} blowing from the northwest. Find, by accurate construction and measurement (with a scale of $1\ \mathrm{cm} = 50\ \mathrm{km.h^{-1}}$), the
   (a) the direction in which the helicopter must fly, and
   (b) the magnitude of the velocity required for it to reach its destination on time.

13. An aeroplane is flying towards a destination 300 km due south from its present position. There is a wind blowing from the north east at 120 km.h^{-1}. The aeroplane needs to reach its destination in 30 minutes. Find, by accurate construction and measurement (with a scale of $1\ \mathrm{cm} = 30\ \mathrm{km.s^{-1}}$), or otherwise, the
   (a) the direction in which the aeroplane must fly and
   (b) the speed which the aeroplane must maintain in order to reach the destination on time.

(c) Confirm your answers in the previous 2 subquestions with calculations.

14. An object of weight W is supported by two cables attached to the ceiling and wall as shown. The tensions in the two cables are T_1 and T_2 respectively. Tension $T_1 = 1200$ N. Determine the tension T_2 and weight W of the object by accurate construction and measurement or by calculation.



15. In a map-work exercise, hikers are required to walk from a tree marked A on the map to another tree marked B which lies 2,0 km due East of A. The hikers then walk in a straight line to a waterfall in position C which has components measured from B of 1,0 km E and 4,0 km N.

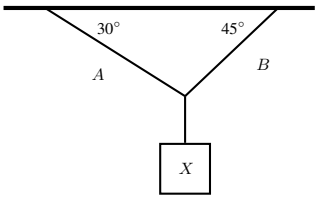
    (a) Distinguish between quantities that are described as being *vector* and *scalar*.

    (b) Draw a labelled displacement-vector diagram (not necessarily to scale) of the hikers' complete journey.

    (c) What is the total distance walked by the hikers from their starting point at A to the waterfall C?

    (d) What are the magnitude and bearing, to the nearest degree, of the displacement of the hikers from their starting point to the waterfall?

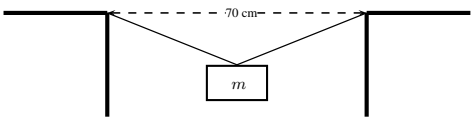
16. An object X is supported by two strings, A and B, attached to the ceiling as shown in the sketch. Each of these strings can withstand a maximum force of 700 N. The weight of X is increased gradually.



    (a) Draw a rough sketch of the triangle of forces, and use it to explain which string will break first.

    (b) Determine the maximum weight of X which can be supported.

17. A rope is tied at two points which are 70 cm apart from each other, on the same horizontal line. The total length of rope is 1 m, and the maximum tension it can withstand in any part is 1000 N. Find the largest mass (m), in kg, that can be carried at the midpoint of the rope, without breaking the rope. Include a vector diagram in your answer.



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(1.) 00nc	(2.) 00nd	(3.) 00ne	(4.) 00nf	(5.) 00ng	(6.) 00nh
(7.) 00ni	(8.) 00nj	(9.) 00nk	(10.) 00nm	(11.) 00nn	(12.) 00np
(13.) 00nq	(14.) 00nr	(15.) 00ns	(16.) 00nt	(17.) 00nu	

Force, Momentum and Impulse

12

12.1 Introduction

ESBEO

In Grade 10 we studied motion but not what caused the motion. In this chapter we will learn that a net force is needed to cause motion. We recall what a force is and learn about how force and motion are related. We are introduced to two new concepts, momentum and impulse, and we learn more about turning forces and the force of gravity.

See introductory video: VPkgi at www.everythingscience.co.za

12.2 Force

Examples of Forces in Physics

ESBER

Most of Physics revolves around the study of forces. Although there are many different forces, all are handled in the same way. All forces in Physics can be put into one of four groups. These are gravitational forces, electromagnetic forces, strong nuclear forces and weak nuclear forces. You will mostly come across gravitational or electromagnetic forces at school.

Gravitational Forces

Gravity is the attractive force between two objects due to the mass of the objects. When you throw a ball in the air, its mass and the Earth's mass attract each other, which leads to a force between them. The ball falls back towards the Earth, and the Earth accelerates towards the ball. The movement of the Earth towards the ball is, however, so small that you couldn't possibly measure it.

Electromagnetic Forces

Almost all of the forces that we experience in everyday life are electromagnetic in origin. They have this unusual name because long ago people thought that electric forces and magnetic forces were different things. After much work and experimentation, it has been realised that they are actually different manifestations of the same underlying theory.

Electric or Electrostatic Forces

If we have objects carrying electrical charge, which are not moving, then we are dealing with electrostatic forces (Coulomb's Law). This force is actually much stronger than gravity. This may seem strange, since gravity is obviously very powerful, and holding a balloon to the wall seems to be the most impressive thing electrostatic forces have done, but if we think about it: for gravity to be detectable, we need to have a very large mass nearby. But a balloon rubbed against someone's hair can stick to a wall with a force so strong that it overcomes the force of gravity between the entire Earth and the balloon—with just the charges in the balloon and the wall!

Magnetic Forces

The magnetic force is a different manifestation of the electromagnetic force. It stems from the interaction between *moving charges* as opposed to the *fixed* charges involved in Coulomb's Law. Examples of the magnetic force in action include magnets, compasses, car engines and computer data storage. Magnets are also used in the wrecking industry to pick up cars and move them around sites.

Friction

According to Newton's First Law (we will discuss this later in the chapter) an object moving *without a force acting on it* will keep on moving. Then why does a box sliding on a table come to a stop? The answer is friction. Friction arises where two surfaces are in contact and moving relative to each other as a result of the interaction between the molecules of the two contact surfaces—for instance the interactions between the molecules on the bottom of the box with molecules on the top of the table. This interaction is electromagnetic in origin, hence friction is just another view of the electromagnetic force. Later in this chapter we will discuss frictional forces a little more.

Drag Forces

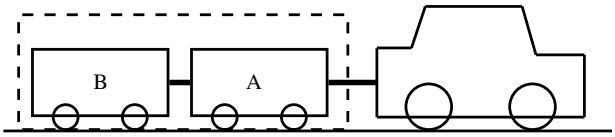
This is the force an object experiences while travelling through a medium like an aeroplane flying through air. When something travels through the air it needs to displace air as it travels and because of this, the air exerts a force on the object. This becomes an important force when you move fast and a lot of thought is taken to try and reduce the amount of drag force a sports car or an aeroplane experiences.

The drag force is very useful for parachutists. They jump from high altitudes and if there was no drag force, then they would continue accelerating all the way to the ground. Parachutes are wide because the more surface area you have, the greater the drag force and hence the slower you hit the ground.

Systems and External Forces

ESBES

The concepts of systems and forces external to such systems are very important in Physics. A system is any collection of objects. If one draws an imaginary box around such a system then an external force is one that is applied by an object or person outside the box. Imagine for example a car pulling two trailers.



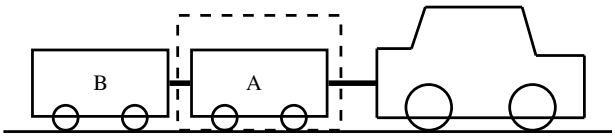
If we draw a box around the two trailers they can be considered a closed system or unit. When we look at the forces on this closed system the following forces will apply (we assume drag forces are absent):

- The force of the car pulling the unit (trailer A and B)
- The force of friction between the wheels of the trailers and the road (opposite to the direction of motion)
- The force of the Earth pulling downwards on the system (gravity)
- The force of the road pushing upwards on the system

These forces are called external forces to the system.
The following forces will not apply:

- The force of A pulling B
- The force of B pulling A
- The force of friction between the wheels of the car and the road (opposite to the direction of motion)

We can also draw a box around trailer A or B, in which case the forces will be different.



If we consider trailer A as a system, the following external forces will apply:

- The force of the car pulling on A (towards the right)
- The force of B pulling on A (towards the left)
- The force of the Earth pulling downwards on the trailer (gravity)
- The force of the road p

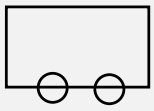
Example 1: *Force diagrams*

QUESTION

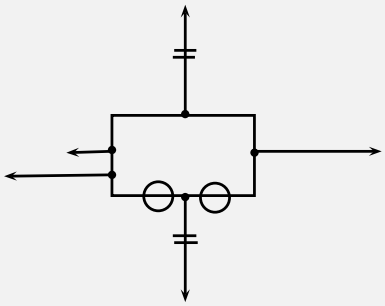
Draw a labelled force diagram to indicate all the forces acting on trailer A in the example above.

SOLUTION

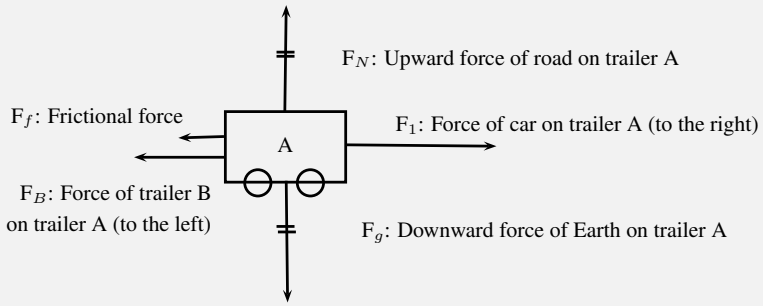
Step 1 : ***Draw a large diagram of the picture from your question***



Step 2 : ***Add all the forces***



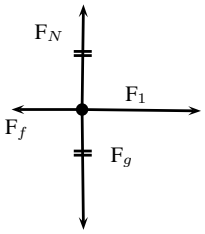
Step 3 : ***Add the labels***



Free Body Diagrams

ESBEU

In a free-body diagram, the object of interest is drawn as a dot and all the forces acting on it are drawn as arrows pointing away from the dot. A free body diagram for the two-trailer-system will therefore look like this:



F_1: Force of car on trailers (to the right)
F_f: Frictional force on trailers (to the left)
F_g: Downward force of Earth on trailers
F_N: Upward force of road on trailers

Example 2: *Free body diagram*

QUESTION

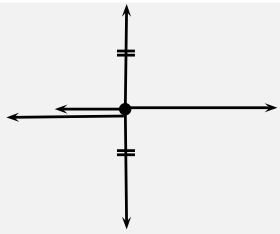
Draw a free body diagram of all the forces acting on trailer A in the example above.

SOLUTION

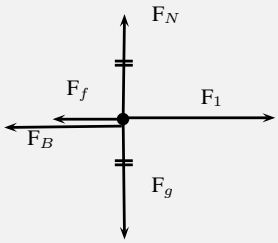
Step 1 : ***Draw a dot to indicate the object***

•

Step 2 : ***Draw arrows to indicate all the forces acting on the object***



Step 3 : ***Label the forces***



F_1: Force of car on trailer A (to the right)
F_B: Force of trailer B on trailer A (to the left)
F_f: Frictional force on trailer A (to the left)
F_g: Downward force of Earth on trailer A
F_N: Upward force of road on trailer A

Finding the Resultant Force

ESBEV

The easiest way to determine a resultant force is to draw a free body diagram. Remember from Chapter 11 that we use the length of the arrow to indicate the vector's magnitude and the direction of the arrow to show which direction it acts in.

After we have done this, we have a diagram of vectors and we simply find the sum of the vectors to get the resultant force.

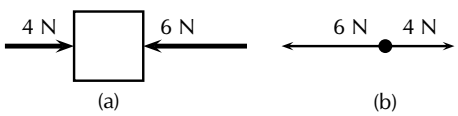


Figure 12.1: (a) Force diagram of 2 forces acting on a box. (b) Free body diagram of the box.

For example, two people push on a box from opposite sides with forces of 4 N and 6 N respectively as shown in Figure 12.1(a). The free body diagram in Figure 12.1(b) shows the object represented by a dot and the two forces are represented by arrows with their tails on the dot.

As you can see, the arrows point in opposite directions and have different lengths. The resultant force is 2 N to the left. This result can be obtained algebraically too, since the two forces act along the same line. First, as in motion in one direction, choose a frame of reference. Secondly, add the two vectors taking their directions into account.

For the example, assume that the positive direction is to the right, then:

$$\begin{aligned} F_R &= (+4\,\mathrm{N}) + (-6\,\mathrm{N}) \\ &= -2\,\mathrm{N} \\ &= 2\,\mathrm{N} \text{ to the left} \end{aligned}$$

Remember that a negative answer means that the force acts in the *opposite* direction to the one that you chose to be positive. You can *choose* the positive direction to be any way you want, but once you have chosen it you *must* keep it.

As you work with more force diagrams in which the forces exactly balance, you may notice that you get a zero answer (e.g. 0 N). This simply means that the forces are balanced and that the object will not accelerate.

Once a force diagram has been drawn the techniques of vector addition introduced in Chapter 11 can be used. Depending on the situation you might choose to use a graphical technique such as the tail-to-head method or the parallelogram method, or else an algebraic approach to determine the resultant. Since force is a vector quantity all of these methods apply.

Example 3: *Finding the resultant force*

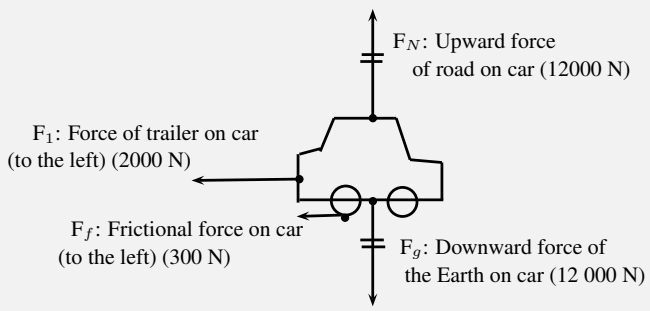
QUESTION

A car (mass 1200 kg) applies a force of 2000 N on a trailer (mass 250 kg). A constant frictional force of 200 N is acting on the trailer, and a constant frictional force of 300 N is acting on the car.

1. *Draw a force diagram of all the forces acting on the car.*
2. *Draw a free body diagram of all the horizontal forces acting on the trailer.*
3. *Use the force diagram to determine the resultant force on the trailer.*

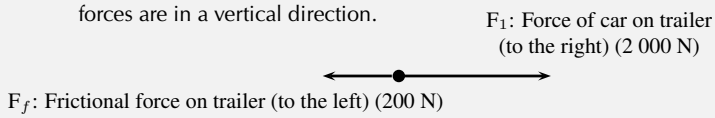
SOLUTION

Step 1 : ***Draw the force diagram for the car.***
The question asks us to draw all the forces on the car. This means that we must include horizontal and vertical forces.



Step 2 : ***Draw the free body diagram for the trailer.***

The question only asks for horizontal forces. We will therefore not include the force of the Earth on the trailer, or the force of the road on the trailer as these forces are in a vertical direction.



Step 3 : ***Determine the resultant force on the trailer.***

To find the resultant force we need to add all the horizontal forces together. We do not add vertical forces as the movement of the car and trailer will be in a horizontal direction, and not up or down. F_R = 2000 + (-200) = 1800 N to the right.

See simulation: VPkgj at www.everythingscience.co.za)

Exercise 12 - 1

1. A force acts on an object. Name three effects that the force can have on the object.
2. Identify each of the following forces as contact or non-contact forces.
   (a) The force between the north pole of a magnet and a paper clip.
   (b) The force required to open the door of a taxi.
   (c) The force required to stop a soccer ball.
   (d) The force causing a ball, dropped from a height of 2 m, to fall to the floor.
3. A book of mass 2 kg is lying on a table. Draw a labelled force diagram indicating all the forces on the book.
4. A boy pushes a shopping trolley (mass 15 kg) with a constant force of 75 N. A constant frictional force of 20 N is present.
   (a) Draw a labelled force diagram to identify all the forces acting on the shopping trolley.
   (b) Draw a free body diagram of all the horizontal forces acting on the trolley.
   (c) Determine the resultant force on the trolley.
5. A donkey (mass 250 kg) is trying to pull a cart (mass 80 kg) with a force of 400 N. The rope between the donkey and the cart makes an angle of 30° with the cart. The cart does not move.
   (a) Draw a free body diagram of all the forces acting on the donkey.
   (b) Draw a force diagram of all the forces acting on the cart.
   (c) Find the magnitude and direction of the frictional force preventing the cart from moving.

More practice video solutions or help at www.everythingscience.co.za

(1.) 01vw (2.) 01vx (3.) 01vy (4.) 01vz (5.) 01w0

12.3 Newton's Laws

ESBEW

In grade 10 you learned about motion, but did not look at how things start to move. You have also learned about forces. In this section we will look at the effect of forces on objects and how we can make things move.

Newton's First Law

ESBEX

Sir Isaac Newton was a scientist who lived in England (1642-1727) who was interested in the motion of objects under various conditions. He suggested that a stationary object will remain stationary unless a force acts on it and that a moving object will continue moving unless a force slows it down, speeds it up or changes its direction of motion. From this he formulated what is known as Newton's First Law of Motion:

> *DEFINITION: Newton's First Law of Motion*
>
> An object will remain in a state of rest or continue travelling at constant velocity, unless acted upon by an unbalanced (net) force.

Let us consider the following situations:

An ice skater pushes herself away from the side of the ice rink and skates across the ice. She will continue to move in a straight line across the ice unless something stops her. Objects are also like that. If we kick a soccer ball across a soccer field, according to Newton's First Law, the soccer ball should keep on moving forever! However, in real life this does not happen. Is Newton's Law wrong? Not really. Newton's First Law applies to situations where there aren't any external forces present. This means that friction is not present. In the case of the ice skater, the friction between the skates and the ice is very little and she will continue moving for quite a distance. In the case of the soccer ball, air resistance (friction between the air and the ball) and friction between the grass and the ball is present and this will slow the ball down.

See video: VPkhy at www.everythingscience.co.za

Newton's First Law in action

We experience Newton's First Law in every day life. Let us look at the following examples:

Rockets:

A spaceship is launched into space. The force of the exploding gases pushes the rocket through the air into space. Once it is in space, the engines are switched off and it will keep on moving at a constant velocity. If the astronauts want to change the direction of the spaceship they need to fire an engine. This will then apply a force on the rocket and it will change its direction.

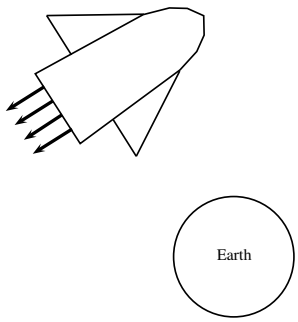
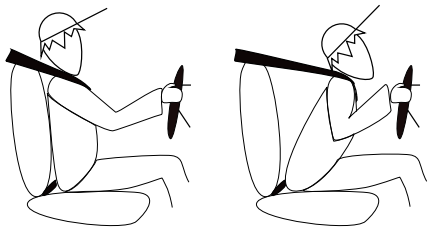


Figure 12.2: Newton's First Law and rockets

Seat belts:

We wear seat belts in cars. This is to protect us when the car is involved in an accident. If a car is travelling at 120 km·hr^{-1}, the passengers in the car is also travelling at 120 km·hr^{-1}. When the car suddenly stops a force is exerted on the car (making it slow down), but not on the passengers. The passengers will carry on moving forward at 120 km·hr^{-1}according to Newton I. If they are wearing seat belts, the seat belts will stop them by exerting a force on them and so prevent them from getting hurt.



Example 4: *Newton's First Law in action*

QUESTION

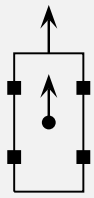
Why do passengers get thrown to the side when the car they are driving in goes around a corner?

SOLUTION

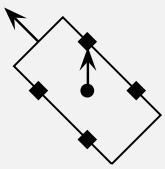
Step 1 : ***What happens before the car turns***
Before the car starts turning both the passengers and the car are travelling at the same velocity. (picture A)

Step 2 : ***What happens while the car turns***
The driver turns the wheels of the car, which then exert a force on the car and the car turns. This force acts on the car but not the passengers, hence (by Newton's First Law) the passengers continue moving with the same original velocity. (picture B)

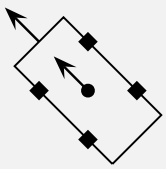
Step 3 : ***Why passengers get thrown to the side?***
If the passengers are wearing seat belts they will exert a force on the passengers until the passengers' velocity is the same as that of the car (picture C). Without a seat belt the passenger may hit the side of the car.



A: Both the car and the person travelling at the same velocity



B: The cars turns but not the person



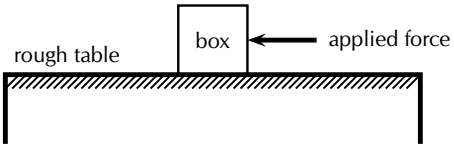
C: Both the car and the person are travelling at the same velocity again

Newton's Second Law of Motion

ESBEY

According to Newton I, things 'like to keep on doing what they are doing'. In other words, if an object is moving, it tends to continue moving (in a straight line and at the same speed) and if an object is stationary, it tends to remain stationary. So how do objects start moving?

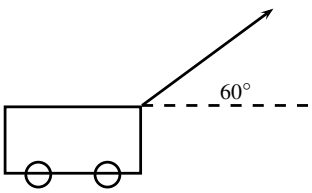
Let us look at the example of a 10 kg box on a rough table. If we push lightly on the box as indicated in the diagram, the box won't move. Let's say we applied a force of 100 N, yet the box remains stationary. At this point a frictional force of 100 N is acting on the box, preventing the box from moving. If we increase the force, let's say to 150 N and the box almost starts to move, the frictional force is 150 N. To be able to move the box, we need to push hard enough to overcome the friction and then move the box. If we therefore apply a force of 200 N remembering that a frictional force of 150 N is present, the 'first' 150 N will be used to overcome or 'cancel' the friction and the other 50 N will be used to move (accelerate) the block. In order to accelerate an object we must have a resultant force acting on the block.



Now, what do you think will happen if we pushed harder, lets say 300 N? Or, what do you think will happen if the mass of the block was more, say 20 kg, or what if it was less? Let us investigate how the motion of an object is affected by mass and force.

Activity:	*Newton's Second Law of Motion*

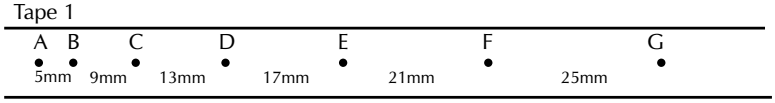
Aim:
To investigate the relation between the acceleration of objects and the application of a constant resultant force.
Method:



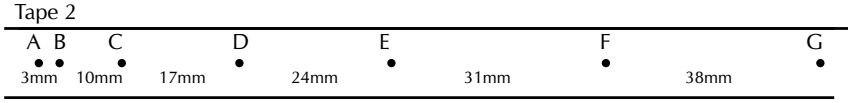
1. A constant force of 20 N, acting at an angle of 60° to the horizontal, is applied to a dynamics trolley.
2. Ticker tape attached to the trolley runs through a ticker timer of frequency 20 Hz as the trolley is moving on the frictionless surface.
3. The above procedure is repeated 4 times, each time using the same force, but varying the mass of the trolley as follows:
   - Case 1: 6,25 kg
   - Case 2: 3,57 kg
   - Case 3: 2,27 kg
   - Case 4: 1,67 kg

4. Shown below are sections of the four ticker tapes obtained. The tapes are marked with the letters A, B, C, D, etc. A is the first dot, B is the second dot and so on. The distance between each dot is also shown.

Tape 1

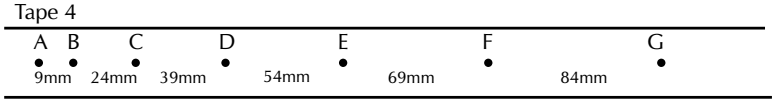


Tape 2



Tape 3

Tape 4



Tapes are not drawn to scale.

Instructions:

1. Use each tape to calculate the instantaneous velocity (in m·s^{-1}) of the trolley at points B and F (remember to convert the distances to m first!). Use these velocities to calculate the trolley's acceleration in each case.
2. Tabulate the mass and corresponding acceleration values as calculated in each case. Ensure that each column and row in your table is appropriately labelled.
3. Draw a graph of acceleration vs. mass, using a scale of 1 cm = 1 m·s^{-2}on the y-axis and 1 cm = 1 kg on the x-axis.
4. Use your graph to read off the acceleration of the trolley if its mass is 5 kg.
5. Write down a conclusion for the experiment.

You will have noted in the investigation above that the heavier the trolley is, the slower it moved. The acceleration is *inversely* proportional to the mass. In mathematical terms:

$$a \propto \frac{1}{m}$$

In a similar investigation where the mass is kept constant, but the applied force is varied, you will find that the bigger the force is, the faster the object will move. The acceleration of the trolley is therefore *directly* proportional to the resultant force. In mathematical terms:

$$a \propto F.$$

Rearranging the above equations, we get $a \propto \frac{F}{m}$ OR $F = ma$

Newton formulated his second law as follows:

DEFINITION: Newton's Second Law of Motion

If a resultant force acts on a body, it will cause the body to accelerate in the direction of the resultant force. The acceleration of the body will be directly proportional to the resultant force and inversely proportional to the mass of the body. The mathematical representation is:

$$F = ma.$$

See video: VPkiq at www.everythingscience.co.za

Applying Newton's Second Law

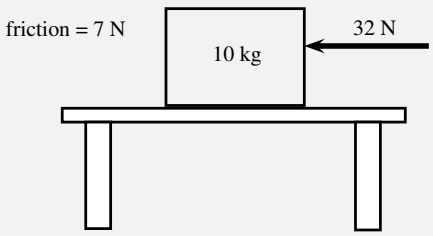
Newton's Second Law can be applied to a variety of situations. We will look at the main types of examples that you need to study.

Example 5: *Newton II - Box on a surface 1*

QUESTION

A 10 kg box is placed on a table. A horizontal force of 32 N is applied to the box. A frictional force of 7 N is present between the surface and the box.

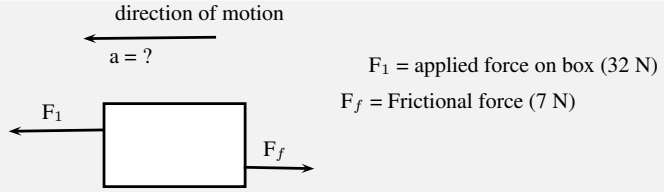
1. *Draw a force diagram indicating all the horizontal forces acting on the box.*
2. *Calculate the acceleration of the box.*



SOLUTION

Step 1 : ***Identify the horizontal forces and draw a force diagram***

We only look at the forces acting in a horizontal direction (left-right) and not vertical (up-down) forces. The applied force and the force of friction will be included. The force of gravity, which is a vertical force, will not be included.



Step 2 : ***Calculate the acceleration of the box***

We have been given:
Applied force F_1 = 32 N
Frictional force F_f = - 7 N
Mass m = 10 kg

To calculate the acceleration of the box we will be using the equation $F_R = ma$. Therefore:

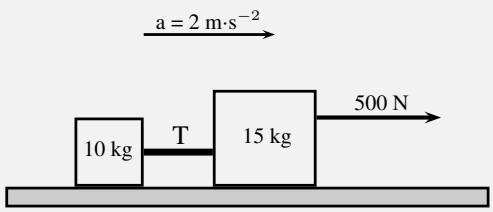
$$\begin{aligned} F_R &= ma \\ F_1 + F_f &= (10)(a) \\ 32 - 7 &= 10\,a \\ 25 &= 10\,a \\ a &= 2{,}5\,\mathrm{m}\cdot\mathrm{s}^{-1} \text{towards the left} \end{aligned}$$

Example 6: *Newton II - box on surface 2*

QUESTION

Two crates, 10 kg and 15 kg respectively, are connected with a thick rope according to the diagram. A force of 500 N is applied. The boxes move with an acceleration of 2 m·s^{-2}. One third of the total frictional force is acting on the 10 kg block and two thirds on the 15 kg block. Calculate:

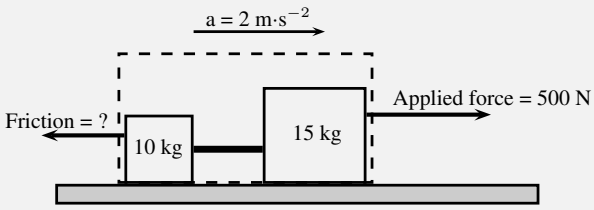
1. *the magnitude and direction of the frictional force present.*
2. *the magnitude of the tension in the rope at T.*



SOLUTION

Step 1 : ***Draw a force diagram***

Always draw a force diagram although the question might not ask for it. The acceleration of the whole system is given, therefore a force diagram of the whole system will be drawn. Because the two crates are seen as a unit, the force diagram will look like this:



Step 2 : ***Calculate the frictional force***

To find the frictional force we will apply Newton's Second Law. We are given the mass (10 + 15 kg) and the acceleration (2 m·s^{-2}). Choose the direction of motion to be the positive direction (to the right is positive).

$$\begin{aligned} F_R &= ma \\ F_{\text{applied}} + F_f &= ma \\ 500 + F_f &= (10+15)(2) \\ F_f &= 50 - 500 \\ F_f &= -450N \end{aligned}$$

The frictional force is 450 N opposite to the direction of motion (to the left).

Step 3 : ***Find the tension in the rope***

To find the tension in the rope we need to look at one of the two crates on their own. Let's choose the 10 kg crate. Firstly, we need to draw a force diagram:

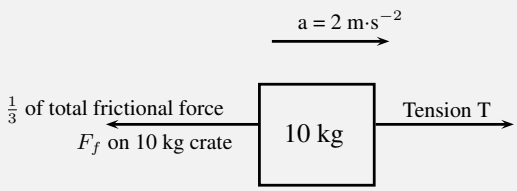


Figure 12.3: Force diagram of 10 kg crate

The frictional force on the 10 kg block is one third of the total, therefore:
$F_f = \frac{1}{3} \times 450$
$F_f = 150$ N

If we apply Newton's Second Law:

$$\begin{aligned} F_R &= ma \\ T + F_f &= (10)(2) \\ T + (-150) &= 20 \\ T &= 170 \text{ N} \end{aligned}$$

Note: If we had used the same principle and applied it to 15 kg crate, our calculations would have been the following:

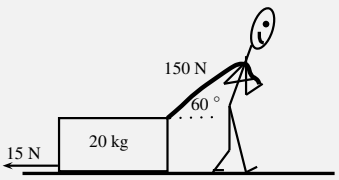
$$\begin{aligned} F_R &= ma \\ F_{\text{applied}} + T + F_f &= (15)(2) \\ 500 + T + (-300) &= 30 \\ T &= -170 \text{ N} \end{aligned}$$

The negative answer here means that the force is in the direction opposite to the motion, in other words to the left, which is correct. However, the question asks for the magnitude of the force and your answer will be quoted as 170 N.

Example 7: *Newton II - Man pulling a box*

QUESTION

A man is pulling a 20 kg box with a rope that makes an angle of 60° with the horizontal. If he applies a force of 150 N and a frictional force of 15 N is present, calculate the acceleration of the box.



SOLUTION

Step 1 : ***Draw a force diagram***

The motion is horizontal and therefore we will only consider the forces in a horizontal direction. Remember that vertical forces do not influence horizontal motion and vice versa.

SOLUTION

Step 1 : ***Draw a force diagram***

Draw a force diagram indicating all the horizontal forces on the system as a whole:

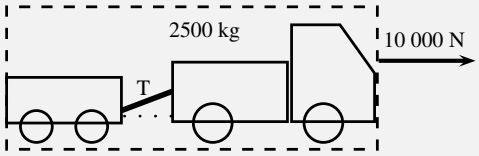


Figure 12.5: Force diagram for truck pulling a trailer

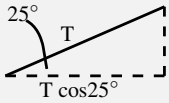
Step 2 : ***Find the acceleration of the system***

In the absence of friction, the only force that causes the system to accelerate is the thrust of the engine. If we now apply Newton's Second Law:

$$\begin{aligned} F_R &= ma \\ 10000 &= (500 + 2000)a \\ a &= 4\,\mathrm{m} \cdot \mathrm{s}^{-2} \text{ to the right} \end{aligned}$$

Step 3 : ***Find the horizontal component of T***

We are asked to find the tension in the tow bar, but because the tow bar is acting at an angle, we need to find the horizontal component first. We will find the horizontal component in terms of T and then use it in the next step to find T.



The horizontal component is T cos 25°.

Step 4 : ***Find the tension in the tow bar***

To find T, we will apply Newton's Second Law:

$$\begin{aligned} F_R &= ma \\ F - T\cos 25^\circ &= ma \\ 10000 - T\cos 25^\circ &= (2000)(4) \\ T\cos 25^\circ &= 2000 \\ T &= 2206{,}76\mathrm{N} \end{aligned}$$

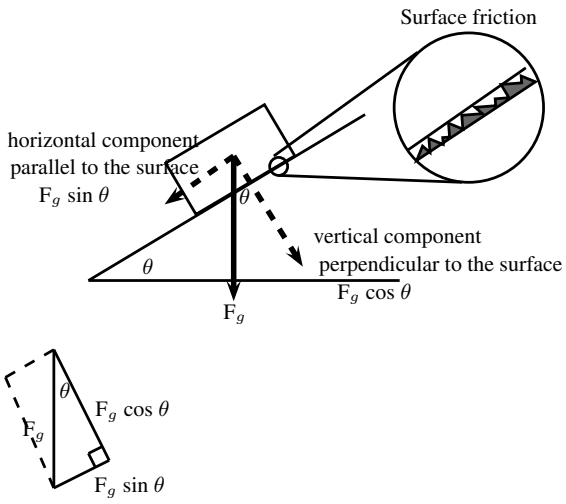
Object on an inclined plane

When we place an object on a slope the force of gravity (F_g) acts straight down and not perpendicular to the slope. Due to gravity pulling straight down, the object will tend to slide down the slope with a

force equal to the horizontal component of the force of gravity ($F_g \sin\theta$). The object will 'stick' to the slope due to the frictional force between the object and the surface. As you increase the angle of the slope, the horizontal component will also increase until the frictional force is overcome and the object starts to slide down the slope. The force of gravity will also tend to push an object 'into' the slope. The vertical component of this force is equal to the vertical component of the force of gravity ($F_g \cos\theta$). There is no movement in this direction as this force is balanced by the slope pushing up against the object. This "pushing force" is called the normal force (N) and is equal to the force required to make the component of the resultant force perpendicularly into the plane zero, $F_g \cos\theta$ in this case, but opposite in direction.

Tip

Do not use the abbreviation W for weight as it is used to abbreviate 'work'. Rather use the force of gravity F_g for weight.

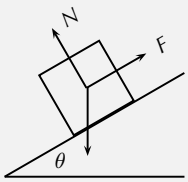


See simulation: VPkjb at www.everythingscience.co.za)

Example 9: *Newton II - Box on inclined plane*

QUESTION

A body of mass M is at rest on an inclined plane.



What is the magnitude of the frictional force acting on the body?

A Mg

B Mg cos θ

C Mg sin θ

D Mg tan θ

SOLUTION

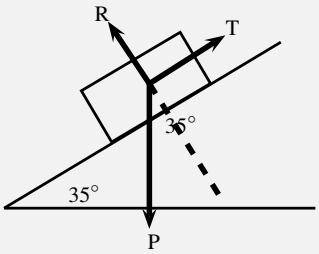
Step 1 : ***Analyse the situation***
The question asks us to identify the frictional force. The body is said to be at rest on the plane, which means that it is not moving and therefore there is no resultant force. The frictional force must therefore be balanced by the force F up the inclined plane.

Step 2 : ***Choose the correct answer***
The frictional force is equal to the component of the weight (Mg) parallel to the surface, which is equal to Mg sin θ.

Example 10: *Newton II - Object on a slope*

QUESTION

A force T = 312 N is required to keep a body at rest on a frictionless inclined plane which makes an angle of 35° with the horizontal. The forces acting on the body are shown. Calculate the magnitudes of forces P and R, giving your answers to three significant figures.



SOLUTION

Step 1 : ***Find the magnitude of P***
We are usually asked to find the magnitude of T, but in this case T is given and we are asked to find P. We can use the same equation. T is the force that balances the component of P parallel to the plane (P_x) and therefore it has the same magnitude.

$$\begin{aligned} T &= P \sin\theta \\ 312 &= P \sin 35^\circ \\ P &= 544 \text{ N} \end{aligned}$$

Step 2 : ***Find the magnitude of R***
R can also be determined with the use of trigonometric ratios. The tan or cos ratio can be used. We recommend that you use the tan ratio because it does not

involve using the value for P (for in case you made a mistake in calculating P).

$$\begin{aligned}
\tan 55^\circ &= \frac{R}{T} \\
\tan 55^\circ &= \frac{R}{312} \\
R &= \tan 55^\circ \times 312 \\
R &= 445{,}6 \text{ N} \\
R &= 446 \text{ N}
\end{aligned}$$

Note that the question asks that the answers be given to 3 significant figures. We therefore round 445,6 N up to 446 N.

Lifts and rockets

So far we have looked at objects being pulled or pushed across a surface, in other words motion parallel to the surface the object rests on. Here we only considered forces parallel to the surface, but we can also lift objects up or let them fall. This is vertical motion where only vertical forces are being considered.

Let us consider a 500 kg lift, with no passengers, hanging on a cable. The purpose of the cable is to pull the lift upwards so that it can reach the next floor or to let go a little so that it can move downwards to the floor below. We will look at five possible stages during the motion of the lift.

Stage 1:
The 500 kg lift is stationary at the second floor of a tall building.
Because the lift is stationary (not moving) there is no resultant force acting on the lift. This means that the upward forces must be balanced by the downward forces. The only force acting down is the force of gravity which is equal to (500 x 9,8 = 4900 N) in this case. The cable must therefore pull upwards with a force of 4900 N to keep the lift stationary at this point.

Stage 2:
The lift moves upwards at an acceleration of 1 m·s^{-2}.
If the lift is accelerating, it means that there is a resultant force in the direction of the motion. This means that the force acting upwards is now greater than the force of gravity F_g (down). To find the magnitude of the force applied by the cable (F_c) we can do the following calculation: (Remember to choose a direction as positive. We have chosen upwards as positive.)

$$\begin{aligned}
F_R &= ma \\
F_c + F_g &= ma \\
F_c + (-4900) &= (500)(1) \\
F_c &= 5400 \text{ N upwards}
\end{aligned}$$

The answer makes sense as we need a bigger force upwards to cancel the effect of gravity as well as make the lift go faster.

Stage 3:
The lift moves at a constant velocity.
When the lift moves at a constant velocity, it means that all the forces are balanced and that there is no resultant force. The acceleration is zero, therefore F_R = 0. The force acting upwards is equal to the force acting downwards, therefore F_c = 4900 N.

Stage 4:
The lift slows down at a rate of 2m·s^{-2}.

As the lift is now slowing down there is a resultant force downwards. This means that the force acting downwards is greater than the force acting upwards. To find the magnitude of the force applied by the cable (F_c) we can do the following calculation: Again we have chosen upwards as positive, which means that the acceleration will be a negative number.

$$\begin{aligned} F_R &= ma \\ F_c + F_g &= ma \\ F_c + (-4900) &= (500)(-2) \\ F_c &= 3900 \text{ N upwards} \end{aligned}$$

This makes sense as we need a smaller force upwards to ensure that the resultant force is downward. The force of gravity is now greater than the upward pull of the cable and the lift will slow down.

Stage 5:
The cable snaps.
When the cable snaps, the force that used to be acting upwards is no longer present. The only force that is present would be the force of gravity. The lift will freefall and its acceleration can be calculated as follows:

$$\begin{aligned} F_R &= ma \\ F_c + F_g &= ma \\ 0 + (-4900) &= (500)(a) \\ a &= -9{,}8\,\text{m} \cdot \text{s}^{-2} \\ a &= 9{,}8\,\text{m} \cdot \text{s}^{-2}\text{downwards} \end{aligned}$$

Rockets

As with lifts, rockets are also examples of objects in vertical motion. The force of gravity pulls the rocket down while the thrust of the engine pushes the rocket upwards. The force that the engine exerts must overcome the force of gravity so that the rocket can accelerate upwards. The worked example below looks at the application of Newton's Second Law in launching a rocket.

Example 11: *Newton II - rocket*

QUESTION

A rocket is launched vertically upwards into the sky at an acceleration of 20 m·s^{-2}. If the mass of the rocket is 5000 kg, calculate the magnitude and direction of the thrust of the rocket's engines.

SOLUTION

Step 1 : ***Analyse what is given and what is asked***
We have the following:
m = 5000 kg
a = 20 m·s^{-2}
F_g = 5000 x 9,8 = 49000 N
We are asked to find the thrust of the rocket engine F_1.

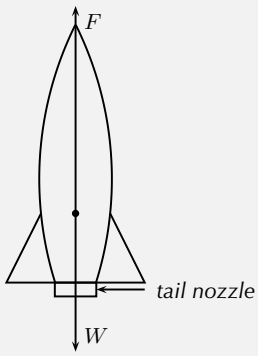
Step 2 : ***Find the thrust of the engine***
We will apply Newton's Second Law:

$$\begin{aligned} F_R &= ma \\ F_1 + F_g &= ma \\ F_1 + (-49000) &= (5000)(20) \\ F_1 &= 149\ 000 \text{ N upwards} \end{aligned}$$

Example 12: *Rockets*

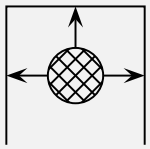
QUESTION

How do rockets accelerate in space?



SOLUTION

- Gas explodes inside the rocket.
- This exploding gas exerts a force on each side of the rocket (as shown in the picture below of the explosion chamber inside the rocket).



Note that the forces shown in this picture are representative. With an explosion there will be forces in all directions.

- Due to the symmetry of the situation, all the forces exerted on the rocket are balanced by forces on the opposite side, except for the force opposite the open side. This force on the upper surface is unbalanced.

- This is therefore the resultant force acting on the rocket and it makes the rocket accelerate forwards.

Example 13: *Newton II - lifts*

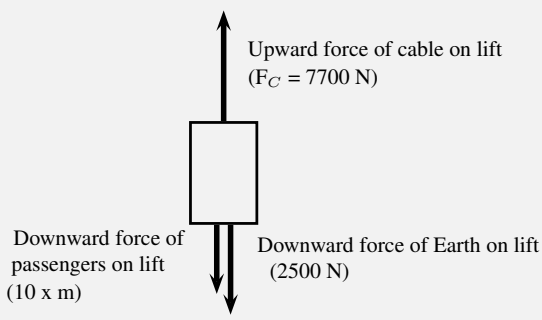
QUESTION

A lift, mass 250 kg, is initially at rest on the ground floor of a tall building. Passengers with an unknown total mass, m, climb into the lift. The lift accelerates upwards at 1,6 m·s^{-2}. The cable supporting the lift exerts a constant upward force of 7700 N. Use g = 10 m·s^{-2}.

1. *Draw a labelled force diagram indicating all the forces acting on the lift while it accelerates upwards.*
2. *What is the maximum mass, m, of the passengers the lift can carry in order to achieve a constant upward acceleration of 1,6 m·s^{-2}.*

SOLUTION

Step 1 : ***Draw a force diagram.***



Step 2 : ***Find the mass, m.***

Let us look at the lift with its passengers as a unit. The mass of this unit will be (250 + m) kg and the force of the Earth pulling downwards (F$_g$) will be (250 + m) x 10 m.s^{-2}. If we apply Newton's Second Law to the situation we get:

$$\begin{aligned} F_{net} &= ma \\ F_C - F_g &= ma \\ 7700 - (250 + m)(10) &= (250 + m)(1{,}6) \\ 7700 - 2500 - 10\,m &= 400 + 1{,}6\,m \\ 4800 &= 11{,}6\,m \\ m &= 413{,}79\,\text{kg} \end{aligned}$$

Exercise 12 - 2

1. A tug is capable of pulling a ship with a force of 100 kN. If two such tugs are pulling on one ship, they can produce any force ranging from a minimum of 0 N to a maximum of 200 kN. Give a detailed explanation of how this is possible. Use diagrams to support your result.
2. A car of mass 850 kg accelerates at 2 $m{\cdot}s^{-2}$. Calculate the magnitude of the resultant force that is causing the acceleration.
3. Find the force needed to accelerate a 3 kg object at 4 $m{\cdot}s^{-2}$.
4. Calculate the acceleration of an object of mass 1000 kg accelerated by a force of 100 N.
5. An object of mass 7 kg is accelerating at 2,5 $m{\cdot}s^{-2}$. What resultant force acts on it?
6. Find the mass of an object if a force of 40 N gives it an acceleration of 2 $m{\cdot}s^{-2}$.
7. Find the acceleration of a body of mass 1 000 kg that has a 150 N force acting on it.
8. Find the mass of an object which is accelerated at 3 $m{\cdot}s^{-2}$ by a force of 25 N.
9. Determine the acceleration of a mass of 24 kg when a force of 6 N acts on it. What is the acceleration if the force were doubled and the mass was halved?
10. A mass of 8 kg is accelerating at 5 $m{\cdot}s^{-2}$.
    (a) Determine the resultant force that is causing the acceleration.
    (b) What acceleration would be produced if we doubled the force and reduced the mass by half?
11. A motorcycle of mass 100 kg is accelerated by a resultant force of 500 N. If the motorcycle starts from rest:
    (a) What is its acceleration?
    (b) How fast will it be travelling after 20 s?
    (c) How long will it take to reach a speed of 35 $m{\cdot}s^{-1}$?
    (d) How far will it travel from its starting point in 15 s?
12. A force of 40 N acting on a trolley on a frictionless horizontal plane causes an acceleration of magnitude 6 $m{\cdot}s^{-2}$. Determine the mass of the trolley.
13. A force of 200 N, acting at 60° to the horizontal, accelerates a block of mass 50 kg along a horizontal plane as shown.

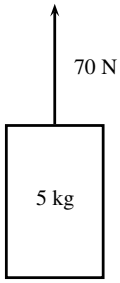
    (a) Calculate the component of the 200 N force that accelerates the block horizontally.

(b) If the acceleration of the block is 1,5 m·s^{-2}, calculate the magnitude of the frictional force on the block.

(c) Calculate the vertical force exerted by the block on the plane.

14. A toy rocket of mass 0,5 kg is supported vertically by placing it in a bottle. The rocket is then ignited. Calculate the force that is required to accelerate the rocket vertically upwards at 8 m·s^{-2}.

15. A constant force of 70 N is applied vertically to a block of mass 5 kg as shown. Calculate the acceleration of the block.



16. A student of mass 70 kg investigates the motion of a lift. While he stands in the lift on a bathroom scale (calibrated in newton), he notes three stages of his journey.

    (a) For 2 s immediately after the lift starts, the scale reads 574 N.

    (b) For a further 6 s it reads 700 N.

    (c) For the final 2 s it reads 854 N.

    Answer the following questions:

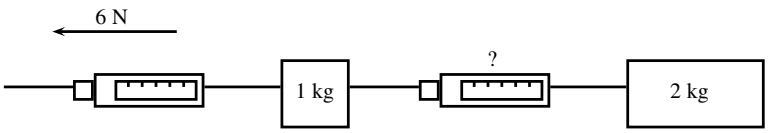
    (a) Is the motion of the lift upward or downward? Give a reason for your answer.

    (b) Write down the magnitude and the direction of the resultant force acting on the student for each of the stages I, II and III.

    (c) Calculate the magnitude of the acceleration of the lift during the first 2s.

17. A car of mass 800 kg accelerates along a level road at 4 m·s^{-2}. A frictional force of 700 N opposes its motion. What force is produced by the car's engine?

18. Two objects, with masses of 1 kg and 2 kg respectively, are placed on a smooth surface and connected with a piece of string. A horizontal force of 6 N is applied with the help of a spring balance to the 1 kg object. Ignoring friction, what will the force acting on the 2 kg mass, as measured by a second spring balance, be?



19. A rocket of mass 200 kg has a resultant force of 4000 N upwards on it.

    (a) What is its acceleration in space, where it has no weight?

    (b) What is its acceleration on the Earth, where it has weight?

    (c) What driving force does the rocket engine need to exert on the back of the rocket in space?

    (d) What driving force does the rocket engine need to exert on the back of the rocket on the Earth?

20. A car going at 20 m·s^{-1}accelerates uniformly and comes to a stop in a distance of 20 m.
    (a) What is its acceleration?
    (b) If the car is 1000 kg how much force do the brakes exert?

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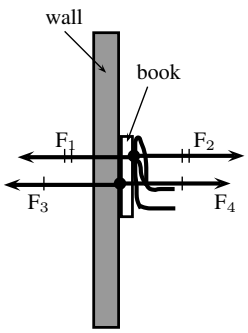
(1.) 00p4	(2.) 00p5	(3.) 00p6	(4.) 00p7	(5.) 00p8	(6.) 00p9
(7.) 00pa	(8.) 00pb	(9.) 00pc	(10.) 00pd	(11.) 00pe	(12.) 00pf
(13.) 00pg	(14.) 00ph	(15.) 00pi	(16.) 00pj	(17.) 00pk	(18.) 00pm
(19.) 00pn	(20.) 00pp	(21.) 00pq			

Newton's Third Law of Motion

ESBEZ

Newton's Third Law of Motion deals with the interaction between pairs of objects. For example, if you hold a book up against a wall you are exerting a force on the book (to keep it there) and the book is exerting a force back at you (to keep you from falling through the book). This may sound strange, but if the book was not pushing back at you, your hand would push through the book! These two forces (the force of the hand on the book (F_1) and the force of the book on the hand (F_2)) are called an action-reaction pair of forces. They have the same magnitude, but act in opposite directions and act on different objects (the one force is onto the book and the other is onto your hand).

There is another action-reaction pair of forces present in this situation. The book is pushing against the wall (action force) and the wall is pushing back at the book (reaction). The force of the book on the wall (F_3) and the force of the wall on the book (F_4) are shown in the diagram.



F_1: force of hand on book
F_2: force of book on hand
F_3: force of book on wall
F_4: force of wall on book

Figure 12.6: Newton's action-reaction pairs

> *DEFINITION: Newton's Third Law of Motion*
>
> If body A exerts a force on body B, then body B exerts a force of equal magnitude on body A, but in the opposite direction.

See video: VPkjr at www.everythingscience.co.za

Newton's action-reaction pairs can be found everywhere in life where two objects interact with one another. The following worked examples will illustrate this:

Example 14: *Newton III - seat belt*

QUESTION

Dineo is seated in the passenger seat of a car with the seat belt on. The car suddenly stops and he moves forwards until the seat belt stops him. Draw a labelled force diagram identifying two action-reaction pairs in this situation.

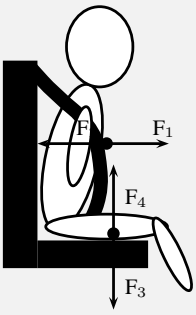
SOLUTION

Step 1 : ***Draw a force diagram***

Start by drawing the picture. You will be using arrows to indicate the forces so make your picture large enough so that detailed labels can also be added. The picture needs to be accurate, but not artistic! Use stickmen if you have to.

Step 2 : ***Label the diagram***

Take one pair at a time and label them carefully. If there is not enough space on the drawing, then use a key on the side.



F_1: The force of Dineo on the seat belt
F_2: The force of the seat belt on Dineo
F_3: The force of Dineo on the seat (downwards)
F_4: The force of the seat on Dineo (upwards)

Example 15: *Newton III - forces in a lift*

QUESTION

Tammy travels from the ground floor to the fifth floor of a hotel in a lift. Which ONE of the following statements is TRUE about the force exerted by the floor of the lift on Tammy's feet?

A It is greater than the magnitude of Tammy's weight.

B It is equal in magnitude to the force Tammy's feet exert on the floor.

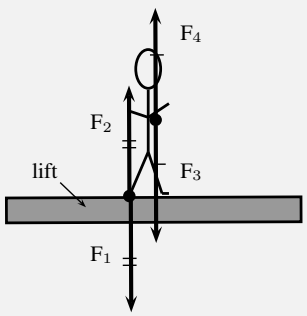
C It is equal to what it would be in a stationary lift.

D It is greater than what it would be in a stationary lift.

SOLUTION

Step 1 : ***Analyse the situation***

This is a Newton's Third Law question and not Newton II. We need to focus on the action-reaction pairs of forces and not the motion of the lift. The following diagram will show the action-reaction pairs that are present when a person is standing on a scale in a lift.



F_1: force of feet on lift (downwards)
F_2: force of lift on feet (upwards)
F_3: force of Earth on person (downwards)
F_4: force of person on Earth (upwards)

Figure 12.7: Newton's action-reaction pairs in a lift

In this question statements are made about the force of the floor (lift) on Tammy's feet. This force corresponds to F_2 in our diagram. The reaction force that pairs up with this one is F_1, which is the force that Tammy's feet exerts on the floor of the lift. The magnitude of these two forces are the same, but they act in opposite directions.

Step 2 : ***Choose the correct answer***

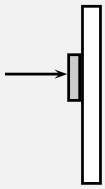
It is important to analyse the question first, before looking at the answers as the answers might confuse you. Make sure that you understand the situation and know what is asked before you look at the options.
The correct answer is B.

Example 16: *Newton III - book and wall*

QUESTION

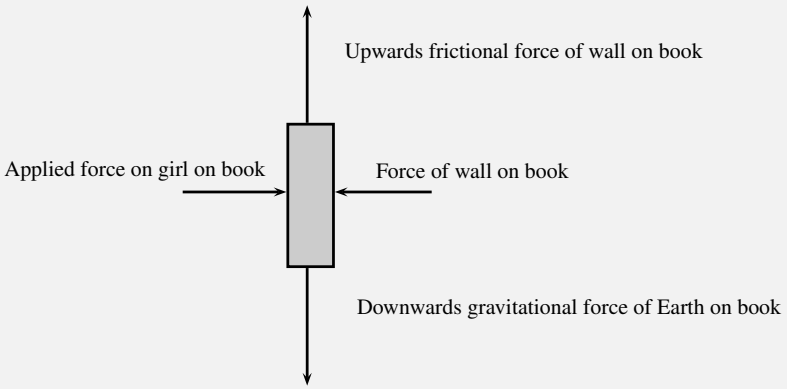
Tumi presses a book against a vertical wall as shown in the sketch.

1. *Draw a labelled force diagram indicating all the forces acting on the book.*
2. *State, in words, Newton's Third Law of Motion.*
3. *Name the action-reaction pairs of forces acting in the horizontal plane.*



SOLUTION

Step 1 : ***Draw a force diagram***
A force diagram will look like this:



Note that we had to draw all the forces acting on the book and not the action-reaction pairs. None of the forces drawn are action-reaction pairs, because they all act on the same object (the book). When you label forces, be as specific as possible, including the direction of the force and both objects involved, for example, do not say gravity (which is an incomplete answer) but rather say 'Downward (direction) gravitational force of the Earth (object) on the book (object)'.

Step 2 : ***State Newton's Third Law***
If body A exerts a force onto body B, then body B will exert a force equal in magnitude, but opposite in direction, onto body A.

Step 3 : ***Name the action-reaction pairs***

The question only asks for action-reaction forces in the horizontal plane. Therefore:
Pair 1: Action: Applied force of the girl on the book; Reaction: The force of the book on the girl.
Pair 2: Action: Force of the book on the wall; Reaction: Force of the wall on the book.
Note that a Newton III pair will always involve the same combination of words, like 'book on wall' and 'wall on book'. The objects are 'swapped around' in naming the pairs.

General experiment: *Balloon Rocket*

Aim: In this experiment for the entire class, you will use a balloon rocket to investigate Newton's Third Law. A fishing line will be used as a track and a plastic straw taped to the balloon will help attach the balloon to the track.
Apparatus: You will need the following items for this experiment:

1. balloons (one for each team)
2. plastic straws (one for each team)
3. tape (cellophane or masking)
4. fishing line, 10 meters in length
5. a stopwatch - optional (a cell phone can also be used)
6. a measuring tape - optional

Method:

1. Divide into groups of at least five.
2. Attach one end of the fishing line to the blackboard with tape. Have one teammate hold the other end of the fishing line so that it is taut and roughly horizontal. The line must be held steady and **must not** be moved up or down during the experiment.
3. Have one teammate blow up a balloon and hold it shut with his or her fingers. Have another teammate tape the straw along the side of the balloon. Thread the fishing line through the straw and hold the balloon at the far end of the line.
4. Let go of the rocket and observe how the rocket moves forward.
5. Optionally, the rockets of each group can be timed to determine a winner of the fastest rocket.
   (a) Assign one teammate to time the event. The balloon should be let go when the time keeper yells "Go!" Observe how your rocket moves toward the blackboard.
   (b) Have another teammate stand right next to the blackboard and yell "Stop!" when the rocket hits its target. If the balloon does not make it all the way to the blackboard, "Stop!" should be called when the balloon stops moving. The timekeeper should record the flight time.

(c) Measure the exact distance the rocket travelled. Calculate the average speed at which the balloon travelled. To do this, divide the distance travelled by the time the balloon was "in flight." Fill in your results for Trial 1 in the Table below.

(d) Each team should conduct two more races and complete the sections in the Table for Trials 2 and 3. Then calculate the average speed for the three trials to determine your team's race entry time.

Results:

	Distance (m)	**Time (s)**	**Speed ($m \cdot s^{-1}$)**
Trial 1			
Trial 2			
Trial 3			
		Average:	

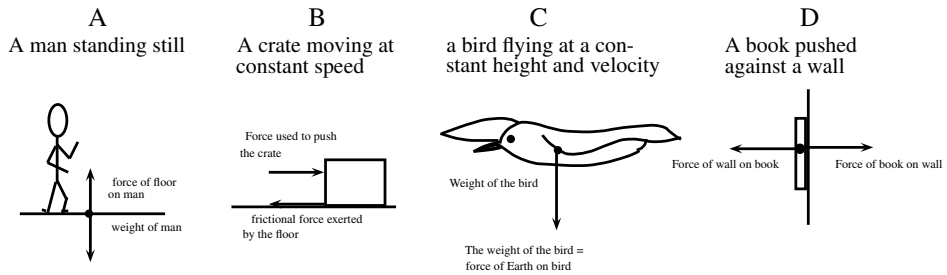
Conclusions: The winner of this race is the team with the fastest average balloon speed.

While doing the experiment, you should think about,

1. What made your rocket move?
2. How is Newton's Third Law of Motion demonstrated by this activity?
3. Draw pictures using labelled arrows to show the forces acting on the inside of the balloon before it was released and after it was released.

Exercise 12 - 3

1. A fly hits the front windscreen of a moving car. Compared to the magnitude of the force the fly exerts on the windscreen, the magnitude of the force the windscreen exerts on the fly during the collision, is:
   (a) zero.
   (b) smaller, but not zero.
   (c) bigger.
   (d) the same.
2. Which of the following pairs of forces correctly illustrates Newton's Third Law?



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(1.) 01w1 (2.) 01w2

Different types of forces

ESBFA

Tension

Tension is the magnitude of the force that exists in objects like ropes, chains and struts that are providing support. For example, there are tension forces in the ropes supporting a child's swing hanging from a tree.

Contact and non-contact forces

In this chapter we have come across a number of different types of forces, for example a push or a pull, tension in a string, frictional forces and the normal force. These are all examples of contact forces where there is a physical point of contact between applying the force and the object. Non-contact forces are forces that act over a distance, for example magnetic forces, electrostatic forces and gravitational forces.

When an object is placed on a surface, two types of surface forces can be identified. Friction is a force that acts between the surface and the object and is parallel to the surface. The normal force is a force that acts between the object and the surface and is perpendicular to the surface.

The normal force

A 5 kg box is placed on a rough surface and a 10 N force is applied at an angle of 36,9° to the horizontal. The box does not move. The normal force (N or F_N) is the force between the box and the surface acting in the vertical direction. If this force is not present the box would fall through the surface because the force of gravity pulls it downwards. The normal force therefore acts upwards. We can calculate the normal force by considering all the forces in the vertical direction. All the forces in the vertical direction must add up to zero because there is no movement in the vertical direction.

$$\begin{aligned} N + F_y + F_g &= 0 \\ N + 6 + (-49) &= 0 \\ N &= 43\,\text{N upwards} \end{aligned}$$

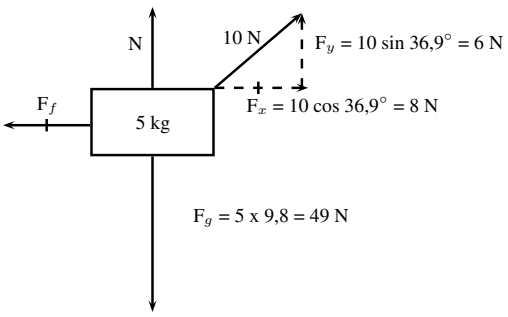


Figure 12.8: Friction and the normal force

The most interesting and illustrative normal force question, that is often asked, has to do with a scale in x-hirpeeCDR(inrce oFr0x a NdA& o?L3

Example 18: *Normal Forces 2*

QUESTION

A man with a mass of 100 kg stands on a scale (measuring newtons) inside a lift that is moving downwards at a constant velocity of 2 m·s^{-1}. What is the reading on the scale?

SOLUTION

Step 1 : ***Identify what information is given and what is asked for***
We are given the mass of the man and the acceleration of the lift. We know the gravitational acceleration that acts on him.

Step 2 : ***Decide which equation to use to solve the problem***
Once again we can use Newton's laws. We know that the sum of all the forces must equal the resultant force, F_r.

$$F_r = F_g + F_N$$

thzTa $pBVecyt$ N $coErkMg$ LTa N 7 **DeceDl to**

Example 19: *Normal Forces 3*

QUESTION

A man with a mass of 100 kg stands on a scale (measuring newtons) inside a lift that is accelerating downwards at 2 m·s^{-2}. What is the reading on the scale?

SOLUTION

Step 1 : ***Identify what information is given and what is asked for***
We are given the mass of the man and his resultant acceleration - this is just the acceleration of the lift. We know the gravitational acceleration also acts on him.

Step 2 : ***Decide which equation to use to solve the problem***
Once again we can use Newton's laws. We know that the sum of all the forces must equal the resultant force, F_r.

$$F_r = F_g + F_N$$

Step 3 : ***Determine the force due to gravity,*** F_g

$$\begin{aligned} F_g &= mg \\ &= (100\,\mathrm{kg})(9{,}8\,\mathrm{m}\cdot\mathrm{s}^{-2}) \\ &= 980\ \mathrm{kg}\cdot\ \mathrm{m}\cdot\mathrm{s}^{-2} \\ &= 980\,\mathrm{N}\ \text{downwards} \end{aligned}$$

Step 4 : ***Determine the resultant force,*** F_r
The resultant force can be calculated by applying Newton's Second Law:

$$\begin{aligned} F_r &= ma \\ F_r &= (100\,\mathrm{kg})(-2\,\mathrm{m}\cdot\mathrm{s}^{-2}) \\ &= -200\ N \\ &= 200\ N\ \text{down} \end{aligned}$$

Step 5 : ***Determine the normal force,*** F_N
The sum of all the vertical forces is equal to the resultant force, therefore

$$\begin{aligned} F_r &= F_g + F_N \\ -200\,\mathrm{N} &= -980\,\mathrm{N} + \mathrm{F_N} \\ F_N &= 780\,\mathrm{N}\ \text{upwards} \end{aligned}$$

Step 6 : ***Quote the final answer***
The normal force is 780 N upwards. It balances the gravitational force downwards just enough so that the man only accelerates downwards at 2 m·s^{-2}. The reading on the scale is 780 N.

Example 20: *Normal Forces 4*

QUESTION

A man with a mass of 100 kg stands on a scale (measuring newtons) inside a lift that is accelerating upwards at 4 m·s^{-2}. What is the reading on the scale?

SOLUTION

Step 1 : ***Identify what information is given and what is asked for***
We are given the mass of the man and his resultant acceleration - this is just the acceleration of the lift. We know the gravitational acceleration also acts on him.

Step 2 : ***Decide which equation to use to solve the problem***
Once again we can use Newton's laws. We know that the sum of all the forces must equal the resultant force, F_r.

$$F_r = F_g + F_N$$

Step 3 : ***Determine the force due to gravity,*** F_g

$$\begin{aligned} F_g &= mg \\ &= (100\,\mathrm{kg})(9{,}8\,\mathrm{m}\cdot\mathrm{s}^{-2}) \\ &= 980\ \mathrm{kg}\cdot\ \mathrm{m}\cdot\mathrm{s}^{-2} \\ &= 980\,\mathrm{N}\ \mathrm{downwards} \end{aligned}$$

Step 4 : ***Determine the resultant force,*** F_r
The resultant force can be calculated by applying Newton's Second Law:

$$\begin{aligned} F_r &= ma \\ F_r &= (100\,\mathrm{kg})(4\,\mathrm{m}\cdot\mathrm{s}^{-2}) \\ &= 400\ N \text{ upwards} \end{aligned}$$

Step 5 : ***Determine the normal force,*** F_N
The sum of all the vertical forces is equal to the resultant force, therefore

$$\begin{aligned} F_r &= F_g + F_N \\ 400\,\mathrm{N} &= -980\,\mathrm{N} + \mathrm{F_N} \\ F_N &= 1380\,\mathrm{N}\ \mathrm{upwards} \end{aligned}$$

Step 6 : ***Quote the final answer***
The normal force is 1380 N upwards. It balances the gravitational force downwards and then in addition applies sufficient force to accelerate the man upwards at 4m·s^{-2}. The reading on the scale is 1380 N.

Friction forces

When the surface of one object slides over the surface of another, each body exerts a frictional force on the other. For example if a book slides across a table, the table exerts a frictional force onto the book and the book exerts a frictional force onto the table (Newton's Third Law). Frictional forces act parallel to surfaces.

A force is not always powerful enough to make an object move, for example a small applied force might not be able to move a heavy crate. The frictional force opposing the motion of the crate is equal to the applied force but acting in the opposite direction. This frictional force is called *static friction*. When we increase the applied force (push harder), the frictional force will also increase until the applied force overcomes it. This frictional force can vary from zero (when no other forces are present and the object is stationary) to a maximum that depends on the surfaces. When the applied force is greater than the maximum frictional force, the crate will move. Once the object moves, the frictional force will decrease and remain at that level, which is also dependent on the surfaces, while the objects are moving. This is called *kinetic friction*. In both cases the maximum frictional force is related to the normal force and can be calculated as follows:

For static friction: $F_f \leq \mu_s$ N

Where μ_s = the coefficient of static friction
and N = normal force

For kinetic friction: $F_f = \mu_k$ N

Where μ_k = the coefficient of kinetic friction
and N = normal force

Remember that static friction is present when the object is not moving and kinetic friction while the object is moving. For example when you drive at constant velocity in a car on a tar road you have to keep the accelerator pushed in slightly to overcome the friction between the tar road and the wheels of the car. However, while moving at a constant velocity the wheels of the car are rolling, so this is not a case of two surfaces "rubbing" against each other and we are in fact looking at static friction. If you should break hard, causing the car to skid to a halt, we would be dealing with two surfaces rubbing against each other and hence kinetic friction. The higher the value for the coefficient of friction, the more 'sticky' the surface is and the lower the value, the more 'slippery' the surface is.

The frictional force (F_f) acts in the horizontal direction and can be calculated in a similar way to the normal for as long as there is no movement. If we use the same example as in Figure 12.8 and we choose to the rightward direction as positive,

$$\begin{aligned} F_f + F_x &= 0 \\ F_f + (+8) &= 0 \\ F_f &= -8 \\ F_f &= 8\,\text{N to the left} \end{aligned}$$

Example 21: *Forces on a slope*

QUESTION

A 50 kg crate is placed on a slope that makes an angle of 30° with the horizontal. The box does not slide down the slope. Calculate the magnitude and direction of the frictional force

and the normal force present in this situation.

SOLUTION

Step 1 : ***Draw a force diagram***

Draw a force diagram and fill in all the details on the diagram. This makes it easier to understand the problem.

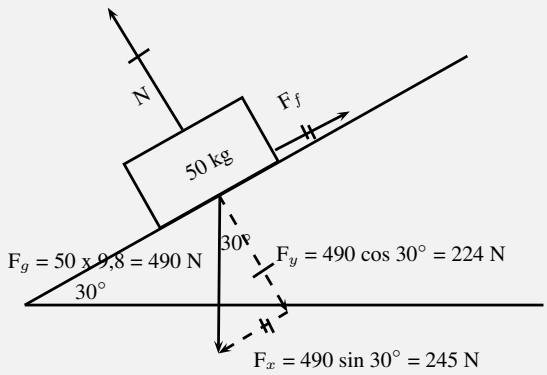


Figure 12.9: Friction and the normal forces on a slope

Step 2 : ***Calculate the normal force***

The normal force acts perpendicular to the surface (and not vertically upwards). It's magnitude is equal to the component of the weight perpendicular to the slope. Therefore:

$$\begin{aligned} N &= F_g \; cos \; 30^\circ \\ N &= 490 \; cos \; 30^\circ \\ N &= 224 \, \text{N perpendicular to the surface} \end{aligned}$$

Step 3 : ***Calculate the frictional force***

The frictional force acts parallel to the sloped surface. It's magnitude is equal to the component of the weight parallel to the slope. Therefore:

$$\begin{aligned} F_f &= F_g \; sin \; 30^\circ \\ F_f &= 490 \; sin \; 30^\circ \\ F_f &= 245 \, \text{N up the slope} \end{aligned}$$

We often think about friction in a negative way but very often friction is useful without us realising it. If there was no friction and you tried to prop a ladder up against a wall, it would simply slide to the ground. Rock climbers use friction to maintain their grip on cliffs. The brakes of cars would be useless if it wasn't for friction!

3. What force T at an angle of 30° above the horizontal, is required to drag a block weighing 20 N to the right at constant speed, if the coefficient of kinetic friction between the block and the surface is 0,20?

4. A block weighing 20 N rests on a horizontal surface. The coefficient of static friction between the block and the surface is 0,40 and the coefficient of dynamic friction is 0,20.

   (a) What is the magnitude of the frictional force exerted on the block while the block is at rest?

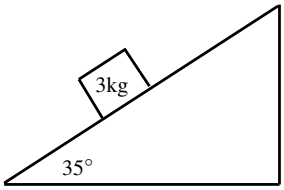
   (b) What will the magnitude of the frictional force be if a horizontal force of 5 N is exerted on the block?

   (c) What is the minimum force required to start the block moving?

   (d) What is the minimum force required to keep the block in motion once it has been started?

   (e) If the horizontal force is 10 N, determine the frictional force.

5. A stationary block of mass 3kg is on top of a plane inclined at 35° to the horizontal.



   (a) Draw a force diagram (not to scale). Include the weight of the block as well as the components of the weight that are perpendicular and parallel to the inclined plane.

   (b) Determine the values of the weight's perpendicular and parallel components.

   (c) There exists a frictional force between the block and plane. Determine this force (magnitude and direction).

6. A lady injured her back when she slipped and fell in a supermarket. She holds the owner of the supermarket accountable for her medical expenses. The owner claims that the floor covering was not wet and meets the accepted standards. He therefore cannot accept responsibility. The matter eventually ends up in court. Before passing judgement, the judge approaches you, a science student, to determine whether the coefficient of static friction of the floor is a minimum of 0,5 as required. He provides you with a tile from the floor, as well as one of the shoes the lady was wearing on the day of the incident.

   (a) Write down an expression for the coefficient of static friction.

   (b) Plan an investigation that you will perform to assist the judge in his judgement. Follow the steps outlined below to ensure that your plan meets the requirements.

      i. Formulate an investigation question.

      ii. Apparatus: List *all* the other apparatus, except the tile and the shoe, that you will need.

      iii. A stepwise method: How will you perform the investigation? Include a relevant, labelled free body-diagram.

      iv. Results: What will you record?

      v. Conclusion: How will you interpret the results to draw a conclusion?

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(1.) 01w3 (2.) 01w4 (3.) 01w5 (4.) 01w6 (5.) 01w7 (6.) 01w8

Forces in equilibrium

ESBFB

At the beginning of this chapter it was mentioned that resultant forces cause objects to accelerate in a straight line. If an object is stationary or moving at constant velocity then either,

- no forces are acting on the object, or
- the forces acting on that object are exactly balanced.

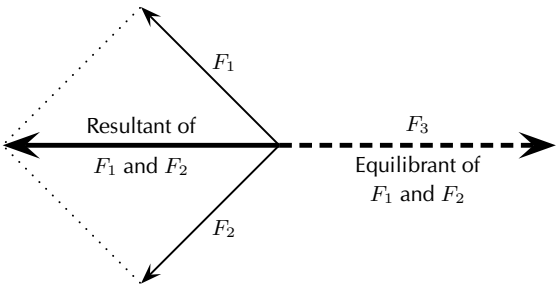
In other words, for stationary objects or objects moving with constant velocity, the resultant force acting on the object is zero. Additionally, if there is a perpendicular moment of force, then the object will rotate. You will learn more about moments of force later in this chapter.

Therefore, in order for an object not to move or to be in *equilibrium*, the sum of the forces (resultant force) must be zero and the sum of the moments of force must be zero.

> *DEFINITION: Equilibrium*
>
> An object in equilibrium has both the sum of the forces acting on it and the sum of the moments of the forces equal to zero.

If a resultant force acts on an object then that object can be brought into equilibrium by applying an additional force that exactly balances this resultant. Such a force is called the *equilibrant* and is equal in magnitude but opposite in direction to the original resultant force acting on the object.

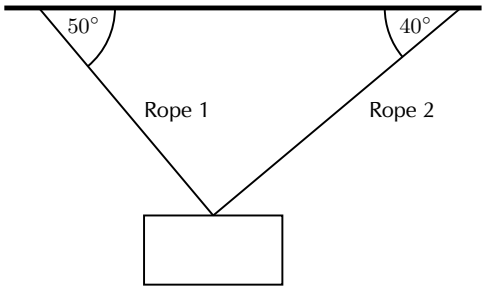
> *DEFINITION: Equilibrant*
>
> The equilibrant of any number of forces is the single force required to produce equilibrium, and is equal in magnitude but opposite in direction to the resultant force.



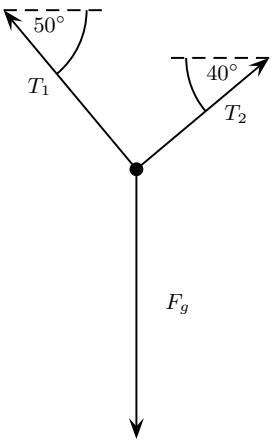
In the figure the resultant of F_1 and F_2 is shown. The equilibrant of F_1 and F_2 is then the vector opposite in direction to this resultant with the same magnitude (i.e. F_3).

- F_1, F_2 and F_3 are in equilibrium
- F_3 is the equilibrant of F_1 and F_2
- F_1 and F_2 are kept in equilibrium by F_3

As an example of an object in equilibrium, consider an object held stationary by two ropes in the arrangement below:

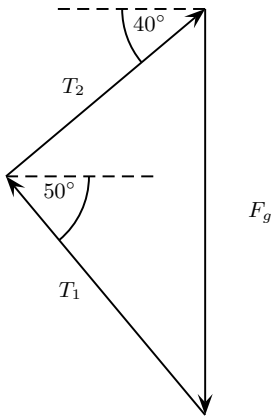


Let us draw a free body diagram for the object. In the free body diagram the object is drawn as a dot and all forces acting on the object are drawn in the correct directions starting from that dot. In this case, three forces are acting on the object.



Each rope exerts a force on the object in the direction of the rope away from the object. These tension forces are represented by T_1 and T_2. Since the object has mass, it is attracted towards the centre of the Earth. This weight is represented in the force diagram as F_g.

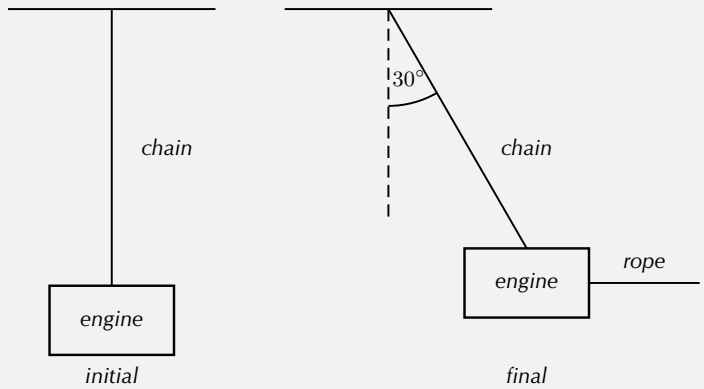
Since the object is stationary, the resultant force acting on the object is zero. In other words the three force vectors drawn tail-to-head form a closed triangle:



Example 23: *Equilibrium*

QUESTION

A car engine of weight 2000 N is lifted by means of a chain and pulley system. The engine is initially suspended by the chain, hanging stationary. Then, the engine is pulled sideways by a mechanic, using a rope. The engine is held in such a position that the chain makes an angle of 30° with the vertical. In the questions that follow, the masses of the chain and the rope can be ignored.

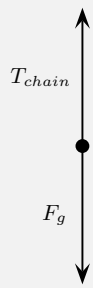


1. *Draw a free body representing the forces acting on the engine in the initial situation.*
2. *Determine the tension in the chain initially.*
3. *Draw a free body diagram representing the forces acting on the engine in the final situation.*
4. *Determine the magnitude of the applied force and the tension in the chain in the final situations.*

SOLUTION

Step 1 : ***Initial free body diagram for the engine***

There are only two forces acting on the engine initially: the tension in the chain, T_{chain} and the weight of the engine, F_g.



Step 2 : ***Determine the tension in the chain***

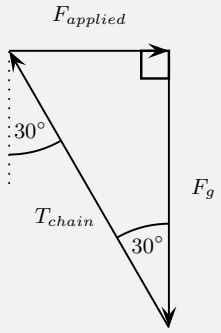
The engine is initially stationary, which means that the resultant force on the engine is zero. There are also no moments of force. Thus the tension in the chain

exactly balances the weight of the engine. The tension in the chain is:

$$\begin{aligned} T_{chain} &= F_g \\ &= 2000\,\mathrm{N} \end{aligned}$$

Step 3 : ***Final free body diagram for the engine***

There are three forces acting on the engine finally: The tension in the chain, the applied force and the weight of the engine.



Step 4 : ***Calculate the magnitude of the applied force and the tension in the chain in the final situation***

Since no method was specified let us calculate the magnitudes algebraically. Since the triangle formed by the three forces is a right-angle triangle this is easily done:

$$\begin{aligned} \frac{F_{applied}}{F_g} &= \tan 30^\circ \\ F_{applied} &= (2000\,\mathrm{N})\tan 30^\circ \\ &= 1\,155\,\mathrm{N} \end{aligned}$$

and

$$\begin{aligned} \frac{T_{chain}}{F_g} &= \frac{1}{\cos 30^\circ} \\ T_{chain} &= \frac{2000\,\mathrm{N}}{\cos 30^\circ} \\ &= 2\,309\,\mathrm{N} \end{aligned}$$

Exercise 12 - 5

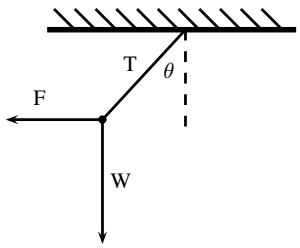
1. The diagram shows an object of weight W, attached to a string. A horizontal force F is applied to the object so that the string makes an angle of θ with the vertical when the object is at rest. The force exerted by the string is T. Which one of the following expressions is incorrect?

   (a) F + T + W = 0

   (b) W = T cos θ

   (c) tan θ = $\frac{F}{W}$

   (d) W = T sin θ



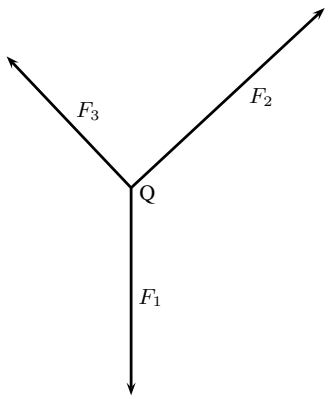
2. The point Q is in equilibrium due to three forces F_1, F_2 and F_3 acting on it. Which of the statements about these forces is INCORRECT?

   (a) The sum of the forces F_1, F_2 and F_3 is zero.

   (b) The three forces all lie in the same plane.

   (c) The resultant force of F_1 and F_3 is F_2.

   (d) The sum of the components of the forces in any direction is zero.



3. A point is acted on by two forces in equilibrium. The forces

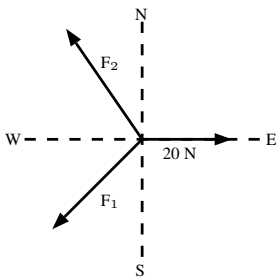
   A have equal magnitudes and directions.

   B have equal magnitudes but opposite directions.

   C act perpendicular to each other.

   D act in the same direction.

4. A point in equilibrium is acted on by three forces. Force F_1 has components 15 N due south and 13 N due west. What are the components of force F_2?



   A 13 N due north and 20 due west

B 13 N due north and 13 N due west

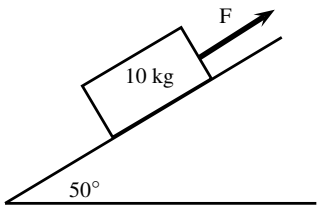
C 15 N due north and 7 N due west

D 15 N due north and 13 N due east

5. (a) Define the term 'equilibrant'.

   (b) Two tugs, one with a pull of 2500 N and the other with a pull of 3 000 N are used to tow an oil drilling platform. The angle between the two cables is 30 °. Determine, either by scale diagram or by calculation (a clearly labelled rough sketch must be given), the equilibrant of the two forces.

6. A 10 kg block is held motionless by a force F on a frictionless plane, which is inclined at an angle of 50° to the horizontal, as shown below:



   (a) Draw a force diagram (not a triangle) indicating all the forces acting on the block.

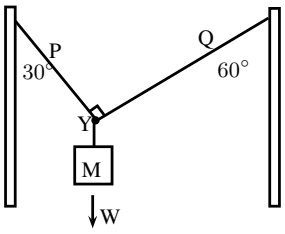
   (b) Calculate the magnitude of force F. Include a labelled diagram showing a triangle of forces in your answer.

7. A rope of negligible mass is strung between two vertical struts. A mass M of weight W hangs from the rope through a hook fixed at point Y

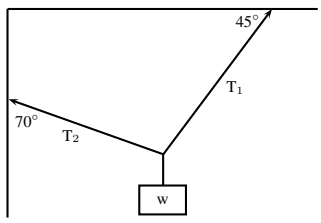
   (a) Draw a vector diagram, plotted head to tail, of the forces acting at point Y. Label each force and show the size of each angle.

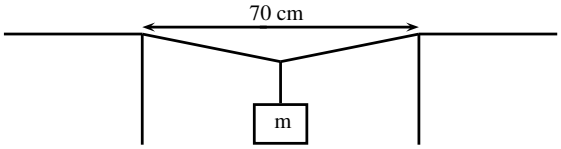
   (b) Where will the tension be greatest? Part P or Q? Motivate your answer.

   (c) When the tension in the rope is greater than 600N it will break. What is the maximum mass that the above set up can support?



8. An object of weight w is supported by two cables attached to the ceiling and wall as shown. The tensions in the two cables are T_1 and T_2 respectively. Tension $T_1 = 1200$ N. Determine the tension T_2 and weight w of the object by accurate construction and measurement or calculation.





9. A rope is tied at two points which are 70 cm apart from each other, on the same horizontal line. The total length of rope is 1 m, and the maximum tension it can withstand is 1000 N. Find the largest mass (m), in kg, that can be carried at the midpoint of the rope, without breaking the rope. Include a labelled diagram showing the triangle of forces in your answer.

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(1.) 01w9 (2.) 01wa (3.) 01wb (4.) 01wc (5.) 01wd (6.) 01we
(7.) 01wf (8.) 01wg (9.) 01wh

12.4 Forces between Masses

ESBFC

In Grade 10, you saw that gravitational fields exert forces on masses in the field. A field is a region of space in which an object experiences a force. The strength of a field is defined by a field strength. For example, the gravitational field strength, g, on or near the surface of the Earth has a value that is approximately 9,8 m·s^{-2}.

The force exerted by a field of strength g on an object of mass m is given by:

$$F = m \cdot g \tag{12.1}$$

This can be re-written in terms of g as:

$$g = \frac{F}{m}$$

This means that g can be understood to be a measure of force exerted per unit mass.

The force defined in Equation 12.1 is known as weight.

Objects in a gravitational field exert forces on each other without touching. The gravitational force is an example of a non-contact force.

Gravity is a force and therefore must be described by a vector - so remember that gravity has both magnitude and direction.

Newton's Law of Universal Gravitation

ESBFD

DEFINITION: Newton's Law of Universal Gravitation

Every point mass attracts every other point mass by a force directed along the line connecting the two. This force is proportional to the product of the masses and inversely proportional to the square of the distance between them.

The magnitude of the attractive gravitational force between the two point masses, F is given by:

$$F = G\frac{m_1 m_2}{r^2} \tag{12.2}$$

where: G is the gravitational constant, m_1 is the mass of the first point mass, m_2 is the mass of the second point mass and r is the distance between the two point masses.

Assuming SI units, F is measured in newtons (N), m_1 and m_2 in kilograms (kg), r in meters (m), and the constant G is approximately equal to $6{,}67 \times 10^{-11} N \cdot m^2 \cdot\ kg^{-2}$. Remember that this is a force of attraction.

For example, consider a man of mass 80 kg standing 10 m from a woman with a mass of 65 kg. The attractive gravitational force between them would be:

$$\begin{aligned} F &= G\frac{m_1 m_2}{r^2} \\ &= (6{,}67 \times 10^{-11}\,\mathrm{N \cdot m^2 \cdot\ kg^{-2}})(\frac{(80\mathrm{kg})(65\mathrm{kg})}{(10\mathrm{m})^2}) \\ &= 3{,}47 \times 10^{-9}\,\mathrm{N} \end{aligned}$$

If the man and woman move to 1 m apart, then the force is:

$$\begin{aligned} F &= G\frac{m_1 m_2}{r^2} \\ &= (6{,}67 \times 10^{-11}\,\mathrm{N \cdot m^2 \cdot\ kg^{-2}})(\frac{(80\mathrm{kg})(65\mathrm{kg})}{(1\mathrm{m})^2}) \\ &= 3{,}47 \times 10^{-7}\,\mathrm{N} \end{aligned}$$

As you can see, these forces are very small.

Now consider the gravitational force between the Earth and the Moon. The mass of the Earth is $5{,}98 \times 10^{24}$ kg, the mass of the Moon is $7{,}35 \times 10^{22}$ kg and the Earth and Moon are $3{,}8 \times 10^8$ m apart. The gravitational force between the Earth and Moon is:

$$\begin{aligned} F &= G\frac{m_1 m_2}{r^2} \\ &= (6{,}67 \times 10^{-11}\,\mathrm{N \cdot m^2 \cdot\ kg^{-2}})(\frac{(5{,}98 \times 10^{24}\mathrm{kg})(7{,}35 \times 10^{22}\mathrm{kg})}{(0{,}38 \times 10^{9}\mathrm{m})^2}) \\ &= 2{,}03 \times 10^{20}\,\mathrm{N} \end{aligned}$$

From this example you can see that the force is very large.

These two examples demonstrate that the greater the masses, the greater the force between them. The $1/r^2$ factor tells us that the distance between the two bodies plays a role as well. The closer two bodies are, the stronger the gravitational force between them is. We feel the gravitational attraction of the Earth most at the surface since that is the closest we can get to it, but if we were in outer-space, we would barely feel the effect of the Earth's gravity!

Remember that

$$F = m \cdot a \tag{12.3}$$

which means that every object on Earth feels the same gravitational acceleration! That means whether you drop a pen or a book (from the same height), they will both take the same length of time to hit the ground... in fact they will be head to head for the entire fall if you drop them at the same time. We can show this easily by using the two equations above (Equations 12.2 and 12.3). The force between the Earth (which has the mass m_e) and an object of mass m_o is

$$F = \frac{G m_o m_e}{r^2} \tag{12.4}$$

and the acceleration of an object of mass m_o (in terms of the force acting on it) is

$$a_o = \frac{F}{m_o} \tag{12.5}$$

So we substitute equation (12.4) into Equation (12.5), and we find that

$$a_o = \frac{G m_e}{r^2} \tag{12.6}$$

Since it doesn't matter what m_o is, this tells us that the acceleration on a body (due to the Earth's gravity) does not depend on the mass of the body. Thus all objects experience the same gravitational acceleration. The force on different bodies will be different but the acceleration will be the same. Due to the fact that this acceleration caused by gravity is the same on all objects we label it differently, instead of using a we use g which we call the gravitational acceleration.

Comparative Problems

ESBFE

Comparative problems involve calculation of something in terms of something else that we know. For example, if you weigh 490 N on Earth and the gravitational acceleration on Venus is 0,903 that of the gravitational acceleration on the Earth, then you would weigh 0,903 x 490 N = 442,5 N on Venus.

Principles for answering comparative problems

- Write out equations and calculate all quantities for the given situation
- Write out all relationships between variable from first and second case
- Write out second case
- Substitute all first case variables into second case
- Write second case in terms of first case

Example 24: *Comparative Problem 1*

QUESTION

A man has a mass of 70 kg. The planet Zirgon is the same size as the Earth but has twice the mass of the Earth. What would the man weigh on Zirgon, if the gravitational acceleration on Earth is 9,8 m·s^{-2}?

SOLUTION

Step 1 : ***Determine what information has been given***
The following has been provided:

- the mass of the man, m
- the mass of the planet Zirgon (m_Z) in terms of the mass of the Earth (m_E), $m_Z = 2m_E$
- the radius of the planet Zirgon (r_Z) in terms of the radius of the Earth (r_E), $r_Z = r_E$

Step 2 : ***Determine how to approach the problem***
We are required to determine the man's weight on Zirgon (w_Z). We can do this by using:

$$w = mg = G\frac{m_1 \cdot m_2}{r^2}$$

to calculate the weight of the man on Earth and then use this value to determine the weight of the man on Zirgon.

Step 3 : ***Situation on Earth***

$$\begin{aligned} w_E &= mg_E = G\frac{m_E \cdot m}{r_E^2} \\ &= (70\,\mathrm{kg})(9{,}8\,\mathrm{m \cdot s^{-2}}) \\ &= 686\,\mathrm{N} \end{aligned}$$

Step 4 : ***Situation on Zirgon in terms of situation on Earth***

Write the equation for the gravitational force on Zirgon and then substitute the values for m_Z and r_Z, in terms of the values for the Earth.

$$\begin{aligned} w_Z = mg_Z &= G\frac{m_Z \cdot m}{r_Z^2} \\ &= G\frac{2m_E \cdot m}{r_E^2} \\ &= 2(G\frac{m_E \cdot m}{r_E^2}) \\ &= 2w_E \\ &= 2(686\,\mathrm{N}) \\ &= 1\,372\,\mathrm{N} \end{aligned}$$

Step 5 : ***Quote the final answer***

The man weighs 1 372 N on Zirgon.

Example 25: *Comparative Problem 2*

QUESTION

A man has a mass of 70 kg. On the planet Beeble how much will he weigh if Beeble has mass half of that of the Earth and a radius one quarter that of the Earth. Gravitational acceleration on Earth is 9,8 m·s^{-2}.

SOLUTION

Step 1 : ***Determine what information has been given***

The following has been provided:

- the mass of the man on Earth, m
- the mass of the planet Beeble (m_B) in terms of the mass of the Earth (m_E), $m_B = \frac{1}{2}m_E$
- the radius of the planet Beeble (r_B) in terms of the radius of the Earth (r_E), $r_B = \frac{1}{4}r_E$

Step 2 : ***Determine how to approach the problem***

We are required to determine the man's weight on Beeble (w_B). We can do this by using:

$$w = mg = G\frac{m_1 \cdot m_2}{r^2} \tag{12.7}$$

to calculate the weight of the man on Earth and then use this value to determine the weight of the man on Beeble.

Step 3 : ***Situation on Earth***

$$\begin{aligned} w_E &= mg_E = G\frac{m_E \cdot m}{r_E^2} \\ &= (70\,\mathrm{kg})(9{,}8\,\mathrm{m}\cdot\mathrm{s}^{-2}) \\ &= 686\,\mathrm{N} \end{aligned}$$

Step 4 : ***Situation on Beeble in terms of situation on Earth***
Write the equation for the gravitational force on Beeble and then substitute the values for m_B and r_B, in terms of the values for the Earth.

$$\begin{aligned} w_B = mg_B &= G\frac{m_B \cdot m}{r_B^2} \\ &= G\frac{\frac{1}{2}m_E \cdot m}{(\frac{1}{4}r_E)^2} \\ &= 8(G\frac{m_E \cdot m}{r_E^2}) \\ &= 8w_E \\ &= 8(686\,\mathrm{N}) \\ &= 5\,488\,\mathrm{N} \end{aligned}$$

Step 5 : ***Quote the final answer***
The man weighs 5 488 N on Beeble.

Exercise 12 - 6

1. Two objects of mass 2m and 3m respectively exert a force F on each other when they are a certain distance apart. What will be the force between two objects situated the same distance apart but having a mass of 5m and 6m respectively?
   (a) 0,2 F
   (b) 1,2 F
   (c) 2,2 F
   (d) 5 F
2. As the distance of an object above the surface of the Earth is greatly increased, the weight of the object would
   (a) increase
   (b) decrease
   (c) increase and then suddenly decrease
   (d) remain the same
3. A satellite circles around the Earth at a height where the gravitational force is a factor 4 less than at the surface of the Earth. If the Earth's radius is R, then the height of the satellite above the surface is:
   (a) R
   (b) 2 R
   (c) 4 R

(d) 16 R

4. A satellite experiences a force F when at the surface of the Earth. What will be the force on the satellite if it orbits at a height equal to the diameter of the Earth:

   (a) $\frac{1}{F}$
   (b) $\frac{1}{2}\ F$
   (c) $\frac{1}{3}\ F$
   (d) $\frac{1}{9}\ F$

5. The weight of a rock lying on surface of the Moon is W. The radius of the Moon is R. On planet Alpha, the same rock has weight 8W. If the radius of planet Alpha is half that of the Moon, and the mass of the Moon is M, then the mass, in kg, of planet Alpha is:

   (a) $\frac{M}{2}$
   (b) $\frac{M}{4}$
   (c) 2 M
   (d) 4 M

6. Consider the symbols of the two physical quantities g and G used in Physics.

   (a) Name the physical quantities represented by g and G.
   (b) Derive a formula for calculating g near the Earth's surface using Newton's Law of Universal Gravitation. M and R represent the mass and radius of the Earth respectively.

7. Two spheres of mass 800g and 500g respectively are situated so that their centres are 200 cm apart. Calculate the gravitational force between them.

8. Two spheres of mass 2 kg and 3 kg respectively are situated so that the gravitational force between them is 2,5 x 10^{-8} N. Calculate the distance between them.

9. Two identical spheres are placed 10 cm apart. A force of 1,6675 x 10^{-9} N exists between them. Find the masses of the spheres.

10. Halley's comet, of approximate mass 1 x 10^{15} kg was 1,3 x 10^{8} km from the Earth, at its point of closest approach during its last sighting in 1986.

    (a) Name the force through which the Earth and the comet interact.
    (b) Is the magnitude of the force experienced by the comet the same, greater than or less than the force experienced by the Earth? Explain.
    (c) Does the acceleration of the comet increase, decrease or remain the same as it moves closer to the Earth? Explain.
    (d) If the mass of the Earth is 6 x 10^{24} kg, calculate the magnitude of the force exerted by the Earth on Halley's comet at its point of closest approach.

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(1.) 01wi (2.) 01wj (3.) 01wk (4.) 01wm (5.) 01wn (6.) 01wp
(7.) 01wq (8.) 01wr (9.) 01ws (10.) 01wt

12.5 Momentum and Impulse

ESBFF

Momentum is a physical quantity which is closely related to forces. Momentum is a property which applies to moving objects.

> *DEFINITION: Momentum*
>
> Momentum is the tendency of an object to continue to move in its direction of travel. Momentum is calculated from the product of the mass and velocity of an object.

The momentum (symbol p) of an object of mass m moving at velocity v is:

$$p = m \cdot v$$

According to this equation, momentum is related to both the mass and velocity of an object. A small car travelling at the same velocity as a big truck will have a smaller momentum than the truck. The smaller the mass, the smaller the velocity.
A car travelling at 120 km·hr^{-1}will have a bigger momentum than the same car travelling at 60 km·hr^{-1}. Momentum is also related to velocity; the smaller the velocity, the smaller the momentum.
Different objects can also have the same momentum, for example a car travelling slowly can have the same momentum as a motor cycle travelling relatively fast. We can easily demonstrate this.

Consider a car of mass 1 000 kg with a velocity of 8 m·s^{-1}(about 30 km·hr^{-1}). The momentum of the car is therefore

$$\begin{aligned} p &= m \cdot v \\ &= (1000\,\mathrm{kg})(8\,\mathrm{m} \cdot \mathrm{s}^{-1}) \\ &= 8000\,\mathrm{kg} \cdot\ \mathrm{m} \cdot \mathrm{s}^{-1} \end{aligned}$$

Now consider a motor cycle of mass 250 kg travelling at 32 m·s^{-1} (about 115 km·hr^{-1}). The momentum of the motor cycle is:

$$\begin{aligned} p &= m \cdot v \\ &= (250\,\mathrm{kg})(32\,\mathrm{m} \cdot \mathrm{s}^{-1}) \\ &= 8000\,\mathrm{kg} \cdot\ \mathrm{m} \cdot \mathrm{s}^{-1} \end{aligned}$$

Even though the motor cycle is considerably lighter than the car, the fact that the motor cycle is travelling much faster than the car means that the momentum of both vehicles is the same.

From the calculations above, you are able to derive the unit for momentum as kg·m·s^{-1}.
Momentum is also vector quantity, because it is the product of a scalar (m) with a vector (v).
This means that whenever we calculate the momentum of an object, we need to include the direction of the momentum. ▶ See video: VPkki at www.everythingscience.co.za

Example 26: *Momentum of a Soccer Ball*

QUESTION

A soccer ball of mass 420 g is kicked at 20 m·s^{-1} towards the goal post. Calculate the momentum of the ball.

SOLUTION

Step 1 : ***Identify what information is given and what is asked for***

The question explicitly gives

- the mass of the ball, and
- the velocity of the ball

The mass of the ball must be converted to SI units.

$$420\ \mathrm{g} = 0{,}42\,\mathrm{kg}$$

We are asked to calculate the momentum of the ball. From the definition of momentum,

$$p = m \cdot v$$

we see that we need the mass and velocity of the ball, which we are given.

Step 2 : ***Do the calculation***

We calculate the magnitude of the momentum of the ball,

$$\begin{aligned} p &= m \cdot v \\ &= (0{,}42\,\mathrm{kg})(20\,\mathrm{m} \cdot \mathrm{s}^{-1}) \\ &= 8{,}4\,\mathrm{kg} \cdot\ \mathrm{m} \cdot \mathrm{s}^{-1} \end{aligned}$$

Step 3 : ***Quote the final answer***

We quote the answer with the direction of motion included, p = 8,4 kg·m·s^{-1} in the direction of the goal post.

Example 27: *Momentum of a cricket ball*

QUESTION

A cricket ball of mass 160 g is bowled at 40 m·s^{-1} towards a batsman. Calculate the momen-

tum of the cricket ball.

SOLUTION

Step 1 : ***Identify what information is given and what is asked for***
The question explicitly gives

- the mass of the ball (m = 160 g = 0,16 kg), and
- the velocity of the ball (v = 40 m·s^{-1})

To calculate the momentum we will use

$$p = m \cdot v$$

Step 2 : ***Do the calculation***

$$\begin{aligned} p &= m \cdot v \\ &= (0{,}16\,\mathrm{kg})(40\,\mathrm{m} \cdot \mathrm{s}^{-1}) \\ &= 6{,}4\,\mathrm{kg} \cdot \mathrm{m} \cdot \mathrm{s}^{-1} \\ &= 6{,}4\,\mathrm{kg} \cdot \mathrm{m} \cdot \mathrm{s}^{-1} \text{in the direction of the batsman} \end{aligned}$$

Example 28: *Momentum of the Moon*

QUESTION

The Moon is 384 400 km away from the Earth and orbits the Earth in 27,3 days. If the Moon has a mass of 7,35 x 10^{22}kg, what is the magnitude of its momentum if we assume a circular orbit?

SOLUTION

Step 1 : ***Identify what information is given and what is asked for***
The question explicitly gives

- the mass of the Moon (m = 7,35 x 10^{22} kg)
- the distance to the Moon (384 400 km = 384 400 000 m = 3,844 x 10^{8} m)
- the time for one orbit of the Moon (27,3 days = 27,3 x 24 x 60 x 60 = 2,36 x 10^{6} s)

We are asked to calculate only the magnitude of the momentum of the Moon (i.e. we do not need to specify a direction). In order to do this we require the mass and the magnitude of the velocity of the Moon, since

$$p = m \cdot v$$

Step 2 : ***Find the magnitude of the velocity of the Moon***

The magnitude of the average velocity is the same as the speed. Therefore:

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

We are given the time the Moon takes for one orbit but not how far it travels in that time. However, we can work this out from the distance to the Moon and the fact that the Moon has a circular orbit. Using the equation for the circumference, C, of a circle in terms of its radius, we can determine the distance travelled by the Moon in one orbit:

$$\begin{aligned} C &= 2\pi r \\ &= 2\pi(3{,}844 \times 10^8 \mathrm{m}) \\ &= 2{,}42 \times 10^9 \ \mathrm{m} \end{aligned}$$

Combining the distance travelled by the Moon in an orbit and the time taken by the Moon to complete one orbit, we can determine the magnitude of the Moon's velocity or speed,

$$\begin{aligned} s &= \frac{d}{\Delta t} \\ &= \frac{C}{T} \\ &= \frac{2{,}42 \times 10^9 m}{2{,}36 \times 10^6 s} \\ &= 1{,}02 \times 10^3 \ \mathrm{m \cdot s^{-1}}. \end{aligned}$$

Step 3 : ***Finally calculate the momentum and quote the answer***

The magnitude of the Moon's momentum is:

$$\begin{aligned} p &= m \cdot v \\ &= (7{,}35 \times 10^{22} \ \mathrm{kg})(1{,}02 \times 10^3 \ \mathrm{m \cdot s^{-1}}) \\ &= 7{,}50 \times 10^{25} \ \mathrm{kg \cdot \ m \cdot s^{-1}} \end{aligned}$$

Vector Nature of Momentum

ESBFG

As we have said, momentum is a vector quantity. Since momentum is a vector, the techniques of vector addition discussed in Chapter 11 must be used to calculate the total momentum of a system.

Example 29: *Calculating the Total Momentum of a System*

QUESTION

Two billiard balls roll towards each other. They each have a mass of 0,3 kg. Ball 1 is moving at $v_1 = 1\,\mathrm{m}\cdot\mathrm{s}^{-1}$ to the right, while ball 2 is moving at $v_2 = 0{,}8\,\mathrm{m}\cdot\mathrm{s}^{-1}$ to the left. Calculate the total momentum of the system.

SOLUTION

Step 1 : ***Identify what information is given and what is asked for***

The question explicitly gives

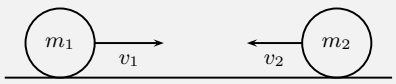
- the mass of each ball,
- the velocity of ball 1, v_1, and
- the velocity of ball 2, v_2,

all in the correct units!

We are asked to calculate the **total momentum of the system**. In this example our system consists of two balls. To find the total momentum we must determine the momentum of each ball and add them.

$$p_{total} = p_1 + p_2$$

Since ball 1 is moving to the right, its momentum is in this direction, while the second ball's momentum is directed towards the left.



Thus, we are required to find the sum of two vectors acting along the same straight line. The algebraic method of vector addition introduced in Chapter 11 can thus be used.

Step 2 : ***Choose a frame of reference***

Let us choose right as the positive direction, then obviously left is negative.

Step 3 : ***Calculate the momentum***

The total momentum of the system is then the sum of the two momenta taking the directions of the velocities into account. Ball 1 is travelling at 1 m·s^{-1}to the right or +1 m·s^{-1}. Ball 2 is travelling at 0,8 m·s^{-1}to the left or -0,8 m·s^{-1}. Thus,

$$\begin{aligned} p_{total} &= m_1 v_1 + m_2 v_2 \\ &= (0{,}3\,\mathrm{kg})(+1\,\mathrm{m}\cdot\mathrm{s}^{-1}) + (0{,}3\,\mathrm{kg})(-0{,}8\,\mathrm{m}\cdot\mathrm{s}^{-1}) \\ &= (+0{,}3\,\mathrm{kg}\cdot\ \mathrm{m}\cdot\mathrm{s}^{-1}) + (-0{,}24\,\mathrm{kg}\cdot\ \mathrm{m}\cdot\mathrm{s}^{-1}) \\ &= +0{,}06\,\mathrm{kg}\cdot\ \mathrm{m}\cdot\mathrm{s}^{-1} \\ &= 0{,}06\,\mathrm{kg}\cdot\ \mathrm{m}\cdot\mathrm{s}^{-1}\text{to the right} \end{aligned}$$

In the last step the direction was added in words. Since the result in the second last line is positive, the total momentum of the system is in the positive direction (i.e. to the right).

Exercise 12 - 7

1. (a) The fastest recorded delivery for a cricket ball is 161,3 km·hr^{-1}, bowled by Shoaib Akhtar of Pakistan during a match against England in the 2003 Cricket World Cup, held in South Africa. Calculate the ball's momentum if it has a mass of 160 g.
   (b) The fastest tennis service by a man is 246,2 km·hr^{-1}by Andy Roddick of the United States of America during a match in London in 2004. Calculate the ball's momentum if it has a mass of 58 g.
   (c) The fastest server in the women's game is Venus Williams of the United States of America, who recorded a serve of 205 km·hr^{-1}during a match in Switzerland in 1998. Calculate the ball's momentum if it has a mass of 58 g.
   (d) If you had a choice of facing Shoaib, Andy or Venus and didn't want to get hurt, who would you choose based on the momentum of each ball.
2. Two golf balls roll towards each other. They each have a mass of 100 g. Ball 1 is moving at v_1 = 2,4 m·s^{-1}to the right, while ball 2 is moving at v_2 = 3 m·s^{-1}to the left. Calculate the total momentum of the system.
3. Two motor cycles are involved in a head on collision. Motorcycle A has a mass of 200 kg and was travelling at 120 km·hr^{-1}south. Motor cycle B has a mass of 250 kg and was travelling north at 100 km·hr^{-1}. A and B are about to collide. Calculate the momentum of the system before the collision takes place.

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(1.) 01wu (2.) 01wv (3.) 01ww

Change in Momentum

ESBFH

Let us consider a tennis ball (mass = 0,1 kg) that is dropped at an initial velocity of 5 m·s^{-1}and bounces back at a final velocity of 3 m·s^{-1}. As the ball approaches the floor it has a momentum that we call the momentum before the collision. When it moves away from the floor it has a different momentum called the momentum after the collision. The bounce on the floor can be thought of as a collision taking place where the floor exerts a force on the tennis ball to change its momentum.

The momentum before the bounce can be calculated as follows:
Because momentum and velocity are vectors, we have to choose a direction as positive. For this example we choose the initial direction of motion as positive, in other words, downwards is positive.

$$\begin{aligned} p_i &= m \cdot v_i \\ &= (0{,}1\,\mathrm{kg})(+5\,\mathrm{m}\cdot\mathrm{s}^{-1}) \\ &= 0{,}5\ \mathrm{kg}\cdot\ \mathrm{m}\cdot\mathrm{s}^{-1}\text{downwards} \end{aligned}$$

When the tennis ball bounces back it changes direction. The final velocity will thus have a negative value. The momentum after the bounce can be calculated as follows:

$$\begin{aligned} p_f &= m \cdot v_f \\ &= (0{,}1\,\mathrm{kg})(-3\,\mathrm{m} \cdot \mathrm{s}^{-1}) \\ &= -0{,}3\,\mathrm{kg} \cdot \mathrm{m} \cdot \mathrm{s}^{-1} \\ &= 0{,}3\ \mathrm{kg} \cdot \mathrm{m} \cdot \mathrm{s}^{-1}\text{upwards} \end{aligned}$$

Now let us look at what happens to the momentum of the tennis ball. The momentum changes during this bounce. We can calculate the change in momentum as follows:
Again we have to choose a direction as positive and we will stick to our initial choice as downwards is positive. This means that the final momentum will have a negative number.

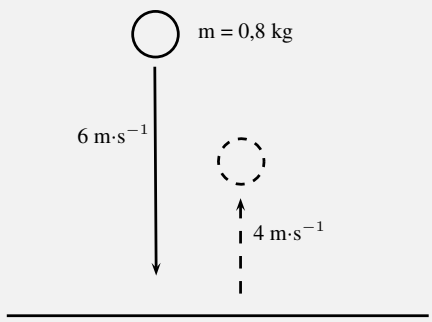
$$\begin{aligned} \Delta p &= p_f - p_i \\ &= m \cdot v_f - m \cdot v_i \\ &= (-0{,}3\,\mathrm{kg}) - (0{,}5\,\mathrm{m} \cdot \mathrm{s}^{-1}) \\ &= -0{,}8\,\mathrm{kg} \cdot \mathrm{m} \cdot \mathrm{s}^{-1} \\ &= 0{,}8\ \mathrm{kg} \cdot \mathrm{m} \cdot \mathrm{s}^{-1}\text{upwards} \end{aligned}$$

You will notice that this number is bigger than the previous momenta calculated. This should be the case as the ball needs to be stopped and then given momentum to bounce back.

Example 30: *Change in Momentum*

QUESTION

A rubber ball of mass 0,8 kg is dropped and strikes the floor with an initial velocity of 6 m·s^{-1}. It bounces back with a final velocity of 4 m·s^{-1}. Calculate the change in the momentum of the rubber ball caused by the floor.



SOLUTION

Step 1 : ***Identify the information given and what is asked***
The question explicitly gives

- the ball's mass (m = 0,8 kg),
- the ball's initial velocity (v_i = 6 m·s^{-1}), and
- the ball's final velocity (v_f = 4 m·s^{-1})

all in the correct units.

We are asked to calculate the change in momentum of the ball,

$$\Delta p = mv_f - mv_i$$

We have everything we need to find Δp. Since the initial momentum is directed downwards and the final momentum is in the upward direction, we can use the algebraic method of subtraction discussed in the vectors chapter.

Step 2 : ***Choose a frame of reference***
Let us choose down as the positive direction.

Step 3 : ***Do the calculation and quote the answer***

$$\begin{aligned}
\Delta p &= mv_f - mv_i \\
&= (0{,}8\,\mathrm{kg})(-4\,\mathrm{m\cdot s^{-1}}) - (0{,}8\,\mathrm{kg})(+6\,\mathrm{m\cdot s^{-1}}) \\
&= (-3{,}2\,\mathrm{kg\cdot\ m\cdot s^{-1}}) - (4{,}8\,\mathrm{kg\cdot\ m\cdot s^{-1}}) \\
&= -8 \\
&= 8\ \mathrm{kg\cdot\ m\cdot s^{-1}}\ \text{upwards}
\end{aligned}$$

Exercise 12 - 8

1. Which expression accurately describes the change of momentum of an object?

   (a) $\frac{F}{m}$

   (b) $\frac{F}{t}$

   (c) $F \cdot m$

   (d) $F \cdot t$

2. A child drops a ball of mass 100 g. The ball strikes the ground with a velocity of 5 m·s^{-1}and rebounds with a velocity of 4 m·s^{-1}. Calculate the change of momentum of the ball.

3. A 700 kg truck is travelling north at a velocity of 40 km·hr^{-1}when it is approached by a 500 kg car travelling south at a velocity of 100 km·hr^{-1}. Calculate the total momentum of the system.

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(1.) 01wx (2.) 01wy (3.) 01wz

Newton's Second Law revisited

ESBFI

You have learned about Newton's Second Law of motion earlier in this chapter. Newton's Second Law describes the relationship between the motion of an object and the net force on the object. We said that the motion of an object, and therefore its momentum, can only change when a resultant force is acting on it. We can therefore say that because a net force causes an object to move, it also causes its momentum to change. We can now define Newton's Second Law of motion in terms of momentum.

> *DEFINITION: Newton's Second Law of Motion (N2)*
>
> The net or resultant force acting on an object is equal to the rate of change of momentum.

Mathematically, Newton's Second Law can be stated as:

$$F_{net} = \frac{\Delta p}{\Delta t}$$

Impulse

ESBFJ

Impulse is the product of the net force and the time interval for which the force acts. Impulse is defined as:

$$\text{Impulse} = F \cdot \Delta t \tag{12.8}$$

However, from Newton's Second Law, we know that

$$\begin{aligned} F &= \frac{\Delta p}{\Delta t} \\ \therefore \quad F \cdot \Delta t &= \Delta p \\ &= \text{Impulse} \end{aligned}$$

Therefore,

$$\text{Impulse} = \Delta p$$

Impulse is equal to the change in momentum of an object. From this equation we see, that for a given change in momentum, $F_{net}\Delta t$ is fixed. Thus, if F_{net} is reduced, Δt must be increased (i.e. a smaller resultant force must be applied for longer to bring about the same change in momentum). Alternatively if Δt is reduced (i.e. the resultant force is applied for a shorter period) then the resultant force must be increased to bring about the same change in momentum.

Example 31: *Impulse and Change in momentum*

QUESTION

A 150 N resultant force acts on a 300 kg trailer. Calculate how long it takes this force to change the trailer's velocity from 2 m·s^{-1}to 6 m·s^{-1}in the same direction. Assume that the forces acts to the right.

SOLUTION

Step 1 : ***Identify what information is given and what is asked for***

The question explicitly gives

- the trailer's mass as 300 kg,
- the trailer's initial velocity as 2 m·s^{-1}to the right,
- the trailer's final velocity as 6 m·s^{-1}to the right, and
- the resultant force acting on the object

all in the correct units!

We are asked to calculate the time taken Δt to accelerate the trailer from the 2 to 6 m·s^{-1}. From the Law of Momentum,

$$\begin{aligned} F_{net}\Delta t &= \Delta p \\ &= mv_f - mv_i \\ &= m(v_f - v_i). \end{aligned}$$

Thus we have everything we need to find Δt!

Step 2 : ***Choose a frame of reference***

Choose right as the positive direction.

Step 3 : ***Do the calculation and quote the final answer***

$$\begin{aligned} F_{net}\Delta t &= m(v_f - v_i) \\ (+150\,\mathrm{N})\Delta\mathrm{t} &= (300\,\mathrm{kg})((+6\,\mathrm{m}\cdot\mathrm{s}^{-1}) - (+2\,\mathrm{m}\cdot\mathrm{s}^{-1})) \\ (+150\,\mathrm{N})\Delta\mathrm{t} &= (300\,\mathrm{kg})(+4\,\mathrm{m}\cdot\mathrm{s}^{-1}) \\ \Delta t &= \frac{(300\,\mathrm{kg})(+4\,\mathrm{m}\cdot\mathrm{s}^{-1})}{+150\,\mathrm{N}} \\ \Delta t &= 8\,\mathrm{s} \end{aligned}$$

It takes 8 s for the force to change the object's velocity from 2 m·s^{-1}to the right to 6 m·s^{-1}to the right.

Example 32: *Impulsive cricketers!*

QUESTION

A cricket ball weighing 156 g is moving at 54 km·hr^{-1}towards a batsman. It is hit by the batsman back towards the bowler at 36 km·hr^{-1}. Calculate

1. *the ball's impulse, and*
2. *the average force exerted by the bat if the ball is in contact with the bat for 0,13 s.*

SOLUTION

Step 1 : ***Identify what information is given and what is asked for***

The question explicitly gives

- the ball's mass,
- the ball's initial velocity,
- the ball's final velocity, and
- the time of contact between bat and ball

We are asked to calculate the impulse

$$\text{Impulse} = \Delta p = F_{net}\Delta t$$

Since we do not have the force exerted by the bat on the ball (F_{net}), we have to calculate the impulse from the change in momentum of the ball. Now, since

$$\begin{aligned} \Delta p &= p_f - p_i \\ &= mv_f - mv_i, \end{aligned}$$

we need the ball's mass, initial velocity and final velocity, which we are given.

Step 2 : ***Convert to S.I. units***

Firstly let us change units for the mass

$$\begin{aligned} 1000\text{ g} &= 1\,\text{kg} \\ \text{So, } 1\text{ g} &= \frac{1}{1000}\text{ kg} \\ \therefore 156 \times 1\text{ g} &= 156 \times \frac{1}{1000}\text{ kg} \\ &= 0{,}156\text{ kg} \end{aligned}$$

Next we change units for the velocity

$$\begin{aligned} 1\text{ km}\cdot\text{h}^{-1} &= \frac{1000\,\text{m}}{3\,600\,\text{s}} \\ \therefore 54 \times 1\text{ km}\cdot\text{h}^{-1} &= 54 \times \frac{1\,000\,\text{m}}{3\,600\,\text{s}} \\ &= 15\,\text{m}\cdot\text{s}^{-1} \end{aligned}$$

Similarly, 36 km·hr^{-1} = 10 m·s^{-1}.

Step 3 : ***Choose a frame of reference***

Let us choose the direction from the batsman to the bowler as the positive direction. Then the initial velocity of the ball is v_i = -15 m·s^{-1}, while the final velocity of the ball is v_f = 10 m·s^{-1}.

Step 4 : ***Calculate the momentum***

Now we calculate the change in momentum,

$$\begin{aligned} p &= p_f - p_i \\ &= mv_f - mv_i \\ &= m(v_f - v_i) \\ &= (0{,}156\,\mathrm{kg})((+10\,\mathrm{m}\cdot\mathrm{s}^{-1}) - (-15\,\mathrm{m}\cdot\mathrm{s}^{-1})) \\ &= +3{,}9\,\mathrm{kg}\cdot\ \mathrm{m}\cdot\mathrm{s}^{-1} \\ &= 3{,}9\,\mathrm{kg}\cdot\ \mathrm{m}\cdot\mathrm{s}^{-1}\text{in the direction from batsman to bowler} \end{aligned}$$

Step 5 : ***Determine the impulse***

Finally since impulse is just the change in momentum of the ball,

$$\begin{aligned} \text{Impulse} &= \Delta p \\ &= 3{,}9\,\mathrm{kg}\cdot\ \mathrm{m}\cdot\mathrm{s}^{-1}\text{in the direction from batsman to bowler} \end{aligned}$$

Step 6 : ***Determine the average force exerted by the bat***

$$\text{Impulse} = F_{net}\Delta t = \Delta p$$

We are given Δt and we have calculated the impulse of the ball.

$$\begin{aligned} F_{net}\Delta t &= \text{Impulse} \\ F_{net}(0{,}13\,\mathrm{s}) &= +3{,}9\,\mathrm{N}\cdot\ \mathrm{s} \\ F_{net} &= \frac{+3{,}9\,\mathrm{N}\cdot\ \mathrm{s}}{0{,}13\,\mathrm{s}} \\ &= +30\,\mathrm{N} \\ &= 30\,\mathrm{N} \quad \text{in the direction from batsman to bowler} \end{aligned}$$

Exercise 12 - 9

1. Which one of the following is NOT a unit of impulse?
   (a) $N \cdot s$
   (b) $kg\cdot\ \mathrm{m}\cdot\mathrm{s}^{-1}$
   (c) $J\cdot\ \mathrm{m}\cdot\mathrm{s}^{-1}$
   (d) $J \cdot m^{-1} \cdot s$
2. A toy car of mass 1 kg moves eastwards with a speed of 2 m·s^{-1}. It collides head-on with a toy train. The train has a mass of 2 kg and is moving at a speed of 1,5 m·s^{-1}westwards. The car rebounds (bounces back) at 3,4 m·s^{-1}and the train rebounds at 1,2 m·s^{-1}.
   (a) Calculate the change in momentum for each toy.
   (b) Determine the impulse for each toy.
   (c) Determine the duration of the collision if the magnitude of the force exerted by each toy is 8 N.

3. A bullet of mass 20 g strikes a target at 300 m·s^{-1}and exits at 200 m·s^{-1}. The tip of the bullet takes 0,0001s to pass through the target. Determine:
   (a) the change of momentum of the bullet.
   (b) the impulse of the bullet.
   (c) the magnitude of the force experienced by the bullet.
4. A bullet of mass 20 g strikes a target at 300 m·s^{-1}. Determine under which circumstances the bullet experiences the greatest change in momentum, and hence impulse:
   (a) When the bullet exits the target at 200 m·s^{-1}.
   (b) When the bullet stops in the target.
   (c) When the bullet rebounds at 200 m·s^{-1}.
5. A ball with a mass of 200 g strikes a wall at right angles at a velocity of 12 m·s^{-1}and rebounds at a velocity of 9 m·s^{-1}.
   (a) Calculate the change in the momentum of the ball.
   (b) What is the impulse of the wall on the ball?
   (c) Calculate the magnitude of the force exerted by the wall on the ball if the collision takes 0,02s.
6. If the ball in the previous problem is replaced with a piece of clay of 200 g which is thrown against the wall with the same velocity, but then sticks to the wall, calculate:
   (a) The impulse of the clay on the wall.
   (b) The force exerted by the clay on the wall if it is in contact with the wall for 0,5 s before it comes to rest.

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(1.) 01x0 (2.) 01x1 (3.) 01x2 (4.) 01x3 (5.) 01x4 (6.) 01x5

Conservation of Momentum

ESBFK

In the absence of an external force acting on a system, momentum is conserved.

> *DEFINITION: Conservation of Linear Momentum*
>
> The total linear momentum of an isolated system is constant. An isolated system has no forces acting on it from the outside.

This means that in an isolated system the total momentum before a collision or explosion is equal to the total momentum after the collision or explosion.

Consider a simple collision of two billiard balls. The balls are rolling on a frictionless surface and the system is isolated. So, we can apply conservation of momentum. The first ball has a mass m_1 and an initial velocity v_{i1}. The second ball has a mass m_2 and moves towards the first ball with an initial velocity v_{i2}. This situation is shown in Figure 12.10.

Figure 12.10: Before the collision.

The total momentum of the system before the collision, p_i is:

$$p_i = m_1 v_{i1} + m_2 v_{i2}$$

After the two balls collide and move away they each have a different momentum. If the first ball has a final velocity of v_{f1} and the second ball has a final velocity of v_{f2} then we have the situation shown in Figure 12.11.

Figure 12.11: After the collision.

The total momentum of the system after the collision, p_f is:

$$p_f = m_1 v_{f1} + m_2 v_{f2}$$

This system of two balls is isolated since there are no external forces acting on the balls. Therefore, by the principle of conservation of linear momentum, the total momentum before the collision is equal to the total momentum after the collision. This gives the equation for the conservation of momentum in a collision of two objects,

$$p_i = p_f$$
$$m_1 v_{i1} + m_2 v_{i2} = m_1 v_{f1} + m_2 v_{f2}$$

m_1	: mass of object 1 (kg)
m_2	: mass of object 2 (kg)
v_{i1}	: initial velocity of object 1 (m·s^{-1} + direction)
v_{i2}	: initial velocity of object 2 (m·s^{-1}- direction)
v_{f1}	: final velocity of object 1 (m·s^{-1}- direction)
v_{f2}	: final velocity of object 2 (m·s^{-1} + direction)

This equation is always true - momentum is always conserved in collisions.

Example 33: *Conservation of Momentum 1*

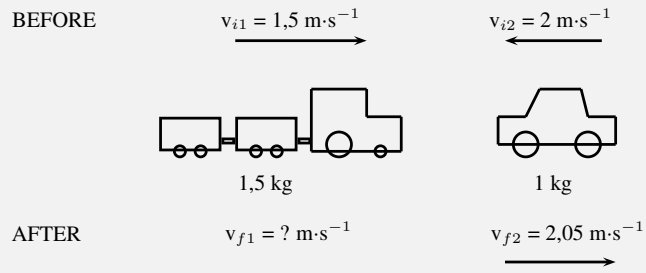
QUESTION

A toy car of mass 1 kg moves westwards with a speed of 2 m·s^{-1}. It collides head-on with a toy train. The train has a mass of 1,5 kg and is moving at a speed of 1,5 m·s^{-1}eastwards. If

the car rebounds at 2,05 m·s^{-1}, calculate the velocity of the train.

SOLUTION

Step 1 : ***Draw rough sketch of the situation***



Step 2 : ***Choose a frame of reference***
We will choose to the east as positive.

Step 3 : ***Apply the Law of Conservation of momentum***

$$\begin{aligned}
p_i &= p_f \\
m_1 v_{i1} + m_2 v_{i2} &= m_1 v_{f1} + m_2 v_{f2} \\
(1{,}5\,\mathrm{kg})(+1{,}5\,\mathrm{m\cdot s^{-1}}) + (2\,\mathrm{kg})(-2\,\mathrm{m\cdot s^{-1}}) &= (1{,}5\,\mathrm{kg})(v_{f1}) + (2\,\mathrm{kg})(2{,}05\,\mathrm{m\cdot s^{-1}}) \\
2{,}25\,\mathrm{kg\cdot\ m\cdot s^{-1}} - 4\,\mathrm{kg\cdot\ m\cdot s^{-1}} - 4{,}1\,\mathrm{kg\cdot\ m\cdot s^{-1}} &= (1{,}5\,\mathrm{kg})\ v_{f1} \\
5{,}85\,\mathrm{kg\cdot\ m\cdot s^{-1}} &= (1{,}5\,\mathrm{kg})\ v_{f1} \\
v_{f1} &= 3{,}9\,\mathrm{m\cdot s^{-1}}\text{eastwards}
\end{aligned}$$

Example 34: *Conservation of Momentum 2*

QUESTION

A helicopter flies at a speed of 275 m·s^{-1}. The pilot fires a missile forward out of a gun barrel at a speed of 700 m·s^{-1}. The respective masses of the helicopter and the missile are 5000 kg and 50 kg. Calculate the new speed of the helicopter immediately after the missile had been

fired.

SOLUTION

Step 1 : ***Draw rough sketch of the situation***

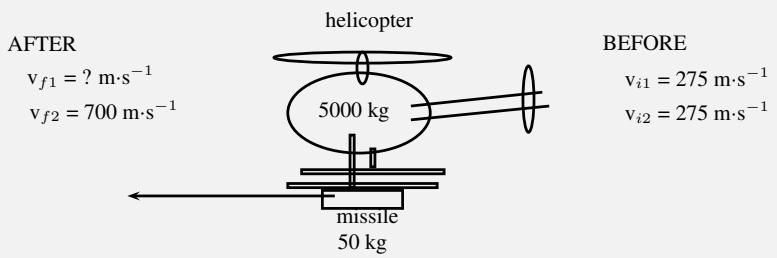


Figure 12.12: helicopter and missile

Step 2 : ***Analyse the question and list what is given***

m_1 = 5000 kg
m_2 = 50 kg
v_{i1} = v_{i2} = 275 m·s^{-1}
v_{f1} = ?
v_{f2} = 700 m·s^{-1}

Step 3 : ***Apply the Law of Conservation of momentum***

The helicopter and missile are connected initially and move at the same velocity. We will therefore combine their masses and change the momentum equation as follows:

$$\begin{aligned}
p_i &= p_f \\
(m_1 + m_2)v_i &= m_1 v_{f1} + m_2 v_{f2} \\
(5000\,\mathrm{kg} + 50\,\mathrm{kg})(275\,\mathrm{m}\cdot\mathrm{s}^{-1}) &= (5000\,\mathrm{kg})(v_{f1}) + (50\,\mathrm{kg})(700\,\mathrm{m}\cdot\mathrm{s}^{-1}) \\
1388750\,\mathrm{kg}\cdot\ \mathrm{m}\cdot\mathrm{s}^{-1} - 35000\,\mathrm{kg}\cdot\ \mathrm{m}\cdot\mathrm{s}^{-1} &= (5000\,\mathrm{kg})(v_{f1}) \\
v_{f1} &= 270{,}75\,\mathrm{m}\cdot\mathrm{s}^{-1}
\end{aligned}$$

Note that speed is asked and not velocity, therefore no direction is included in the answer.

Example 35: *Conservation of Momentum 3*

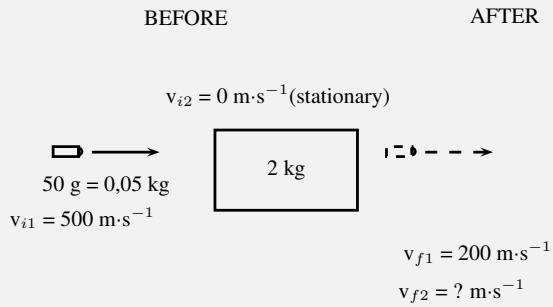
QUESTION

A bullet of mass 50 g travelling horizontally at 500 m·s^{-1}strikes a stationary wooden block of mass 2 kg resting on a smooth horizontal surface. The bullet goes through the block and comes out on the other side at 200 m·s^{-1}. Calculate the speed of the block after the bullet

has come out the other side.

SOLUTION

Step 1 : ***Draw rough sketch of the situation***



Step 2 : ***Choose a frame of reference***
We will choose to the right as positive.

Step 3 : ***Apply the Law of Conservation of momentum***

$$\begin{aligned}
p_i &= p_f \\
m_1 v_{i1} + m_2 v_{i2} &= m_1 v_{f1} + m_2 v_{f2} \\
(0{,}05\,\mathrm{kg})(+500\,\mathrm{m\cdot s^{-1}}) + (2\,\mathrm{kg})(0\,\mathrm{m\cdot s^{-1}}) &= (0{,}05\,\mathrm{kg})(+200\,\mathrm{m\cdot s^{-1}}) + (2\,\mathrm{kg})(v_{f2}) \\
25 + 0 - 10 &= 2\,v_{f2} \\
v_{f2} &= 7{,}5\,\mathrm{m\cdot s^{-1}} \text{in the same direction as the bullet}
\end{aligned}$$

Physics in Action: Impulse

ESBFL

A very important application of impulse is improving safety and reducing injuries. In many cases, an object needs to be brought to rest from a certain initial velocity. This means there is a certain specified change in momentum. If the time during which the momentum changes can be increased then the force that must be applied will be less and so it will cause less damage. This is the principle behind arrestor beds for trucks, airbags, and bending your knees when you jump off a chair and land on the ground.

Air-Bags in Motor Vehicles

Air bags are used in motor vehicles because they are able to reduce the effect of the force experienced by a person during an accident. Air bags extend the time required to stop the momentum of the driver and passenger. During a collision, the motion of the driver and passenger carries them towards the windshield. If they are stopped by a collision with the windshield, it would result in a large force exerted over a short time in order to bring them to a stop. If instead of hitting the windshield, the driver and passenger hit an air bag, then the time of the impact is increased. Increasing the time of the impact results in a decrease in the force.

Padding as Protection During Sports

The same principle explains why wicket keepers in cricket use padded gloves or why there are padded mats in gymnastics. In cricket, when the wicket keeper catches the ball, the padding is slightly compressible, thus reducing the effect of the force on the wicket keepers hands. Similarly, if a gymnast falls, the padding compresses and reduces the effect of the force on the gymnast's body.

Arrestor Beds for Trucks

An arrestor bed is a patch of ground that is softer than the road. Trucks use these when they have to make an emergency stop. When a trucks reaches an arrestor bed the time interval over which the momentum is changed is increased. This decreases the force and causes the truck to slow down.

Follow-Through in Sports

In sports where rackets and bats are used, like tennis, cricket, squash, badminton and baseball, the hitter is often encouraged to follow-through when striking the ball. High speed films of the collisions between bats/rackets and balls have shown that following through increases the time over which the collision between the racket/bat and ball occurs. This increase in the time of the collision causes an increase in the velocity change of the ball. This means that a hitter can cause the ball to leave the racket/bat faster by following through. In these sports, returning the ball with a higher velocity often increases the chances of success.

Crumple Zones in Cars

Another safety application of trying to reduce the force experienced is in crumple zones in cars. When two cars have a collision, two things can happen:

1. the cars bounce off each other, or
2. the cars crumple together.

Which situation is more dangerous for the occupants of the cars? When cars bounce off each other, or rebound, there is a larger change in momentum and therefore a larger impulse. A larger impulse means that a greater force is experienced by the occupants of the cars. When cars crumple together, there is a smaller change in momentum and therefore a smaller impulse. The smaller impulse means that the occupants of the cars experience a smaller force. Car manufacturers use this idea and design crumple zones into cars, such that the car has a greater chance of crumpling than rebounding in a collision. Also, when the car crumples, the change in the car's momentum happens over a longer time. Both these effects result in a smaller force on the occupants of the car, thereby increasing their chances of survival.

Activity:	*Egg Throw*

This activity demonstrates the effect of impulse and how it is used to improve safety. Have two learners hold up a bed sheet or large piece of fabric. Then toss an egg at the sheet. The egg should not break, because the collision between the egg and the bed sheet lasts over an extended period of time since the bed sheet has some give in it. By increasing the time of the

collision, the force of the impact is minimised. Take care to aim at the sheet, because if you miss the sheet, you will definitely break the egg and have to clean up the mess!

Exercise 12 - 10

1. A canon, mass 500 kg, fires a shell, mass 1 kg, horizontally to the right at 500 m·s^{-1}. What is the magnitude and direction of the initial recoil velocity of the canon?
2. A trolley of mass 1 kg is moving with a speed of 3 m·s^{-1}. A block of wood, mass 0,5 kg, is dropped vertically into the trolley. Immediately after the collision, the speed of the trolley and block is 2 m·s^{-1}. By way of calculation, show whether momentum is conserved in the collision.
3. A 7200 kg empty railway truck is stationary. A fertiliser firm loads 10800 kg fertiliser into the truck. A second, identical, empty truck is moving at 10 m·s^{-1}when it collides with the loaded truck.
   (a) If the empty truck stops completely immediately after the collision, use a conservation law to calculate the velocity of the loaded truck immediately after the collision.
   (b) Calculate the distance that the loaded truck moves after collision, if a constant frictional force of 24 kN acts on the truck.
4. A child drops a squash ball of mass 0,05 kg. The ball strikes the ground with a velocity of 4 m·s^{-1}and rebounds with a velocity of 3 m·s^{-1}. Does the law of conservation of momentum apply to this situation? Explain.
5. A bullet of mass 50 g travelling horizontally at 600 m·s^{-1}strikes a stationary wooden block of mass 2 kg resting on a smooth horizontal surface. The bullet gets stuck in the block.
   (a) Name and state the principle which can be applied to find the speed of the block-and-bullet system after the bullet entered the block.
   (b) Calculate the speed of the bullet-and-block system immediately after impact.
   (c) If the time of impact was 5 x 10^{-4} seconds, calculate the force that the bullet exerts on the block during impact.

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12.6 Torque and Levers

ESBFM

Torque

ESBFN

This chapter has dealt with forces and how they lead to motion in a straight line. In this section, we examine how forces lead to rotational motion.

When an object is fixed or supported at one point and a force acts on it a distance away from the support, it tends to make the object turn. The moment of force or *torque* (symbol, τ read *tau*) is defined

as the product of the distance from the support or pivot (r) and the component of force perpendicular to the object, $F_\perp$.

$$\tau = F_\perp \cdot r \tag{12.9}$$

Torque can be seen as a rotational force. The unit of torque is N·m and torque is a vector quantity. Some examples of where torque arises are shown in Figures 12.13, 12.14 and 12.15.

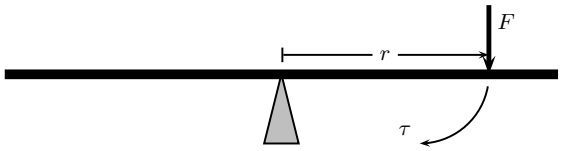


Figure 12.13: The force exerted on one side of a see-saw causes it to swing.

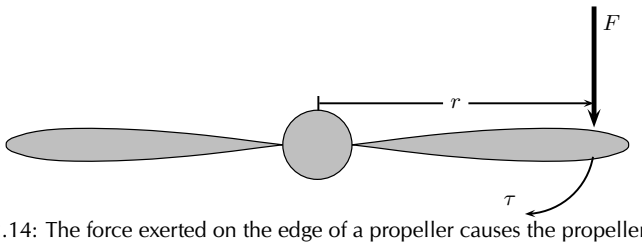


Figure 12.14: The force exerted on the edge of a propeller causes the propeller to spin.

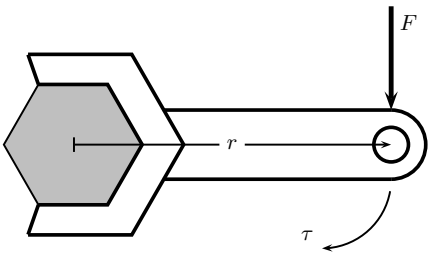


Figure 12.15: The force exerted on a spanner helps to loosen the bolt.

Tip

Loosening a bolt: if you are trying to loosen (or tighten) a bolt, apply the force on the spanner further away from the bolt, as this results in a greater torque to the bolt making it easier to loosen.

For example in Figure 12.15, if a force F of 10 N is applied perpendicularly to the spanner at a distance r of 0,3 m from the centre of the bolt, then the torque applied to the bolt is:

$$\begin{aligned} \tau &= F_\perp \cdot r \\ &= (10\ \mathrm{N})(0{,}3\,\mathrm{m}) \\ &= 3\,\mathrm{N}\cdot\mathrm{m} \end{aligned}$$

If the force of 10 N is now applied at a distance of 0,15 m from the centre of the bolt, then the torque is:

$$\begin{aligned} \tau &= F_\perp \cdot r \\ &= (10\ \mathrm{N})(0{,}15\,\mathrm{m}) \\ &= 1{,}5\,\mathrm{N}\cdot\mathrm{m} \end{aligned}$$

This shows that there is less torque when the force is applied closer to the bolt than further away.

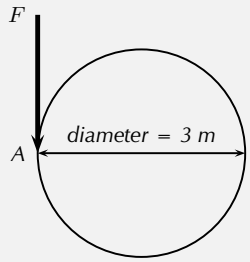
Tip

Any component of a force exerted parallel to an object will not cause the object to turn. Only perpendicular components cause turning.

Example 36: *Merry-go-round*

QUESTION

Several children are playing in the park. One child pushes the merry-go-round with a force of 50 N. The diameter of the merry-go-round is 3,0 m. What torque does the child apply if the force is applied perpendicularly at point A?



SOLUTION

Step 1 : ***Identify what has been given***

The following has been given:

- the force applied, F = 50 N
- the diameter of the merry-go-round, $2r$ = 3 m, therefore r = 1,5 m.

The quantities are in SI units.

Step 2 : ***Decide how to approach the problem***

We are required to determine the torque applied to the merry-go-round. We can do this by using:

$$\tau = F_{\perp} \cdot r$$

We are given $F_{\perp}$ and we are given the diameter of the merry-go-round. Therefore, r = 1,5 m.

Step 3 : ***Solve the problem***

$$\begin{aligned} \tau &= F_{\perp} \cdot r \\ &= (50\,\mathrm{N})(1{,}5\,\mathrm{m}) \\ &= 75\,\mathrm{N} \cdot \mathrm{m} \end{aligned}$$

Step 4 : ***Write the final answer***

75 $\mathrm{N} \cdot \mathrm{m}$ of torque is applied to the merry-go-round.

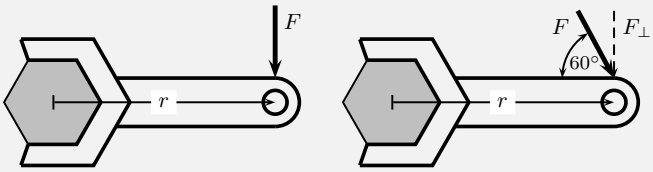
Tip

Torques: the direction of a torque is either clockwise or anticlockwise. When torques are added, choose one direction as positive and the opposite direction as negative. If equal clockwise and anticlockwise torques are applied to an object, they will cancel out and there will be no net turning effect.

Example 37: *Flat tyre*

QUESTION

Kevin is helping his dad replace the flat tyre on the car. Kevin has been asked to undo all the wheel nuts. Kevin holds the spanner at the same distance for all nuts, but applies the force at two angles (90° and 60°). If Kevin applies a force of 60 N, at a distance of 0,3 m away from the nut, which angle is the best to use? Prove your answer by means of calculations.



SOLUTION

Step 1 : ***Identify what has been given***

The following has been given:

- the force applied, F = 60 N
- the angles at which the force is applied, $\theta = 90°$ and $\theta = 60°$
- the distance from the centre of the nut at which the force is applied, r = 0,3 m

The quantities are in SI units.

Step 2 : ***Decide how to approach the problem***

We are required to determine which angle is more better to use. This means that we must find which angle gives the higher torque. We can use

$$\tau = F_{\perp} \cdot r$$

to determine the torque. We are given F for each situation. $F_{\perp} = F \sin\theta$ and we are given θ. We are also given the distance away from the nut, at which the force is applied.

Step 3 : ***Solve the problem for*** $\theta = 90°$

$F_{\perp} = F$

$$\begin{aligned} \tau &= F_{\perp} \cdot r \\ &= (60\,\mathrm{N})(0{,}3\,\mathrm{m}) \\ &= 18\,\mathrm{N} \cdot \mathrm{m} \end{aligned}$$

Step 4 : ***Solve the problem for*** $\theta = 60°$

$$\begin{aligned} \tau &= F_{\perp} \cdot r \\ &= F \sin\theta \cdot r \\ &= (60\,\mathrm{N}) \sin(\theta)(0{,}3\,\mathrm{m}) \\ &= 15{,}6\,\mathrm{N} \cdot \mathrm{m} \end{aligned}$$

Step 5 : ***Write the final answer***

The torque from the perpendicular force is greater than the torque from the force applied at $60°$. Therefore, the best angle is $90°$.

Mechanical Advantage and Levers

ESBFO

We can use our knowledge about the moments of forces (torque) to determine whether situations are balanced. For example two mass pieces are placed on a seesaw as shown in Figure 12.16. The one mass is 3 kg and the other is 6 kg. The masses are placed at distances of 2 m and 1 m (respectively) from the pivot. By looking at the clockwise and anti-clockwise moments, we can determine whether the seesaw will pivot (move) or not. If the sum of the clockwise and anti-clockwise moments is zero, the seesaw is in equilibrium (i.e. balanced).

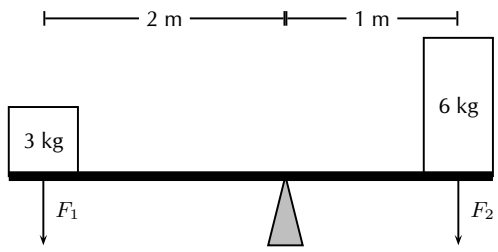


Figure 12.16: The moments of force are balanced.

The clockwise moment can be calculated as follows:

$$\begin{aligned}\tau_1 &= F_\perp \cdot r \\ \tau_1 &= (6\,\mathrm{kg})(9{,}8\,\mathrm{m}\cdot\mathrm{s}^{-2})(1m) \\ \tau_1 &= 58{,}8N \cdot m \text{ clockwise}\end{aligned}$$

The anti-clockwise moment can be calculated as follows:

$$\begin{aligned}\tau_2 &= F_\perp \cdot r \\ \tau_2 &= (3\,\mathrm{kg})(9{,}8\,\mathrm{m}\cdot\mathrm{s}^{-2})(2m) \\ \tau_2 &= 58{,}8N \cdot m \text{ anti-clockwise}\end{aligned}$$

The sum of the moments of force will be zero:

The resultant moment is zero as the clockwise and anti-clockwise moments of force are in opposite directions and therefore cancel each other.

As we see in Figure 12.16, we can use different distances away from a pivot to balance two different forces. This principle is applied to a lever to make lifting a heavy object much easier.

DEFINITION: Lever

A lever is a rigid object that is used with an appropriate fulcrum or pivot point to multiply the mechanical force that can be applied to another object.

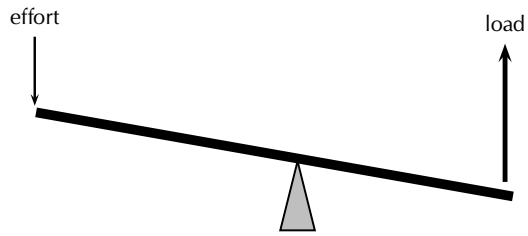


Figure 12.17: A lever is used to put in a small effort to get out a large load.

FACT

Archimedes reputedly said: *Give me a lever long enough and a fulcrum on which to place it, and I shall move the world.*

The concept of getting out more than the effort is termed mechanical advantage, and is one example of the principle of moments. The lever allows one to apply a smaller force over a greater distance. For instance to lift a certain unit of weight with a lever with an effort of half a unit we need a distance from the fulcrum in the effort's side to be twice the distance of the weight's side. It also means that to lift the weight 1 meter we need to push the lever for 2 meters. The amount of work done is always the same and independent of the dimensions of the lever (in an ideal lever). The lever only allows to trade force for distance.

Ideally, this means that the mechanical advantage of a system is the ratio of the force that performs the work (output or load) to the applied force (input or effort), assuming there is no friction in the system. In reality, the mechanical advantage will be less than the ideal value by an amount determined by the amount of friction.

$$\text{mechanical advantage} = \frac{\text{load}}{\text{effort}}$$

For example, you want to raise an object of mass 100 kg. If the pivot is placed as shown in Figure 12.18, what is the mechanical advantage of the lever?

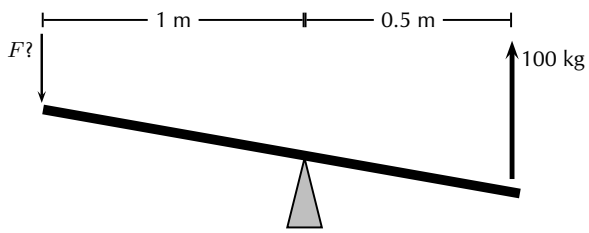


Figure 12.18: A lever is used to put in a small effort to get out a large load.

Tip

Effort is the input force and load is the output force.

In order to calculate mechanical advantage, we need to determine the load and effort.

The load is easy to calculate, it is simply the weight of the 100 kg object.

$$F_{load} = m \cdot g = 100\,\text{kg} \cdot 9{,}8\,\text{m} \cdot \text{s}^{-2} = 980\,\text{N}$$

The effort is found by balancing torques.

$$\begin{aligned} F_{load} \cdot r_{load} &= F_{effort} \cdot r_{effort} \\ 980\,\mathrm{N} \cdot 0.5\,\mathrm{m} &= F_{effort} \cdot 1\,\mathrm{m} \\ F_{effort} &= \frac{980\,\mathrm{N} \cdot 0.5\,\mathrm{m}}{1\,\mathrm{m}} \\ &= 490\,\mathrm{N} \end{aligned}$$

The mechanical advantage is:

$$\begin{aligned} \text{mechanical advantage} &= \frac{\text{load}}{\text{effort}} \\ &= \frac{980\,\mathrm{N}}{490\,\mathrm{N}} \\ &= 2 \end{aligned}$$

Since mechanical advantage is a ratio, it does not have any units.

Extension:	*Pulleys*

Pulleys change the direction of a tension force on a flexible material, e.g. a rope or cable. In addition, pulleys can be "added together" to create mechanical advantage, by having the flexible material looped over several pulleys in turn. More loops and pulleys increases the mechanical advantage.

Classes of levers

ESBFP

Class 1 levers
In a class 1 lever the fulcrum is between the effort and the load. Examples of class 1 levers are the seesaw, crowbar and equal-arm balance. The mechanical advantage of a class 1 lever can be increased by moving the fulcrum closer to the load.

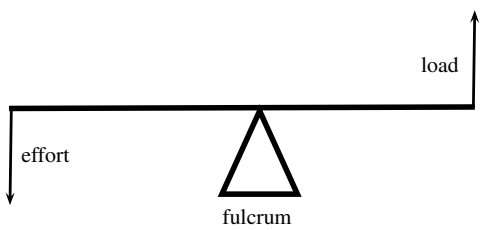


Figure 12.19: Class 1 levers

Class 2 levers
In class 2 levers the fulcrum is at the one end of the bar, with the load closer to the fulcrum and the effort on the other end of bar. The mechanical advantage of this type of lever can be increased by increasing the length of the bar. A bottle opener or wheel barrow are examples of class 2 levers.

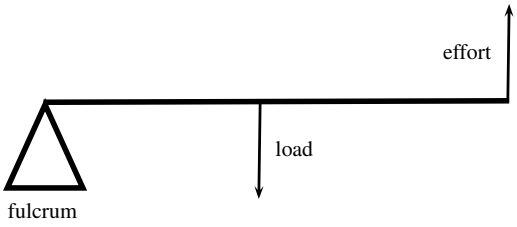


Figure 12.20: Class 2 levers

Class 3 levers
In class 3 levers the fulcrum is also at the end of the bar, but the effort is between the fulcrum and the load. An example of this type of lever is the human arm.

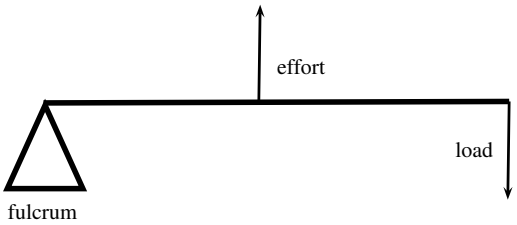
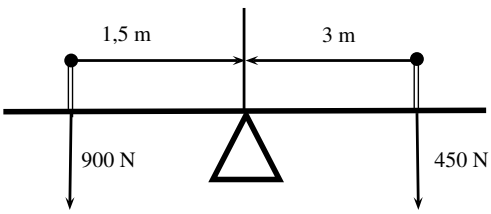


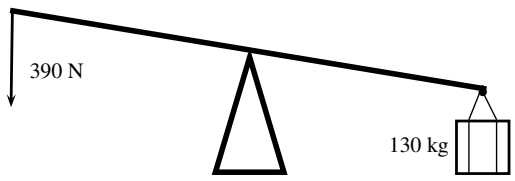
Figure 12.21: Class 3 levers

Exercise 12 - 11

1. Riyaad applies a force of 120 N on a spanner to undo a nut.
   (a) Calculate the moment of the force if he applies the force 0,15 m from the bolt.
   (b) The nut does not turn, so Riyaad moves his hand to the end of the spanner and applies the same force 0,2 m away from the bolt. Now the nut begins to move. Calculate the force. Is it bigger or smaller than before?
   (c) Once the nuts starts to turn, the moment needed to turn it is less than it was to start it turning. It is now 20 N·m. Calculate the new moment of force that Riyaad now needs to apply 0,2 m away from the nut.
2. Calculate the clockwise and anticlockwise moments of force in the figure below to see if the see-saw is balanced.



3. Jeffrey uses a force of 390 N to lift a load of 130 kg.



(a) Calculate the mechanical advantage of the lever that he is using.
(b) What type of lever is he using? Give a reason for your answer.
(c) If the force is applied 1 m from the pivot, calculate the maximum distance between the pivot and the load.

4. A crowbar is used to lift a box of weight 400 N. The box is placed 75 cm from the pivot. A crow bar is a class 1 lever.
   (a) Why is a crowbar a class 1 lever? Draw a diagram to explain your answer.
   (b) What force F needs to be applied at a distance of 1,25 m from the pivot to balance the crowbar?
   (c) If force F was applied at a distance of 2 m, what would the magnitude of F be?
5. A wheelbarrow is used to carry a load of 200 N. The load is 40 cm from the pivot and the force F is applied at a distance of 1,2 m from the pivot.
   (a) What type of lever is a wheelbarrow?
   (b) Calculate the force F that needs to be applied to lift the load.
6. The bolts holding a car wheel in place is tightened to a torque of 90 N · m. The mechanic has two spanners to undo the bolts, one with a length of 20 cm and one with a length of 30 cm. Which spanner should he use? Give a reason for your answer by showing calculations and explaining them.

More practice video solutions or help at www.everythingscience.co.za

(1.) 01xb (2.) 01xc (3.) 01xd (4.) 01xe (5.) 01xf (6.) 01xg

Chapter 12 — Summary

See the summary presentation (Presentation: VPkkv at www.everythingscience.co.za)

Newton's First Law Every object will remain at rest or in uniform motion in a straight line unless it is made to change its state by the action of an *unbalanced force*.

Newton's Second Law The resultant force acting on a body will cause the body to accelerate in the direction of the resultant force The acceleration of the body is directly proportional to the magnitude of the resultant force and inversely proportional to the mass of the object.

Newton's Third Law If body A exerts a force on body B then body B will exert an equal but opposite force on body A.

Newton's Law of Universal Gravitation Every body in the universe exerts a force on every other body. The force is directly proportional to the product of the masses of the bodies and inversely proportional to the square of the distance between them.

Equilibrium Objects at rest or moving with constant velocity are in *equilibrium* and have a *zero resultant force*.

Equilibrant The *equilibrant* of any number of forces is the single force required to produce equilibrium.

Triangle Law for Forces in Equilibrium Three forces in equilibrium can be represented in magnitude and direction by the three sides of a triangle taken in order.

Momentum The *momentum* of an object is defined as its mass multiplied by its velocity.

Momentum of a System The *total momentum of a system* is the sum of the momenta of each of the objects in the system.

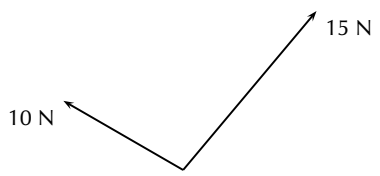
Principle of Conservation of Linear Momentum: 'The total linear momentum of an isolated system is constant' or 'In an isolated system the total momentum before a collision (or explosion) is equal to the total momentum after the collision (or explosion)'.

Law of Momentum: The applied resultant force acting on an object is equal to the rate of change of the object's momentum and this force is in the direction of the change in momentum.

Chapter 12 End of Chapter Exercises

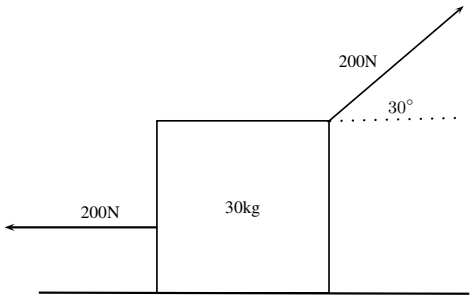
Forces and Newton's Laws

1. [SC 2003/11] A constant, resultant force acts on a body which can move freely in a straight line. Which physical quantity will remain constant?
   (a) acceleration
   (b) velocity
   (c) momentum
   (d) kinetic energy
2. [SC 2005/11 SG1] Two forces, 10 N and 15 N, act at an angle at the same point.

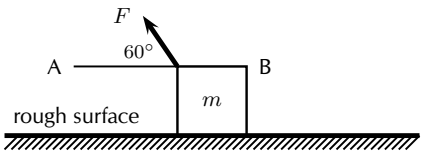


   Which of the following **cannot** be the resultant of these two forces?
   (a) 2 N
   (b) 5 N
   (c) 8 N
   (d) 20 N
3. A concrete block weighing 250 N is at rest on an inclined surface at an angle of 20°. The magnitude of the normal force, in newtons, is
   (a) 250
   (b) 250 cos 20°
   (c) 250 sin 20°
   (d) 2500 cos 20°

4. A 30 kg box sits on a flat frictionless surface. Two forces of 200 N each are applied to the box as shown in the diagram. Which statement best describes the motion of the box?
   (a) The box is lifted off the surface.
   (b) The box moves to the right.
   (c) The box does not move.
   (d) The box moves to the left.



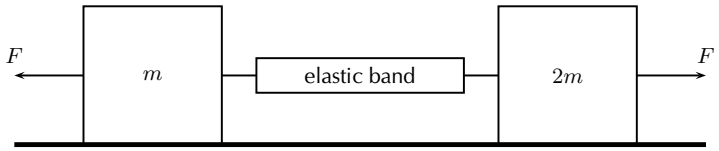
5. A concrete block weighing 200 N is at rest on an inclined surface at an angle of 20°. The normal reaction, in newtons, is
   (a) 200
   (b) 200 cos 20°
   (c) 200 sin 20°
   (d) 2000 cos 20°
6. [SC 2003/11]A box, mass m, is at rest on a rough horizontal surface. A force of constant magnitude F is then applied on the box at an angle of 60°to the horizontal, as shown.



   If the box has a uniform horizontal acceleration of magnitude, a, the frictional force acting on the box is . . .
   (a) $F\cos 60° - ma$ in the direction of A
   (b) $F\cos 60° - ma$ in the direction of B
   (c) $F\sin 60° - ma$ in the direction of A
   (d) $F\sin 60° - ma$ in the direction of B
7. [SC 2002/11 SG] Thabo stands in a train carriage which is moving eastwards. The train suddenly brakes. Thabo continues to move eastwards due to the effect of:
   (a) his inertia.
   (b) the inertia of the train.
   (c) the braking force on him.
   (d) a resultant force acting on him.
8. [SC 2002/11 HG1] A body slides down a frictionless inclined plane. Which one of the following physical quantities will remain constant throughout the motion?
   (a) velocity
   (b) momentum
   (c) acceleration
   (d) kinetic energy

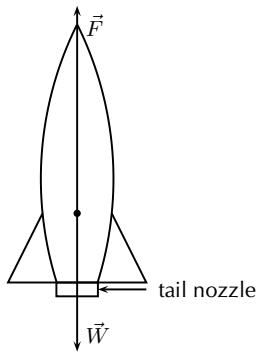
9. [SC 2002/11 HG1] A body moving at a *CONSTANT VELOCITY* on a horizontal plane, has a number of unequal forces acting on it. Which one of the following statements is TRUE?
   (a) At least two of the forces must be acting in the same direction.
   (b) The resultant of the forces is zero.
   (c) Friction between the body and the plane causes a resultant force.
   (d) The vector sum of the forces causes a resultant force which acts in the direction of motion.

10. [IEB 2005/11 HG] Two masses of m and $2m$ respectively are connected by an elastic band on a frictionless surface. The masses are pulled in opposite directions by two forces each of magnitude F, stretching the elastic band and holding the masses stationary.



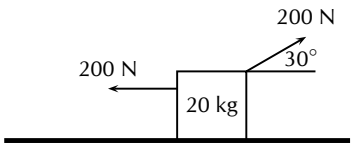
Which of the following gives the magnitude of the tension in the elastic band?
   (a) zero
   (b) $\frac{1}{2}F$
   (c) F
   (d) $2F$

11. [IEB 2005/11 HG] A rocket takes off from its launching pad, accelerating up into the air.



The rocket accelerates because the magnitude of the upward force, F is greater than the magnitude of the rocket's weight, W. Which of the following statements **best** describes how force F arises?
   (a) F is the force of the air acting on the base of the rocket.
   (b) F is the force of the rocket's gas jet *pushing down* on the air.
   (c) F is the force of the rocket's gas jet *pushing down* on the ground.
   (d) F is the reaction to the force that the rocket exerts on the gases which escape out through the tail nozzle.

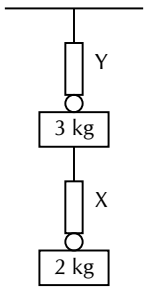
12. [SC 2001/11 HG1] A box of mass 20 kg rests on a smooth horizontal surface. What will happen to the box if two forces each of magnitude 200 N are applied simultaneously to the box as shown in the diagram.



The box will:

(a) be lifted off the surface.
(b) move to the left.
(c) move to the right.
(d) remain at rest.

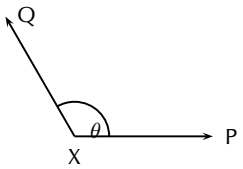
13. [SC 2001/11 HG1] A 2 kg mass is suspended from spring balance X, while a 3 kg mass is suspended from spring balance Y. Balance X is in turn suspended from the 3 kg mass. Ignore the weights of the two spring balances.



The readings (in N) on balances X and Y are as follows:

	X	**Y**
(A)	20	30
(B)	20	50
(C)	25	25
(D)	50	50

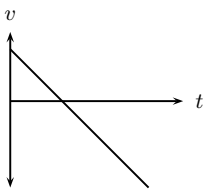
14. [SC 2002/03 HG1] P and Q are two forces of equal magnitude applied simultaneously to a body at X.



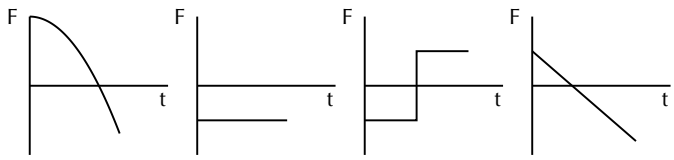
As the angle θ between the forces is **decreased** from 180° to 0°, the magnitude of the resultant of the two forces will

(a) initially increase and then decrease.
(b) initially decrease and then increase.
(c) increase only.
(d) decrease only.

15. [SC 2002/03 HG1] The graph below shows the velocity-time graph for a moving object:

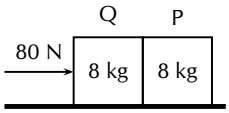


Which of the following graphs could best represent the relationship between the resultant force applied to the object and time?



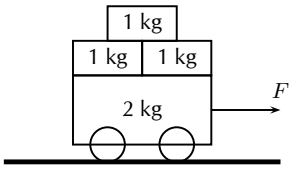
(a) (b) (c) (d)

16. [SC 2002/03 HG1] Two blocks each of mass 8 kg are in contact with each other and are accelerated along a frictionless surface by a force of 80 N as shown in the diagram. The force which block Q will exert on block P is equal to ...



(a) 0 N
(b) 40 N
(c) 60 N
(d) 80 N

17. [SC 2002/03 HG1] Three 1 kg mass pieces are placed on top of a 2 kg trolley. When a force of magnitude F is applied to the trolley, it experiences an acceleration a.



If one of the 1 kg mass pieces falls off while F is still being applied, the trolley will accelerate at ...

(a) $\frac{1}{5}a$
(b) $\frac{4}{5}a$
(c) $\frac{5}{4}a$
(d) $5a$

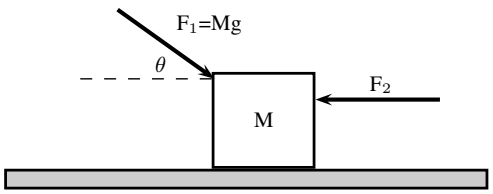
18. [IEB 2004/11 HG1] A car moves along a horizontal road at constant velocity. Which of the following statements is true?

(a) The car is not in equilibrium.
(b) There are no forces acting on the car.
(c) There is zero resultant force.
(d) There is no frictional force.

19. [IEB 2004/11 HG1] A crane lifts a load vertically upwards at constant speed. The upward force exerted on the load is F. Which of the following statements is correct?

(a) The acceleration of the load is 9,8 m.s^{-2} downwards.
(b) The resultant force on the load is F.
(c) The load has a weight equal in magnitude to F.
(d) The forces of the crane on the load, and the weight of the load, are an example of a Newton's third law 'action-reaction' pair.

20. [IEB 2004/11 HG1] A body of mass M is at rest on a smooth horizontal surface with two forces applied to it as in the diagram below. Force F_1 is equal to Mg. The force F_1 is applied to the right at an angle θ to the horizontal, and a force of F_2 is applied horizontally to the left.



How is the body affected when the angle θ is increased?

(a) It remains at rest.

(b) It lifts up off the surface, and accelerates towards the right.

(c) It lifts up off the surface, and accelerates towards the left.

(d) It accelerates to the left, moving along the smooth horizontal surface.

21. [IEB 2003/11 HG1] Which of the following statements correctly explains why a passenger in a car, who is not restrained by the seat belt, continues to move forward when the brakes are applied suddenly?

    (a) The braking force applied to the car exerts an equal and opposite force on the passenger.

    (b) A forward force (called inertia) acts on the passenger.

    (c) A resultant forward force acts on the passenger.

    (d) A zero resultant force acts on the passenger.

22. [IEB 2004/11 HG1]

    A rocket (mass 20 000 kg) accelerates from rest to 40 m·s^{-1}in the first 1,6 seconds of its journey upwards into space.
    The rocket's propulsion system consists of exhaust gases, which are pushed out of an outlet at its base.

    (a) Explain, with reference to the appropriate law of Newton, how the escaping exhaust gases exert an upwards force (thrust) on the rocket.

    (b) What is the magnitude of the total thrust exerted on the rocket during the first 1,6 s?

    (c) An astronaut of mass 80 kg is carried in the space capsule. Determine the resultant force acting on him during the first 1,6 s.

    (d) Explain why the astronaut, seated in his chair, feels "heavier" while the rocket is launched.

23. [IEB 2003/11 HG1 - Sports Car]

    (a) State Newton's Second Law of Motion.

    (b) A sports car (mass 1 000 kg) is able to accelerate uniformly from rest to 30 m·s^{-1}in a minimum time of 6 s.

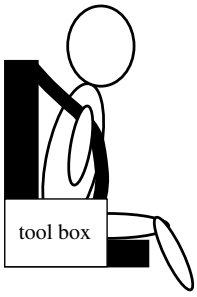
        i. Calculate the magnitude of the acceleration of the car.

        ii. What is the magnitude of the resultant force acting on the car during these 6 s?

    (c) The magnitude of the force that the wheels of the vehicle exert on the road surface as it accelerates is 7500 N. What is the magnitude of the retarding forces acting on this car?

    (d) By reference to a suitable Law of Motion, explain why a headrest is important in a car with such a rapid acceleration.

24. [IEB 2005/11 HG1] A child (mass 18 kg) is strapped in his car seat as the car moves to the right at constant velocity along a straight level road. A tool box rests on the seat beside him.



The driver brakes suddenly, bringing the car rapidly to a halt. There is negligible friction between the car seat and the box.

(a) Draw a labelled free-body diagram of **the forces acting on the child** during the time that the car is being braked.

(b) Draw a labelled free-body diagram of **the forces acting on the box** during the time that the car is being braked.

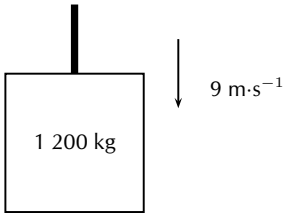
(c) What is the rate of change of the child's momentum as the car is braked to a standstill from a speed of 72 km.h^{-1} in 4 s.

Modern cars are designed with safety features (besides seat belts) to protect drivers and passengers during collisions e.g. the crumple zones on the car's body. Rather than remaining rigid during a collision, the crumple zones allow the car's body to collapse steadily.

(d) State Newton's second law of motion.

(e) Explain how the crumple zone on a car reduces the force of impact on it during a collision.

25. [SC 2003/11 HG1]The total mass of a lift together with its load is 1 200 kg. It is moving downwards at a constant velocity of 9 m·s^{-1}.



(a) What will be the magnitude of the force exerted by the cable on the lift while it is moving downwards at constant velocity? Give an explanation for your answer. *The lift is now uniformly brought to rest over a distance of 18 m.*

(b) Calculate the magnitude of the acceleration of the lift.

(c) Calculate the magnitude of the force exerted by the cable while the lift is being brought to rest.

26. A driving force of 800 N acts on a car of mass 600 kg.

(a) Calculate the car's acceleration.

(b) Calculate the car's speed after 20 s.

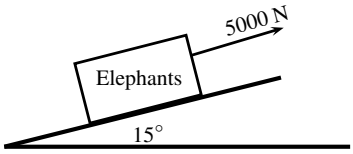
(c) Calculate the new acceleration if a frictional force of 50 N starts to act on the car after 20 s.

(d) Calculate the speed of the car after another 20 s (i.e. a total of 40 s after the start).

27. [IEB 2002/11 HG1 - A Crate on an Inclined Plane]

Elephants are being moved from the Kruger National Park to the Eastern Cape. They are loaded into crates that are pulled up a ramp (an inclined plane) on frictionless rollers.

The diagram shows a crate being held stationary on the ramp by means of a rope parallel to the ramp. The tension in the rope is 5 000 N.



(a) Explain how one can deduce the following: "The forces acting on the crate are in equilibrium".
(b) Draw a labelled free-body diagram of the forces acting on the crane and elephant. (Regard the crate and elephant as one object, and represent them as a dot. Also show the relevant angles between the forces.)
(c) The crate has a mass of 800 kg. Determine the mass of the elephant.
(d) The crate is now pulled up the ramp at a constant speed. How does the crate being pulled up the ramp at a constant speed affect the forces acting on the crate and elephant? Justify your answer, mentioning any law or principle that applies to this situation.

28. [IEB 2002/11 HG1 - Car in Tow]
Car A is towing Car B with a light tow rope. The cars move along a straight, horizontal road.
(a) Write down a statement of Newton's Second Law of Motion (in words).
(b) As they start off, Car A exerts a forwards force of 600 N at its end of the tow rope. The force of friction on Car B when it starts to move is 200 N. The mass of Car B is 1 200 kg. Calculate the acceleration of Car B.
(c) After a while, the cars travel at constant velocity. The force exerted on the tow rope is now 300 N while the force of friction on Car B increases. What is the magnitude and direction of the force of friction on Car B now?
(d) Towing with a rope is very dangerous. A solid bar should be used in preference to a tow rope. This is especially true should Car A suddenly apply brakes. What would be the advantage of the solid bar over the tow rope in such a situation?
(e) The mass of Car A is also 1 200 kg. Car A and Car B are now joined by a solid tow bar and the total braking force is 9 600 N. Over what distance could the cars stop from a velocity of 20 $m{\cdot}s^{-1}$?

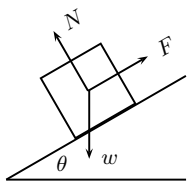
29. [IEB 2001/11 HG1] - **Testing the Brakes of a Car**

A braking test is carried out on a car travelling at 20 $m{\cdot}s^{-1}$. A braking distance of 30 m is measured when a braking force of 6 000 N is applied to stop the car.
(a) Calculate the acceleration of the car when a braking force of 6 000 N is applied.
(b) **Show** that the mass of this car is 900 kg.
(c) How long (in s) does it take for this car to stop from 20 $m{\cdot}s^{-1}$under the braking action described above?
(d) A trailer of mass 600 kg is attached to the car and the braking test is repeated from 20 $m{\cdot}s^{-1}$using the same braking force of 6 000 N. How much longer will it take to stop the car with the trailer in tow?

30. [IEB 2001/11 HG1] A rocket takes off from its launching pad, accelerating up into the air. Which of the following statements best describes the reason for the upward acceleration of the rocket?
(a) The force that the atmosphere (air) exerts underneath the rocket is greater than the weight of the rocket.
(b) The force that the ground exerts on the rocket is greater than the weight of the rocket.
(c) The force that the rocket exerts on the escaping gases is less than the weight of the rocket.

(d) The force that the escaping gases exerts on the rocket is greater than the weight of the rocket.

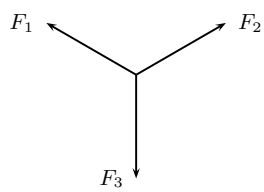
31. [IEB 2005/11 HG] A box is held stationary on a smooth plane that is inclined at angle θ to the horizontal.



F is the force exerted by a rope on the box. w is the weight of the box and N is the normal force of the plane on the box. Which of the following statements is correct?

(a) $\tan\theta = \frac{F}{w}$
(b) $\tan\theta = \frac{F}{N}$
(c) $\cos\theta = \frac{F}{w}$
(d) $\sin\theta = \frac{N}{w}$

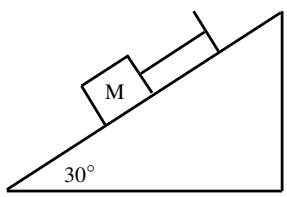
32. [SC 2001/11 HG1] As a result of three forces F_1, F_2 and F_3 acting on it, an object at point P is in equilibrium.



Which of the following statements is **not true** with reference to the three forces?

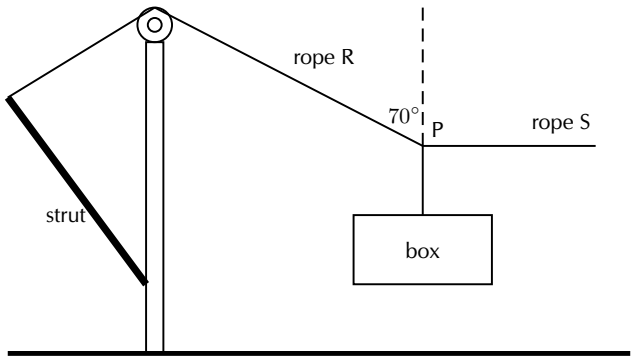
(a) The resultant of forces F_1, F_2 and F_3 is zero.
(b) Forces F_1, F_2 and F_3 lie in the same plane.
(c) Forces F_3 is the resultant of forces F_1 and F_2.
(d) The sum of the components of all the forces in any chosen direction is zero.

33. A block of mass M is held stationary by a rope of negligible mass. The block rests on a frictionless plane which is inclined at $30°$ to the horizontal.



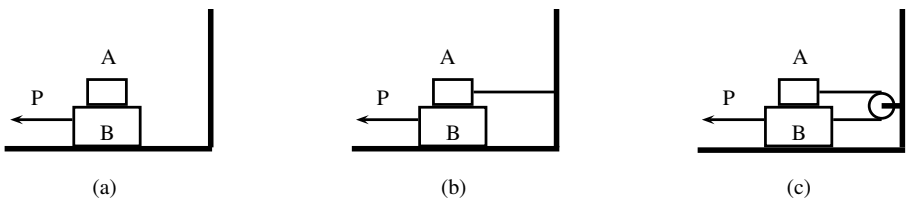
(a) Draw a labelled force diagram which shows all the forces acting on the block.
(b) Resolve the force due to gravity into components that are parallel and perpendicular to the plane.
(c) Calculate the weight of the block when the force in the rope is 8N.

34. [SC 2003/11] A heavy box, mass m, is lifted by means of a rope R which passes over a pulley fixed to a pole. A second rope S, tied to rope R at point P, exerts a horizontal force and pulls the box to the right. After lifting the box to a certain height, the box is held stationary as shown in the sketch below. Ignore the masses of the ropes. The tension in rope R is 5 850 N.



(a) Draw a diagram (with labels) of all the forces acting at the point P, when P is in equilibrium.
(b) By resolving the force exerted by rope R into components, calculate the . . .
  i. magnitude of the force exerted by rope S.
  ii. mass, m, of the box.
(c) Will the tension in rope R, increase, decrease or remain the same if rope S is pulled further to the right (the length of rope R remains the same)? Give a reason for your choice.

35. A tow truck attempts to tow a broken down car of mass 400 kg. The coefficient of static friction is 0,60 and the coefficient of kinetic (dynamic) friction is 0,4. A rope connects the tow truck to the car. Calculate the force required:
  (a) to just move the car if the rope is parallel to the road.
  (b) to keep the car moving at constant speed if the rope is parallel to the road.
  (c) to just move the car if the rope makes an angle of 30° to the road.
  (d) to keep the car moving at constant speed if the rope makes an angle of 30° to the road.
36. A crate weighing 2000 N is to be lowered at constant speed down skids 4 m long, from a truck 2 m high.
  (a) If the coefficient of sliding friction between the crate and the skids is 0,30, will the crate need to be pulled down or held back?
  (b) How great is the force needed parallel to the skids?
37. Block A in the figures below weighs 4 N and block B weighs 8 N. The coefficient of kinetic friction between all surfaces is 0,25. Find the force P necessary to drag block B to the left at constant speed if
  (a) A rests on B and moves with it
  (b) A is held at rest
  (c) A and B are connected by a light flexible cord passing around a fixed frictionless pulley



(a) (b) (c)

Gravitation

1. [SC 2003/11]An object attracts another with a gravitational force F. If the distance between the centres of the two objects is now decreased to a third ($\frac{1}{3}$) of the original distance, the force of attraction that the one object would exert on the other would become. . .

(a) $\frac{1}{9}F$
(b) $\frac{1}{3}F$
(c) $3F$
(d) $9F$

2. [SC 2003/11] An object is dropped from a height of 1 km above the Earth. If air resistance is ignored, the acceleration of the object is dependent on the . . .
   (a) mass of the object
   (b) radius of the earth
   (c) mass of the earth
   (d) weight of the object
3. A man has a mass of 70 kg on Earth. He is walking on a new planet that has a mass four times that of the Earth and the radius is the same as that of the Earth (M_E = 6 x 10^{24} kg, r_E = 6 x 10^6 m)
   (a) Calculate the force between the man and the Earth.
   (b) What is the man's mass on the new planet?
   (c) Would his weight be bigger or smaller on the new planet? Explain how you arrived at your answer.
4. Calculate the distance between two objects, 5000 kg and 6 x 10^{12} kg respectively, if the magnitude of the force between them is 3 x $10^{?8}$ N.
5. Calculate the mass of the Moon given that an object weighing 80 N on the Moon has a weight of 480 N on Earth and the radius of the Moon is 1,6 x 10^{16} m.
6. The following information was obtained from a free-fall experiment to determine the value of g with a pendulum.
   Average falling distance between marks = 920 mm
   Time taken for 40 swings = 70 s
   Use the data to calculate the value of g.
7. An astronaut in a satellite 1600 km above the Earth experiences gravitational force of the magnitude of 700 N on Earth. The Earth's radius is 6400 km. Calculate
   (a) The magnitude of the gravitational force which the astronaut experiences in the satellite.
   (b) The magnitude of the gravitational force on an object in the satellite which weighs 300 N on Earth.
8. An astronaut of mass 70 kg on Earth lands on a planet which has half the Earth's radius and twice its mass. Calculate the magnitude of the force of gravity which is exerted on him on the planet.
9. Calculate the magnitude of the gravitational force of attraction between two spheres of lead with a mass of 10 kg and 6 kg respectively if they are placed 50 mm apart.
10. The gravitational force between two objects is 1200 N. What is the gravitational force between the objects if the mass of each is doubled and the distance between them halved?
11. Calculate the gravitational force between the Sun with a mass of 2 x 10^{30} kg and the Earth with a mass of 6 x 10^{24} kg if the distance between them is 1,4 x 10^8 km.
12. How does the gravitational force of attraction between two objects change when
    (a) the mass of each object is doubled.
    (b) the distance between the centres of the objects is doubled.
    (c) the mass of one object is halved, and the distance between the centres of the objects is halved.
13. Read each of the following statements and say whether you agree or not. Give reasons for your answer and rewrite the statement if necessary:
    (a) The gravitational acceleration g is constant.
    (b) The weight of an object is independent of its mass.
    (c) G is dependent on the mass of the object that is being accelerated.

14. An astronaut weighs 750 N on the surface of the Earth.
    (a) What will his weight be on the surface of Saturn, which has a mass 100 times greater than the Earth, and a radius 5 times greater than the Earth?
    (b) What is his mass on Saturn?
15. A piece of space garbage is at rest at a height 3 times the Earth's radius above the Earth's surface. Determine its acceleration due to gravity. Assume the Earth's mass is 6,0 x 10^{24} kg and the Earth's radius is 6400 km.
16. Your mass is 60 kg in Paris at ground level. How much less would you weigh after taking a lift to the top of the Eiffel Tower, which is 405 m high? Assume the Earth's mass is 6,0 x 10^{24} kg and the Earth's radius is 6400 km.
17. (a) State Newton's Law of Universal Gravitation.
    (b) Use Newton's Law of Universal Gravitation to determine the magnitude of the acceleration due to gravity on the Moon.
    The mass of the Moon is $7{,}40 \times 10^{22}$ kg.
    The radius of the Moon is $1{,}74 \times 10^{6}$ m.
    (c) Will an astronaut, kitted out in his space suit, jump higher on the Moon or on the Earth? Give a reason for your answer.

Momentum

1. [SC 2003/11]A projectile is fired vertically upwards from the ground. At the highest point of its motion, the projectile explodes and separates into two pieces of equal mass. If one of the pieces is projected vertically upwards after the explosion, the second piece will . . .
    (a) drop to the ground at zero initial speed.
    (b) be projected downwards at the same initial speed at the first piece.
    (c) be projected upwards at the same initial speed as the first piece.
    (d) be projected downwards at twice the initial speed as the first piece.
2. [IEB 2004/11 HG1] A ball hits a wall horizontally with a speed of 15 m·s^{-1}. It rebounds horizontally with a speed of 8 m·s^{-1}. Which of the following statements about the system of the ball and the wall is **true**?
    (a) The total linear momentum of the system is not conserved during this collision.
    (b) The law of conservation of energy does not apply to this system.
    (c) The change in momentum of the wall is equal to the change in momentum of the ball.
    (d) Energy is transferred from the ball to the wall.
3. [IEB 2001/11 HG1] A block of mass M collides with a stationary block of mass 2M. The two blocks move off together with a velocity of v. What is the velocity of the block of mass M immediately **before** it collides with the block of mass 2M?
    (a) v
    (b) 2v
    (c) 3v
    (d) 4v
4. [IEB 2003/11 HG1] A cricket ball and a tennis ball move horizontally towards you with the <u>same momentum</u>. A cricket ball has greater mass than a tennis ball. You apply the same force in stopping each ball.
    How does the time taken to stop each ball compare?
    (a) It will take longer to stop the cricket ball.
    (b) It will take longer to stop the tennis ball.
    (c) It will take the same time to stop each of the balls.
    (d) One cannot say how long without knowing the kind of collision the ball has when stopping.

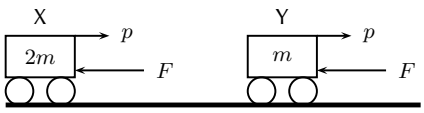
5. [IEB 2004/11 HG1] Two identical billiard balls collide head-on with each other. The first ball hits the second ball with a speed of V, and the second ball hits the first ball with a speed of 2V. After the collision, the first ball moves off in the opposite direction with a speed of 2V. Which expression correctly gives the speed of the second ball after the collision?

   (a) V
   (b) 2V
   (c) 3V
   (d) 4V

6. [SC 2002/11 HG1] Which one of the following physical quantities is the same as the rate of change of momentum?

   (a) resultant force
   (b) work
   (c) power
   (d) impulse

7. [IEB 2005/11 HG] Cart X moves along a smooth track with momentum p. A resultant force F applied to the cart stops it in time t. Another cart Y has only half the mass of X, but it has the same momentum p.



   In what time will cart Y be brought to rest when the same resultant force F acts on it?

   (a) $\frac{1}{2}t$
   (b) t
   (c) $2t$
   (d) $4t$

8. [SC 2002/03 HG1] A ball with mass m strikes a wall perpendicularly with a speed, v. If it rebounds in the opposite direction with the same speed, v, the magnitude of the change in momentum will be ...

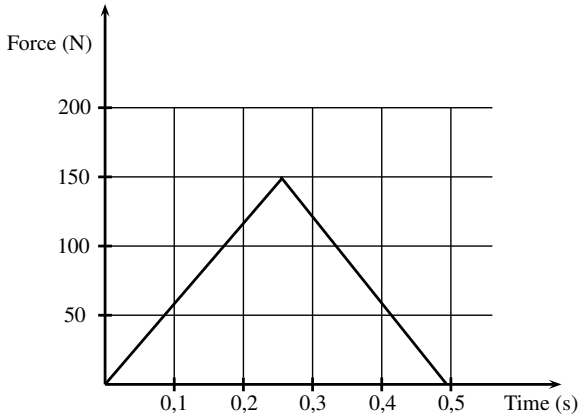
   (a) $2mv$
   (b) mv
   (c) $\frac{1}{2}mv$
   (d) $0\ mv$

9. Show that impulse and momentum have the same units.

10. A golf club exerts an average force of 3 kN on a ball of mass 0,06 kg. If the golf club is in contact with the golf ball for 5 x 10^{-4} seconds, calculate

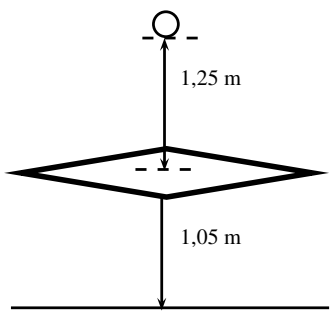
    (a) the change in the momentum of the golf ball.
    (b) the velocity of the golf ball as it leaves the club.

11. During a game of hockey, a player strikes a stationary ball of mass 150 g. The graph below shows how the force of the ball varies with the time.



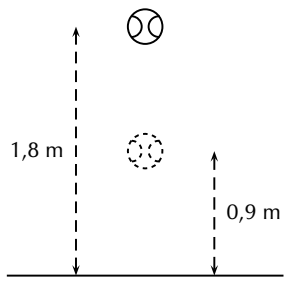
(a) What does the area under this graph represent?
(b) Calculate the speed at which the ball leaves the hockey stick.
(c) The same player hits a practise ball of the same mass, but which is made from a softer material. The hit is such that the ball moves off with the same speed as before. How will the **area**, the **height** and the **base** of the triangle that forms the graph, compare with that of the original ball?

12. The fronts of modern cars are deliberately designed in such a way that in case of a head-on collision, the front would crumple. Why is it desirable that the front of the car should crumple?
13. A ball of mass 100 g strikes a wall horizontally at 10 m·s^{-1}and rebounds at 8 m·s^{-1}. It is in contact with the wall for 0,01 s.
    (a) Calculate the average force exerted by the wall on the ball.
    (b) Consider a lump of putty also of mass 100 g which strikes the wall at 10 m·s^{-1}and comes to rest in 0,01 s against the surface. Explain qualitatively (no numbers) whether the force exerted on the putty will be less than, greater than of the same as the force exerted on the ball by the wall. Do not do any calculations.
14. Shaun swings his cricket bat and hits a stationary cricket ball vertically upwards so that it rises to a height of 11,25 m above the ground. The ball has a mass of 125 g. Determine
    (a) the speed with which the ball left the bat.
    (b) the impulse exerted by the bat on the ball.
    (c) the impulse exerted by the ball on the bat.
    (d) for how long the ball is in the air.
15. A glass plate is mounted horizontally 1,05 m above the ground. An iron ball of mass 0,4 kg is released from rest and falls a distance of 1,25 m before striking the glass plate and breaking it. The total time taken from release to hitting the ground is recorded as 0,80 s. Assume that the time taken to break the plate is negligible.

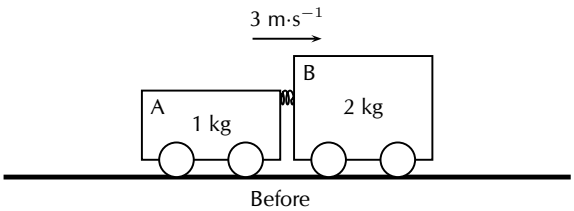


(a) Calculate the speed at which the ball strikes the glass plate.
(b) Show that the speed of the ball immediately after breaking the plate is 2,0 m·s^{-1}.
(c) Calculate the magnitude and give the direction of the change of momentum which the ball experiences during its contact with the glass plate.
(d) Give the magnitude and direction of the impulse which the glass plate experiences when the ball hits it.

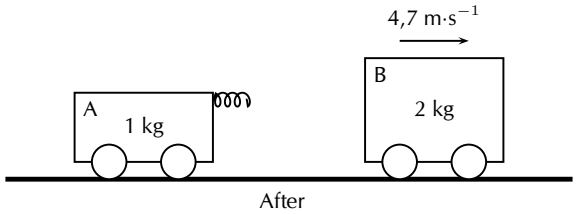
16. [SC 2004/11 HG1]A cricket ball, mass 175 g is thrown directly towards a player at a velocity of 12 m·s^{-1}. It is hit back in the opposite direction with a velocity of 30 m·s^{-1}. The ball is in contact with the bat for a period of 0,05 s.
    (a) Calculate the impulse of the ball.
    (b) Calculate the magnitude of the force exerted by the bat on the ball.
17. [IEB 2005/11 HG1] A ball bounces to a vertical height of 0,9 m when it is dropped from a height of 1,8 m. It rebounds immediately after it strikes the ground, and the effects of air resistance are negligible.



    (a) How long (in s) does it take for the ball to hit the ground after it has been dropped?
    (b) At what speed does the ball strike the ground?
    (c) At what speed does the ball rebound from the ground?
    (d) How long (in s) does the ball take to reach its maximum height after the bounce?
    (e) Draw a velocity-time graph for the motion of the ball from the time it is dropped to the time when it rebounds to 0,9 m. Clearly, show the following on the graph:
        i. the time when the ball hits the ground
        ii. the time when it reaches 0,9 m
        iii. the velocity of the ball when it hits the ground, and
        iv. the velocity of the ball when it rebounds from the ground.
18. [SC 2002/11 HG1] In a railway shunting yard, a locomotive of mass 4 000 kg, travelling due east at a velocity of 1,5 m·s^{-1}, collides with a stationary goods wagon of mass 3 000 kg in an attempt to couple with it. The coupling fails and instead the goods wagon moves due east with a velocity of 2,8 m·s^{-1}.
    (a) Calculate the magnitude and direction of the velocity of the locomotive immediately after collision.
    (b) Name and state in words the law you used to answer question (18a)
19. [SC 2005/11 SG1] A combination of trolley A (fitted with a spring) of mass 1 kg, and trolley B of mass 2 kg, moves to the right at 3 m·s^{-1} along a frictionless, horizontal surface. The spring is kept compressed between the two trolleys.



While the combination of the two trolleys is moving at 3 m·s^{-1} , the spring is released and when it has expanded completely, the 2 kg trolley is then moving to the right at 4,7 m·s^{-1} as shown below.

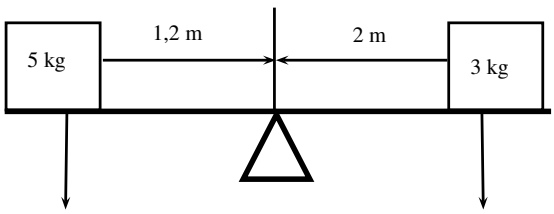


(a) State, in words, the principle of *conservation of linear momentum*.
(b) Calculate the magnitude and direction of the velocity of the 1 kg trolley immediately after the spring has expanded completely.

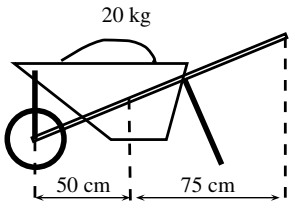
20. [IEB 2002/11 HG1] A ball bounces back from the ground. Which of the following statements is true of this event?
    (a) The magnitude of the change in momentum of the ball is equal to the magnitude of the change in momentum of the Earth.
    (b) The magnitude of the impulse experienced by the ball is greater than the magnitude of the impulse experienced by the Earth.
    (c) The speed of the ball before the collision will always be equal to the speed of the ball after the collision.
    (d) Only the ball experiences a change in momentum during this event.
21. [SC 2002/11 SG] A boy is standing in a small stationary boat. He throws his schoolbag, mass 2 kg, horizontally towards the jetty with a velocity of 5 m·s^{-1}. The *combined mass* of the boy and the boat is 50 kg.
    (a) Calculate the magnitude of the horizontal momentum of the bag immediately after the boy has thrown it.
    (b) Calculate the velocity (magnitude and direction) of the *boat-and-boy* immediately after the bag is thrown.

Torque and levers

1. State whether each of the following statements are true or false. If the statement is false, rewrite the statement correcting it.
    (a) The torque tells us what the turning effect of a force is.
    (b) To increase the mechanical advantage of a spanner you need to move the effort closer to the load.
    (c) A class 2 lever has the effort between the fulcrum and the load.
    (d) An object will be in equilibrium if the clockwise moment and the anticlockwise moments are equal.
    (e) Mechanical advantage is a measure of the difference between the load and the effort.
    (f) The force times the perpendicular distance is called the mechanical advantage.
2. Study the diagram below and determine whether the seesaw is balanced. Show all your calculations.



3. Two children are playing on a seesaw. Tumi has a weight of 200 N and Thandi weighs 240 N. Tumi is sitting at a distance of 1,2 m from the pivot.
   (a) What type of lever is a seesaw?
   (b) Calculate the moment of the force that Tumi exerts on the seesaw.
   (c) At what distance from the pivot should Thandi sit to balance the seesaw?
4. An applied force of 25 N is needed to open the cap of a glass bottle using a bottle opener. The distance between the applied force and the fulcrum is 10 cm and the distance between the load and the fulcrum is 1 cm.
   (a) What type of lever is a bottle opener? Give a reason for your answer.
   (b) Calculate the mechanical advantage of the bottle opener.
   (c) Calculate the force that the bottle cap is exerting.
5. Determine the force needed to lift the 20 kg load in the wheelbarrow in the diagram below.



6. A body builder picks up a weight of 50 N using his right hand. The distance between the body builder's hand and his elbow is 45 cm. The distance between his elbow and where his muscles are attached to his forearm is 5 cm.
   (a) What type of lever is the human arm? Explain your answer using a diagram.
   (b) Determine the force his muscles need to apply to hold the weight steady.

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Force and Newton's laws

(1.) 00p4	(2.) 00p5	(3.) 00p6	(4.) 00p7	(5.) 00p8	(6.) 00p9
(7.) 00pa	(8.) 00pb	(9.) 00pc	(10.) 00pd	(11.) 00pe	(12.) 00pf
(13.) 00pg	(14.) 00ph	(15.) 00pi	(16.) 00pj	(17.) 00pk	(18.) 00pm
(19.) 00pn	(20.) 00pp	(21.) 00pq	(22.) 00pr	(23.) 00ps	(24.) 00pt
(25.) 00pu	(26.) 00pv	(27.) 00pw	(28.) 00px	(29.) 00py	(30.) 00pz
(31.) 00q0	(32.) 00q1	(33.) 00q2	(34.) 00q3	(35.) 00q4	(36.) 00q5
(37.) 00q6					

Gravitation

(1.) 00q7	(2.) 00q8	(3.) 00q9	(4.) 00qa	(5.) 00qb	(6.) 00qc
(7.) 00qd	(8.) 00qe	(9.) 00qf	(10.) 00qg	(11.) 00qh	(12.) 00qi
(13.) 00qj	(14.) 00qk	(15.) 00qm	(16.) 00qn	(17.) 00qp	

Gravitation

(1.) 00qq	(2.) 00qr	(3.) 00qs	(4.) 00qt	(5.) 00qu	(6.) 00qv
(7.) 00qw	(8.) 00qx	(9.) 00qy	(10.) 00qz	(11.) 00r0	(12.) 00r1
(13.) 00r2	(14.) 00r3	(15.) 00r4	(16.) 00r5	(17.) 00r6	(18.) 00r7
(19.) 00r8	(20.) 00r9	(21.) 00ra			

Torque and levers

(1.) 00rb (2.) 00rc (3.) 00rd (4.) 00re (5.) 00rf (6.) 00rg

Geometrical Optics 13

13.1 Introduction

ESBFQ

In Grade 10, we studied how light is reflected and refracted. This chapter builds on what you have learnt in Grade 10. You will learn about lenses, how the human eye works as well as how telescopes and microscopes work.

See introductory video: VPkmu at www.everythingscience.co.za

13.2 Lenses

ESBFR

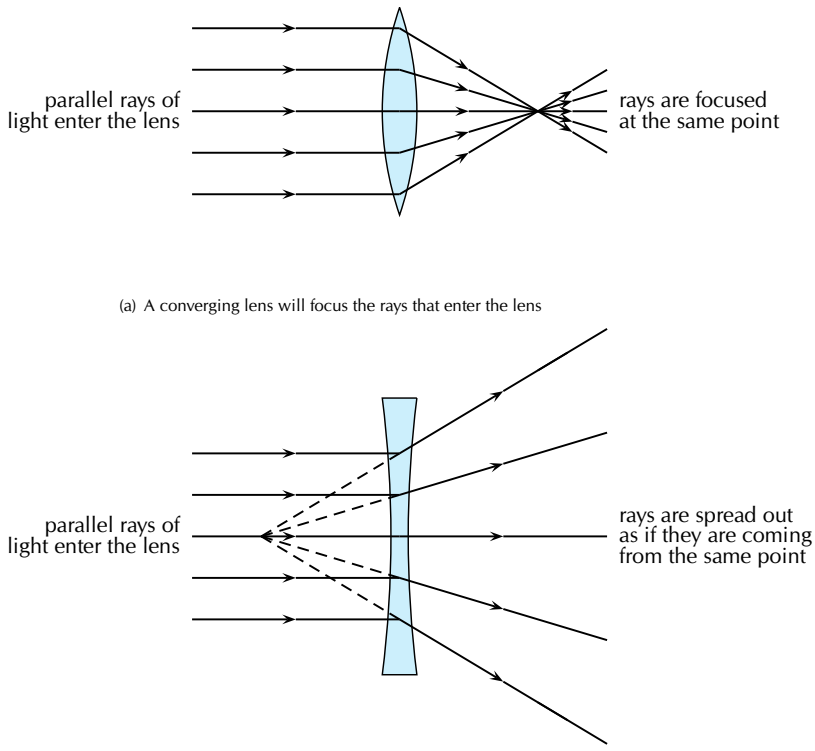
In this section we will discuss properties of **thin lenses**. In Grade 10, you learnt about two kinds of mirrors: concave mirrors which were also known as converging mirrors and convex mirrors which were also known as diverging mirrors. Similarly, there are two types of lenses: converging and diverging lenses.

We have learnt how light travels in different materials, and we are now ready to learn how we can control the direction of light rays. We use *lenses* to control the direction of light. When light enters a lens, the light rays bend or change direction as shown in Figure 13.1.

> *DEFINITION: Lens*
>
> A lens is any transparent material (e.g. glass) of an appropriate shape that can take parallel rays of incident light and either converge the rays to a point or diverge the rays from a point.

Some lenses will focus light rays to a single point. These lenses are called converging or convex lenses. Other lenses spread out the light rays so that it looks like they all come from the same point. These lenses are called diverging or concave lenses. Lenses change the direction of light rays by *refraction*. They are designed so that the image appears in a certain place or as a certain size. Lenses are used in eyeglasses, cameras, microscopes, and telescopes. You also have lenses in your eyes!

> *DEFINITION: Converging Lenses*
>
> Converging lenses converge parallel rays of light and are thicker in the middle than at the edges.



(a) A converging lens will focus the rays that enter the lens

(b) A diverging lens will spread out the rays that enter the lens

Figure 13.1: The behaviour of parallel light rays entering either a converging or diverging lens.

> *DEFINITION: Diverging Lenses*
>
> Diverging lenses diverge parallel rays of light and are thicker at the edges than in the middle.

Examples of converging and diverging lenses are shown in Figure 13.2.

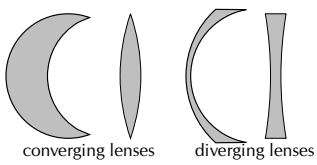


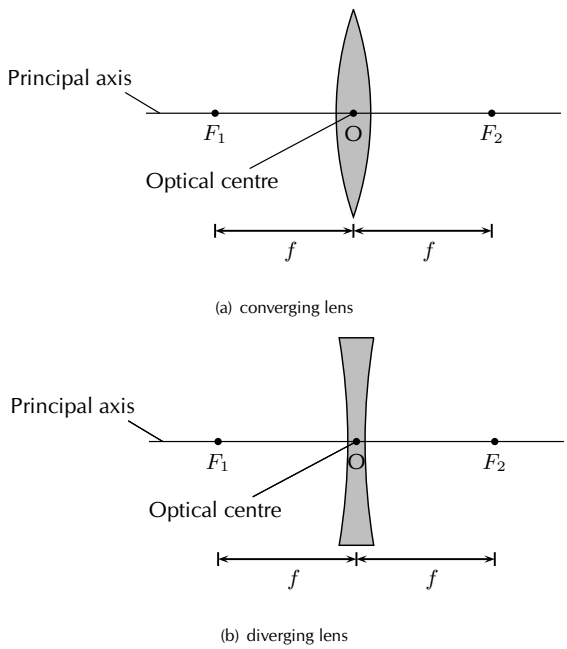
Figure 13.2: Types of lenses

Before we study lenses in detail, there are a few important terms that must be defined. Figure 13.3 shows important lens properties:

- The **principal axis** is the line which runs horizontally straight through the *optical centre* of the lens. It is also sometimes called the *optic axis*.
- The **optical centre** (O) of a convex lens is usually the centre point of the lens. The direction of all light rays which pass through the optical centre, remains unchanged.
- The **focus** or **focal point** of the lens is the position on the *principal axis* where all light rays which run *parallel* to the principal axis through the lens converge (come together) at a point. Since light

can pass through the lens either from right to left or left to right, there is a focal point on each side of the lens (F_1 and F_2), at the same distance from the optical centre in each direction. (**Note:** the plural form of the word focus is *foci*.)

- The **focal length** (f) is the distance between the *optical centre* and the *focal point*.



(a) converging lens

(b) diverging lens

Figure 13.3: Properties of lenses.

Converging Lenses

ESBFS

We will only discuss double convex converging lenses as shown in Figure 13.4. Converging lenses are thinner on the outside and thicker on the inside.

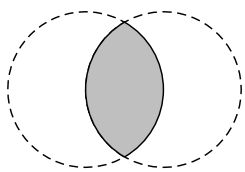


Figure 13.4: A double convex lens is a converging lens.

Figure 13.5 shows a convex lens. Light rays travelling through a **convex** lens are bent **towards** the principal axis. For this reason, convex lenses are called **converging** lenses.

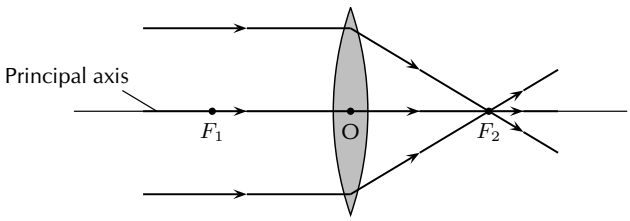


Figure 13.5: Light rays bend towards each other or *converge* when they travel through a convex lens. F_1 and F_2 are the foci of the lens.

When an object is placed in front of a lens, the light rays coming from the object are refracted by the lens. An image of the object is produced at the point where the light rays intersect. The type of images created by a convex lens is dependent on the position of the object. We will examine the following cases:

1. the object is placed at a distance greater than $2f$ from the lens
2. the object is placed at a distance equal to $2f$ from the lens
3. the object is placed at a distance between $2f$ and f from the lens
4. the object is placed at a distance less than f from the lens

We examine the properties of the image in each of these cases by drawing ray diagrams. We can find the image by tracing the path of three light rays through the lens. Any two of these rays will show us the location of the image. The third ray is used to check that the location is correct.

Activity:	*Lenses A*

Aim:
To determine the focal length of a convex lens.
Method:

1. Using a distant object from outside, adjust the position of the convex lens so that it gives the smallest possible focus on a sheet of paper that is held parallel to the lens.
2. Measure the distance between the lens and the sheet of paper as accurately as possible.

Results:
The focal length of the lens is _____ cm

Activity:	*Lenses B*

Aim:
To investigate the position, size and nature of the image formed by a convex lens.
Method:

1. Set up a candle, and the lens from Experiment Lenses A in its holder and the screen in a straight line on the metre rule. Make sure the lens holder is on the 50 cm mark.

   From your knowledge of the focal length of your lens, note where f and $2f$ are on both sides of the lens.
2. Using the position indicated on the table below, start with the candle at a position that

is greater than $2f$ and adjust the position of the screen until a sharp focused image is obtained. Note that there are two positions for which a sharp focused image will not be obtained on the screen. When this is so, remove the screen and look at the candle through the lens.

3. Fill in the relevant information on the table below

Results:

Relative position of object	Relative position of image	Image upright or inverted	Relative size of image	Nature of image
Beyond $2f$ _____ cm				
At $2f$ _____ cm				
Between $2f$ and f _____ cm				
At f _____ cm				
Between f and the lens _____ cm				

QUESTIONS:

1. When a convex lens is being used:
   (a) A real inverted image is formed when an object is placed _____
   (b) No image is formed when an object is placed _____
   (c) An upright, enlarged, virtual image is formed when an object is placed _____
2. Write a conclusion for this investigation.

Activity: *Lenses C*

Aim:
To determine the mathematical relationship between d_0, d_i and f for a lens.
Method:

1. Using the same arrangement as in Experiment Lenses B, place the object (candle) at the distance indicated from the lens.
2. Move the screen until a clear sharp image is obtained. Record the results on the table below.

Results:
f = focal length of lens
d_0 = object distance
d_i = image distance

Object distance d_0 (cm)	Image distance d_i (cm)	$\frac{1}{d_0}$ (cm^{-1})	$\frac{1}{d_i}$ (cm^{-1})	$\frac{1}{d_0}+\frac{1}{d_i}$ (cm^{-1})
25,0				
20,0				
18,0				
15,0				
				Average = _____

$$\text{Reciprocal of average} = \left(\frac{1}{\frac{1}{d_0}+\frac{1}{d_i}}\right) = \_\_\_\_\_ \text{ (a)}$$

$$\text{Focal length of lens} = \_\_\_\_\_ \text{ (b)}$$

Questions:

1. Compare the values for (a) and (b) above and explain any similarities or differences
2. What is the name of the mathematical relationship between d_0, d_i and f?
3. Write a conclusion for this part of the investigation.

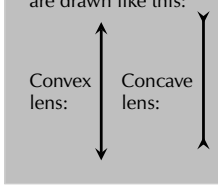
Drawing Ray Diagrams for Converging Lenses

Ray diagrams are normally drawn using three rays. The three rays are labelled R_1, R_2 and R_3. The ray diagrams that follow will use this naming convention.

1. The first ray (R_1) travels from the object to the lens *parallel* to the principal axis. This ray is bent by the lens and travels through the **focal point**.
2. *Any* ray travelling parallel to the principal axis is bent through the focal point.
3. If a light ray passes through a focal point *before* it enters the lens, then it will leave the lens *parallel* to the principal axis. The second ray (R_2) is therefore drawn to pass through the focal point before it enters the lens.
4. A ray that travels through the centre of the lens does not change direction. The third ray (R_3) is drawn through the centre of the lens.
5. The point where all three of the rays (R_1, R_2 and R_3) intersect is the **image** of the point where they all started. The image will form at this point.

Tip

In ray diagrams, lenses are drawn like this:



CASE 1:
Object placed at a distance greater than $2f$ from the lens

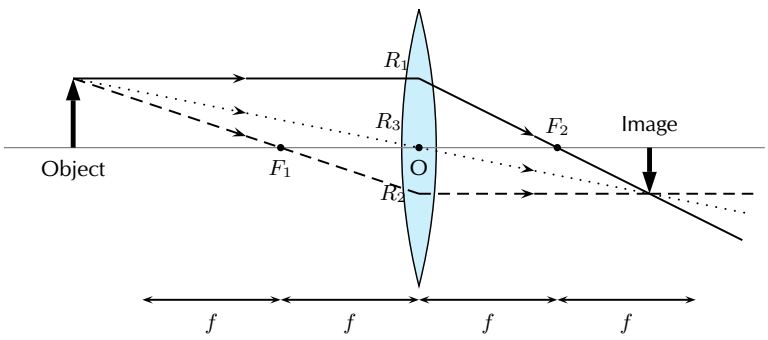


Figure 13.7: An object is placed at a distance greater than $2f$ away from the converging lens. Three rays are drawn to locate the image, which is real, and smaller than the object and inverted.

We can locate the position of the image by drawing our three rays. R_1 travels from the object to the lens parallel to the principal axis, is bent by the lens and then travels through the focal point. R_2 passes through the focal point before it enters the lens and therefore must leave the lens parallel to the principal axis. R_3 travels through the centre of the lens and does not change direction. The point where R_1, R_2 and R_3 intersect is the image of the point where they all started.

The image of an object placed at a distance greater than $2f$ from the lens is upside down or *inverted*. This is because the rays which began at the top of the object, *above* the principal axis, after passing through the lens end up *below* the principal axis. The image is called a **real image** because it is on the opposite side of the lens to the object and you can trace all the light rays directly from the image back to the object.

The image is also smaller than the object and is located closer to the lens than the object.

Tip

In reality, light rays come from *all* points along the length of the object. In ray diagrams we only draw three rays (all starting at the top of the object) to keep the diagram clear and simple.

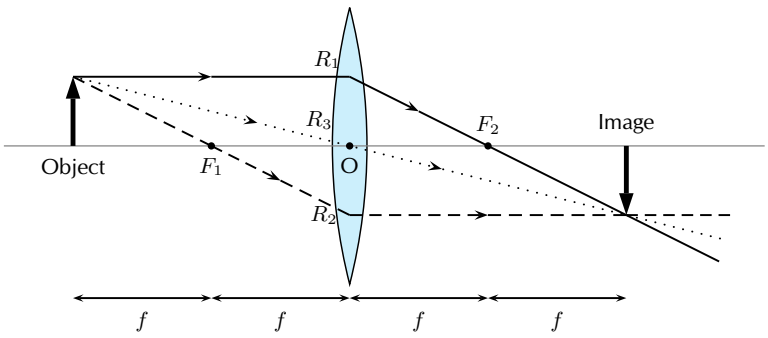


Figure 13.8: An object is placed at a distance equal to $2f$ away from the converging lens. Three rays are drawn to locate the image, which is real, the same size as the object and inverted.

CASE 2:
Object placed at a distance equal to $2f$ from the lens

We can locate the position of the image by drawing our three rays. R_1 travels from the object to the lens parallel to the principal axis and is bent by the lens and then travels through the focal point. R_2 passes through the focal point before it enters the lens and therefore must leave the lens parallel to the principal axis. R_3 travels through the centre of the lens and does not change direction. The point where R_1, R_2 and R_3 intersect is the image of the point where they all started.

The image of an object placed at a distance equal to $2f$ from the lens is upside down or *inverted*. This is because the rays which began at the top of the object, *above* the principal axis, after passing through the lens end up *below* the principal axis. The image is called a **real image** because it is on the opposite side of the lens to the object and you can trace all the light rays directly from the image back to the object.

The image is the same size as the object and is located at a distance $2f$ away from the lens.

CASE 3:
Object placed at a distance between $2f$ and f from the lens

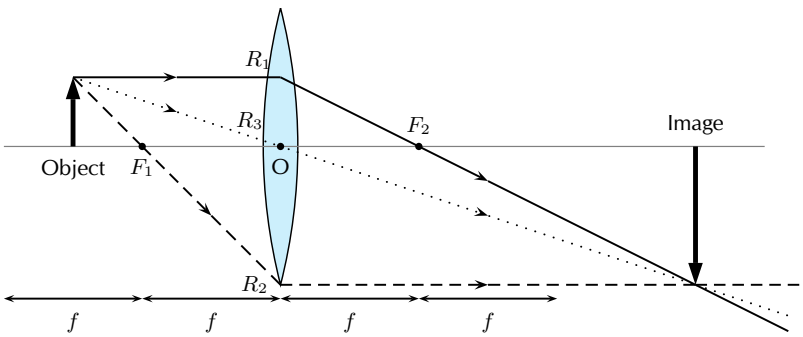


Figure 13.9: An object is placed at a distance between $2f$ and f away from the converging lens. Three rays are drawn to locate the image, which is real, larger than the object and inverted.

We can locate the position of the image by drawing our three rays. R_1 travels from the object to the lens parallel to the principal axis and is bent by the lens and then travels through the focal point. R_2 passes through the focal point before it enters the lens and therefore must leave the lens parallel to the principal axis. R_3 travels through the centre of the lens and does not change direction. The point where R_1, R_2 and R_3 intersect is the image of the point where they all started.

The image of an object placed at a distance between $2f$ and f from the lens is upside down or *inverted*. This is because the rays which began at the top of the object, *above* the principal axis, after passing through the lens end up *below* the principal axis. The image is called a real image because it is on the opposite side of the lens to the object and you can trace all the light rays directly from the image back to the object.

The image is larger than the object and is located at a distance greater than $2f$ away from the lens.

CASE 4:
Object placed at a distance less than f from the lens

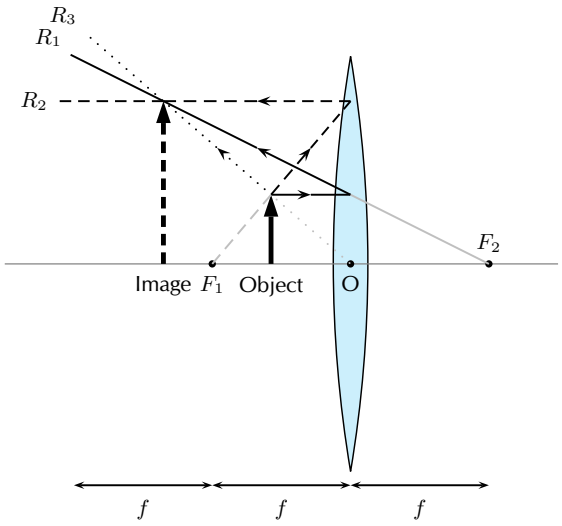


Figure 13.10: An object is placed at a distance less than f away from the converging lens. Three rays are drawn to locate the image, which is virtual, larger than the object and upright.

We can locate the position of the image by drawing our three rays. R_1 travels from the object to the lens parallel to the principal axis and is bent by the lens and then travels through the focal point. R_2 passes through the focal point before it enters the lens and therefore must leave the lens parallel to the principal axis. R_3 travels through the centre of the lens and does not change direction. The point where R_1, R_2 and R_3 intersect is the image of the point where they all started.

The image of an object placed at a distance less than f from the lens is upright. The image is called a **virtual image** because it is on the same side of the lens as the object and you *cannot* trace all the light rays directly from the image back to the object.

The image is larger than the object and is located further away from the lens than the object.

Extension:	*The thin lens equation and magnification*

The Thin Lens Equation

We can find the position of the image of a lens mathematically as there is a mathematical relation between the object distance, image distance, and focal length. The equation is:

$$\frac{1}{f} = \frac{1}{d_o} + \frac{1}{d_i}$$

where f is the focal length, d_o is the object distance and d_i is the image distance.

The object distance d_o is the distance from the object to the lens. d_o is positive if the object is on the same side of the lens as the light rays enter the lens. This should make sense: we

expect the light rays to travel from the object to the lens. The image distance d_i is the distance from the lens to the image. Unlike mirrors, which reflect light back, lenses refract light through them. We expect to find the image on the same side of the lens as the light leaves the lens. If this is the case, then d_i is *positive* and the image is **real** (see Figure 13.9). Sometimes the image will be on the same side of the lens as the light rays enter the lens. Then d_i is *negative* and the image is **virtual** (Figure 13.10). If we know any two of the three quantities above, then we can use the Thin Lens Equation to solve for the third quantity.

Magnification

It is possible to calculate the magnification of an image. The magnification is how much *bigger* or *smaller* the image is than the object.

$$m = -\frac{d_i}{d_o}$$

where m is the magnification, d_o is the object distance and d_i is the image distance.

If d_i and d_o are both positive, the magnification is negative. This means the image is inverted, or upside down. If d_i is negative and d_o is positive, then the image is not inverted, or right side up. If the absolute value of the magnification is *greater than one*, the image is *larger* than the object. For example, a magnification of -2 means the image is *inverted* and *twice as big* as the object.

Example 1: *Using the lens equation*

QUESTION

An object is placed 6 cm from a converging lens with a focal point of 4 cm.

1. *Calculate the position of the image*
2. *Calculate the magnification of the lens*
3. *Identify three properties of the image*

SOLUTION

Step 1 : ***Identify what is given and what is being asked***

$$\begin{aligned} f &= 4\text{ cm} \\ d_o &= 6\text{ cm} \\ d_i &= ? \\ m &= ? \end{aligned}$$

Properties of the image are required.

Step 2 : ***Calculate the image distance (d_i)***

$$\begin{aligned}
\frac{1}{f} &= \frac{1}{d_o} + \frac{1}{d_i} \\
\frac{1}{4} &= \frac{1}{6} + \frac{1}{d_i} \\
\frac{1}{4} - \frac{1}{6} &= \frac{1}{d_i} \\
\frac{3-2}{12} &= \frac{1}{d_i} \\
d_i &= 12 \text{ cm}
\end{aligned}$$

Step 3 : ***Calculate the magnification***

$$\begin{aligned}
m &= -\frac{d_i}{d_o} \\
&= -\frac{12}{6} \\
&= -2
\end{aligned}$$

Step 4 : ***Write down the properties of the image***
The image is real, d_i is positive, inverted (because the magnification is negative) and enlarged (magnification is > 1)

Example 2: *Locating the image position of a convex lens: I*

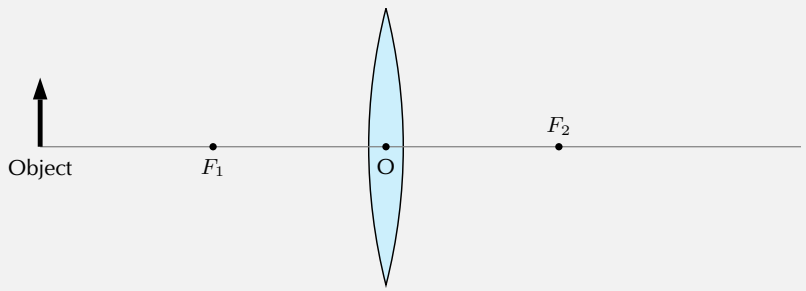
QUESTION

An object is placed 5 cm to the left of a converging lens which has a focal length of 2,5 cm.

1. *What is the position of the image?*
2. *Is the image real or virtual?*

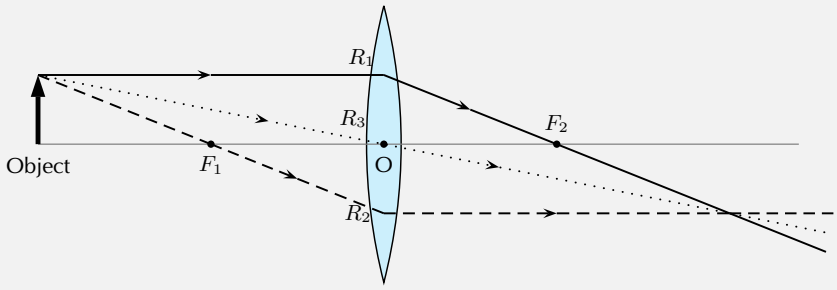
SOLUTION

Step 1 : ***Set up the ray diagram***
Draw the lens, the object and mark the focal points.

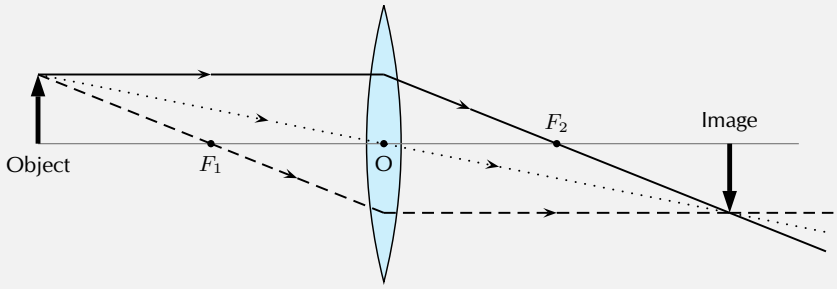


Step 2 : ***Draw the three rays***

- R_1 goes from the top of the object parallel to the principal axis, through the lens and through the focal point F_2 on the other side of the lens.
- R_2 goes from the top of the object through the focal point F_1, through the lens and out parallel to the principal axis.
- R_3 goes from the top of the object through the optical centre with its direction unchanged.



Step 3 : ***Find the image***
The image is at the place where all the rays intersect. Draw the image.



Step 4 : ***Measure the distance between the lens and the image***
The image is 5 cm away from the lens, on the opposite side of the lens to the object.

Step 5 : ***Is the image virtual or real?***
Since the image is on the opposite side of the lens to the object, the image is real.

Example 3: *Locating the image position of a convex lens: II*

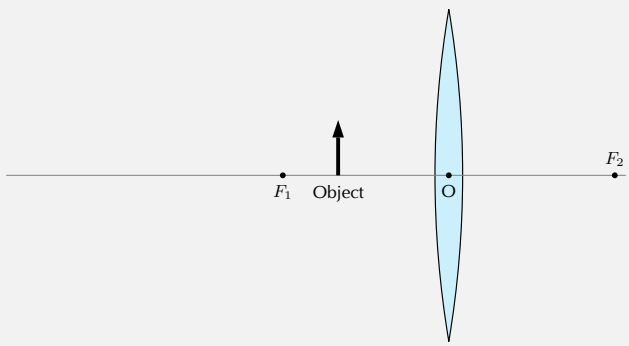
QUESTION

An object, 1 cm high, is placed 2 cm to the left of a converging lens which has a focal length of 3,0 cm. The image is found also on the left side of the lens.

1. *Is the image real or virtual?*
2. *What is the position and height of the image?*

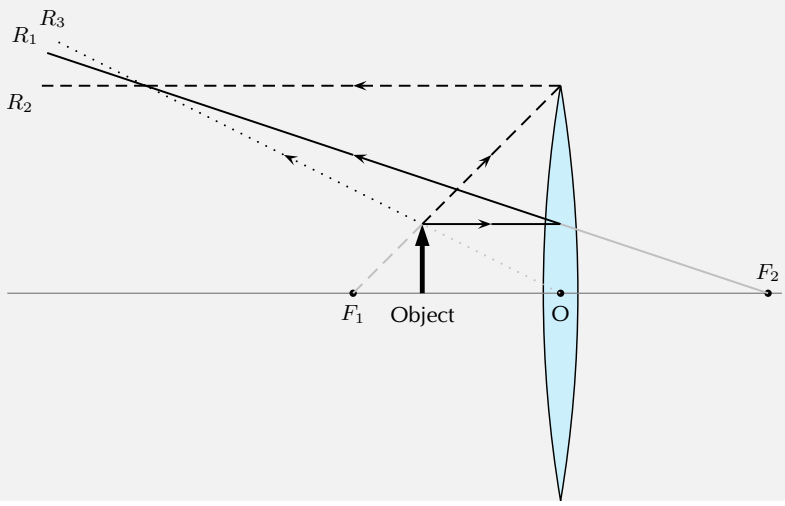
SOLUTION

Step 1 : ***Draw the picture to set up the problem***
Draw the lens, principal axis, focal points and the object.

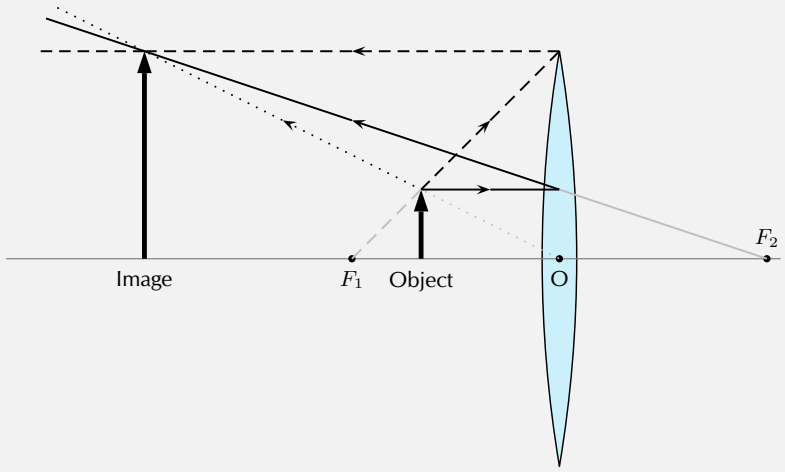


Step 2 : ***Draw the three rays to locate image***

- R_1 goes from the top of the object parallel to the principal axis, through the lens and through the focal point F_2 on the other side of the lens.
- R_2 is the light ray which should go through the focal point F_1 but the object is placed *after* the focal point! This is not a problem, just trace the line from the focal point F_1, through the top of the object, to the lens. This ray then leaves the lens parallel to the principal axis.
- R_3 goes from the top of the object through the optical centre with its direction unchanged.
- Do not write R_1, R_2 and R_3 on your diagram, otherwise it becomes too cluttered.
- Since the rays do not intersect on the right side of the lens, we need to trace them backwards to find the place where they do come together (these are the light gray lines). Again, this is the position of the image.



Step 3 : ***Draw the image***



Step 4 : ***Measure distance to image***
The image is 6 cm away from the lens, on the same side as the object.

Step 5 : ***Measure the height of the image***
The image is 3 cm high.

Step 6 : ***Is image real or virtual?***
Since the image is on the same side of the lens as the object, the image is virtual.

Exercise 13 - 1

1. Which type of lens can be used as a magnifying glass? Draw a diagram to show how it works. An image of the sun is formed at the principal focus of a magnifying glass.
2. In each case state whether a real or virtual image is formed:
   (a) Much further than $2f$
   (b) Just further than $2f$
   (c) At $2f$
   (d) Between $2f$ and f
   (e) At f
   (f) Between f and 0
3. Is a virtual image always inverted?
4. An object stands 50 mm from a lens (focal length 40 mm). Draw an accurate sketch to determine the position of the image. Is it enlarged or shrunk; upright or inverted?
5. Draw a scale diagram (scale: 1 cm = 50 mm) to find the position of the image formed by a convex lens with a focal length of 200 mm. The distance of the object is 100 mm and the size of the object is 50 mm. Determine whether the image is enlarged or shrunk. What is the height of the image? What is the magnification?

6. An object, 20 mm high, is 80 mm from a convex lens with focal length 50 mm. Draw an accurate scale diagram and find the position and size of the image, and hence the ratio between the image size and object size.
7. An object, 50 mm high, is placed 100 mm from a convex lens with a focal length of 150 mm. Construct an accurate ray diagram to determine the nature of the image, the size of the image and the magnification. Check your answer for the magnification by using a calculation.
8. What would happen if you placed the object right at the focus of a converging lens? Hint: Draw the picture.

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(1.) 00rm (2.) 00rn (3.) 00rp (4.) 00rq (5.) 00rr (6.) 00rs
(7.) 00rt (8.) 01xh

Diverging Lenses

ESBFT

We will only discuss double concave diverging lenses as shown in Figure 13.11. Concave lenses are thicker on the outside and thinner on the inside.

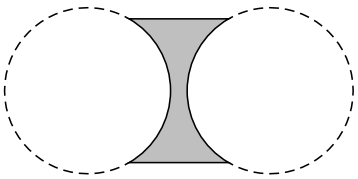


Figure 13.11: A double concave lens is a diverging lens.

Figure 13.12 shows a concave lens with light rays travelling through it. You can see that concave lenses have the opposite curvature to convex lenses. This causes light rays passing through a concave lens to **diverge** or be spread out *away* from the principal axis. For this reason, concave lenses are called **diverging lenses.** Images formed by concave lenses are *always* virtual.

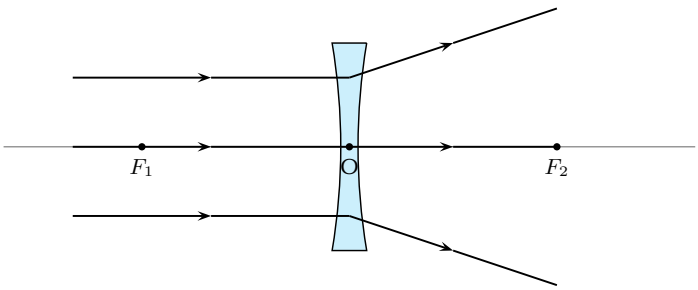


Figure 13.12: Light rays bend *away from* each other or *diverge* when they travel through a concave lens. F_1 and F_2 are the foci of the lens.

Unlike converging lenses, the type of images created by a concave lens is not dependent on the position of the object. The image is *always* upright, smaller than the object, and located closer to the lens than the object.

We examine the properties of the image by drawing ray diagrams. We can find the image by tracing the path of three light rays through the lens. Any two of these rays will show us the location of the image. You can use the third ray to check the location, but it is not necessary to show it on your diagram.

Drawing Ray Diagrams for Diverging Lenses
Draw the three rays starting at the top of the object.

1. Ray R_1 travels parallel to the principal axis. The ray bends and lines up with a focal point. However, the concave lens is a *diverging* lens, so the ray must line up with the focal point on the same side of the lens where light rays enter it. This means that we must project an imaginary line backwards through that focal point (F_1) (shown by the dashed line extending from R_1).

2. Ray R_2 points towards the focal point F_2 on the opposite side of the lens. When it hits the lens, it is bent parallel to the principal axis.

3. Ray R_3 passes through the optical centre of the lens. Like for the convex lens, this ray passes through with its direction unchanged.

4. We find the image by locating the point where the rays meet. Since the rays diverge, they will only meet if projected backward to a point on the same side of the lens as the object. This is why concave lenses *always* have virtual images. (Since the light rays do not actually meet at the image, the image cannot be real.)

Figure 13.13 shows an object placed at an arbitrary distance from the diverging lens.

We can locate the position of the image by drawing our three rays for a diverging lens.

Figure 13.13 shows that the image of an object is upright. The image is called a **virtual image** because it is on the same side of the lens as the object.

The image is smaller than the object and is closer to the lens than the object.

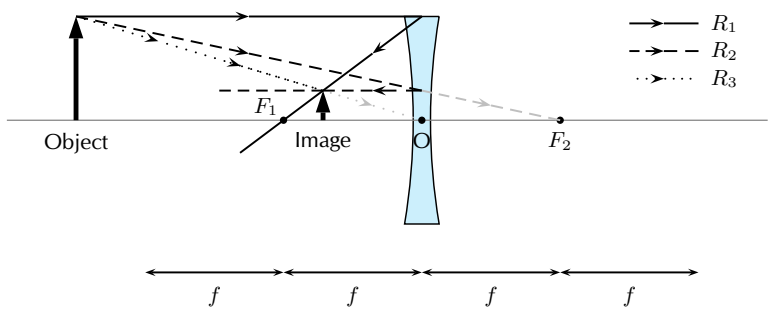


Figure 13.13: Three rays are drawn to locate the image, which is virtual, smaller than the object and upright.

Example 4: *Locating the image position for a diverging lens: I*

QUESTION

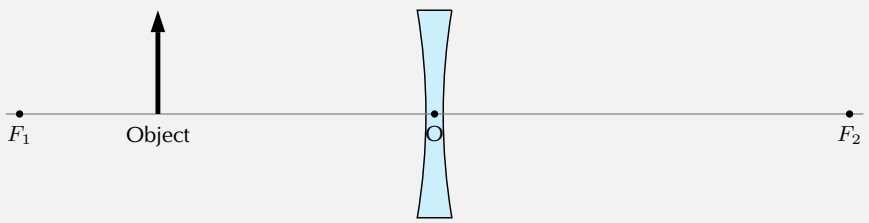
An object is placed 4 cm to the left of a diverging lens which has a focal length of 6 cm.

1. *What is the position of the image?*
2. *Is the image real or virtual?*

SOLUTION

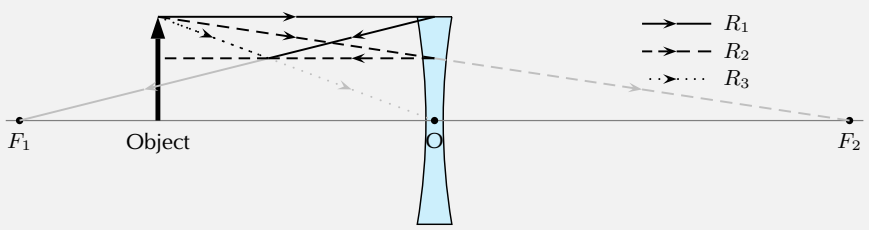
Step 1 : ***Set up the problem***

Draw the lens, object, principal axis and focal points.



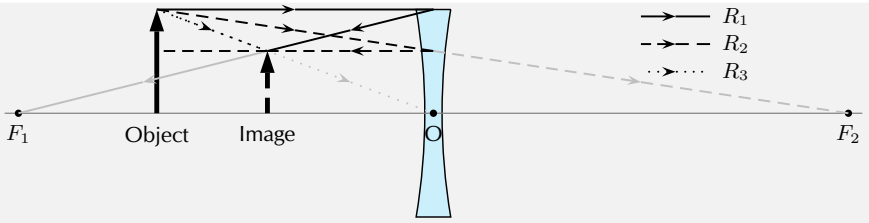
Step 2 : ***Draw the three light rays to locate the image***

- R_1 goes from the top of the object parallel to the principal axis. To determine the angle it has when it leaves the lens on the other side, we draw the dashed line from the focus F_1 through the point where R_1 hits the lens. (Remember: for a diverging lens, the light ray on the opposite side of the lens to the object has to bend *away* from the principal axis.)
- R_2 goes from the top of the object in the direction of the other focal point F_2. After it passes through the lens, it travels parallel to the principal axis.
- R_3 goes from the top of the lens, straight through the optical centre with its direction unchanged.
- Just like for converging lenses, the image is found at the position where all the light rays intersect.



Step 3 : ***Draw the image***

Draw the image at the point where all three rays intersect.



Step 4 : ***Measure the distance to the object***
The distance to the object is 2,4 cm.

Step 5 : ***Determine type of object***
The image is on the same side of the lens as the object, and is upright. Therefore it is virtual. (*Remember:* The image from a diverging lens is *always* virtual.)

Summary of Image Properties

ESBFU

The properties of the images formed by converging and diverging lenses depend on the position of the object. The properties are summarised in the Table 13.1.

Table 13.1: Summary of image properties for converging and diverging lenses

		Image Properties			
Lens type	**Object Position**	**Position**	**Orientation**	**Size**	**Type**
Converging	$> 2f$	$< 2f$	inverted	smaller	real
Converging	$2f$	$2f$	inverted	same size	real
Converging	$> f, < 2f$	$> 2f$	inverted	larger	real
Converging	f	no image formed			
Converging	$< f$	$> f$	upright	larger	virtual
Diverging	any position	$< f$	upright	smaller	virtual

Exercise 13 - 2

1. An object 3 cm high is at right angles to the principal axis of a concave lens of focal length 15 cm. If the distance from the object to the lens is 30 cm, find the distance of the image from the lens, and its height. Is it real or virtual?

2. The image formed by a concave lens of focal length 10 cm is 7,5 cm from the lens and is 1,5 cm high. Find the distance of the object from the lens, and its height.

3. An object 6 cm high is 10 cm from a concave lens. The image formed is 3 cm high. Find the focal length of the lens and the distance of the image from the lens.

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(1.) 00ru (2.) 00rv (3.) 00rw

13.3 The Human Eye

ESBFV

Activity: *Model of the Human Eye*

This demonstration shows that:

1. The eyeball has a spherical shape.
2. The pupil is a small hole in the front and middle of the eye that lets light into the eye.
3. The retina is at the back of the eyeball.
4. The images that we see are formed on the retina.
5. The images on the retina are upside down. The brain inverts the images so that what we see is the right way up.

You will need:

1. a round, clear glass bowl
2. water
3. a sheet of cardboard covered with black paper
4. a sheet of cardboard covered with white paper
5. a small desk lamp with an incandescent light-bulb or a candle and a match

You will have to:

1. Fill the glass bowl with water.
2. Make a small hole in the middle of the black cardboard.
3. Place the black cardboard against one side of the bowl and the white cardboard on the other side of the bowl so that it is opposite the black cardboard.
4. Turn on the lamp (or light the candle).
5. Place the lamp so it is shining through the hole in the black cardboard.
6. Make the room as dark as possible.
7. Move the white cardboard until an image of the light bulb or candle appears on it.

You now have a working model of the human eye.

1. The hole in the black cardboard represents the pupil. The pupil is a small hole in the front of the eyeball that lets light into the eye.
2. The round bowl of water represents the eyeball.
3. The white cardboard represents the retina. Images are projected onto the retina and are then sent to the brain via the optic nerve.

Tasks

1. Is the image on the retina right-side up or upside down? Explain why.
2. Draw a simple labelled diagram of the model of the eye showing which part of the eye each part of the model represents.

Structure of the Eye

ESBFW

Eyesight begins with lenses. As light rays enter your eye, they pass first through the **cornea** and then through the **crystalline lens**. These form a double lens system and focus light rays onto the back wall of the eye, called the **retina**. **Rods** and **cones** are nerve cells on the retina that transform light into electrical signals. These signals are sent to the brain via the **optic nerve**. A cross-section of the eye is shown in Figure 13.14.

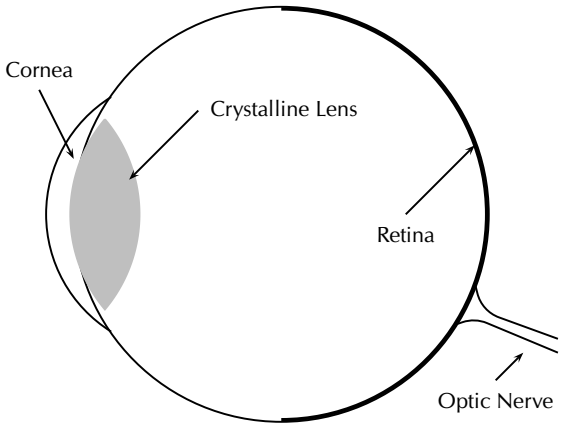


Figure 13.14: A cross-section of the human eye.

For clear vision, the image must be formed right on the retina, not in front of or behind it. To accomplish this, you may need a long or short focal length, depending on the object distance. How do we get the exact right focal length we need? Remember that the lens system has two parts. The cornea is fixed in place but the crystalline lens is flexible – it can change shape. When the shape of the lens changes, its focal length also changes. You have muscles in your eye called **ciliary muscles** that control the shape of the crystalline lens. When you focus your gaze on something, you are squeezing (or relaxing) these muscles. This process of **accommodation** changes the focal length of the lens and allows you to see an image clearly.

The lens in the eye creates a real image that is smaller than the object and is inverted (Figure 13.15).

Defects of Vision

ESBFX

In a normal eye the image is focused on the retina.

If the muscles in the eye are unable to accommodate adequately, the image will not be in focus. This leads to problems with vision. There are three basic conditions that arise:

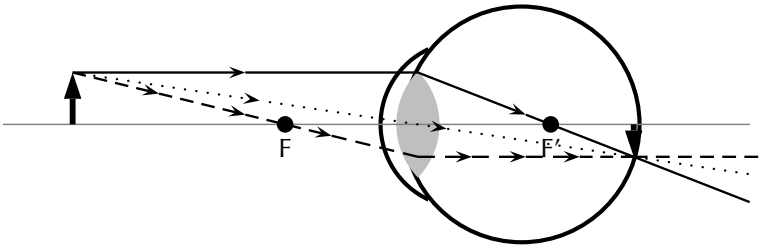


Figure 13.15: Normal eye

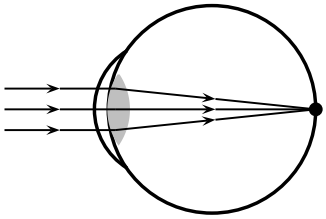
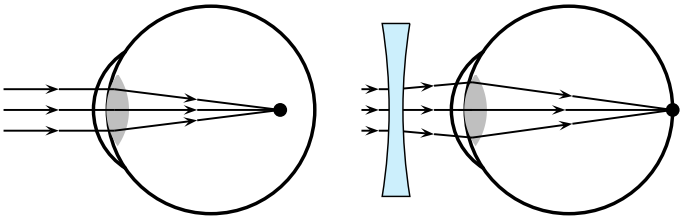


Figure 13.16: Normal eye

1. short-sightedness
2. long-sightedness
3. astigmatism

Short-sightedness

Short-sightedness or **myopia** is a defect of vision which means that the image is focused in front of the retina. Close objects are seen clearly but distant objects appear blurry. This condition can be corrected by placing a diverging lens in front of the eye. The diverging lens spreads out light rays before they enter the eye. The situation for short-sightedness and how to correct it is shown in Figure 13.17.

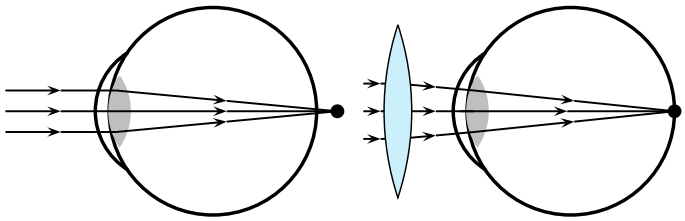


(a) Short-sightedness : Light rays are focused in front of the retina. (b) Short-sightedness corrected by a diverging lens.

Figure 13.17: Short-sightedness

Long-sightedness

Long-sightedness or **hyperopia** is a defect of vision which means that the image is focused in behind the retina. People with this condition can see distant objects clearly, but not close ones. A converging lens in front of the eye corrects long-sightedness by converging the light rays slightly before they enter the eye. Reading glasses are an example of a converging lens used to correct long-sightedness.



(a) Long-sightedness : Light rays are focused in behind the retina. (b) Long-sightedness corrected by a converging lens.

Figure 13.18: Long-sightedness

Astigmatism

Astigmatism is characterised by a cornea or lens that is not spherical, but is more curved in one plane compared to another. This means that horizontal lines may be focused at a different point to vertical lines. Astigmatism causes blurred vision and is corrected by a special lens, which has different focal lengths in the vertical and horizontal planes.

13.4 Telescopes

ESBFY

We have seen how a simple lens can be used to correct eyesight. Lenses and mirrors are also combined to magnify (or make bigger) objects that are far away.

Telescopes use combinations of lenses to gather and focus light. Telescopes collect light from objects that are large but far away, like planets and galaxies. For this reason, telescopes are the tools of astronomers. **Astronomy** is the study of objects outside the Earth, like stars, planets, galaxies, comets, and asteroids.

Usually the object viewed with a telescope is very far away. Objects closer to Earth, such as the moon, appear larger, and with a powerful enough telescope, we are able to see craters on the Moon's surface. Objects which are much further, such as stars, appear as points of light. Even with the most powerful telescopes currently built, we are unable to see details on the surfaces of stars.

There are many kinds of telescopes, but we will look at two basic types: reflecting and refracting.

Refracting Telescopes

ESBFZ

A **refracting telescope** like the one pictured in Figure 13.19 uses two convex lenses to enlarge an image. The refracting telescope has a large primary lens with a long focal length to gather a lot of light. The lenses of a refracting telescope share a focal point. This ensures that parallel rays entering the telescope are again parallel when they reach your eye.

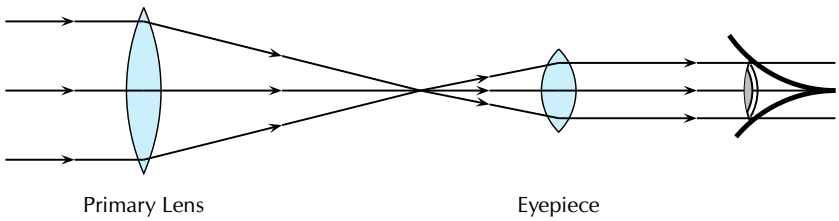


Figure 13.19: Layout of lenses in a refracting telescope

Reflecting Telescopes

ESBGA

Some telescopes use mirrors as well as lenses and are called reflecting telescopes. Specifically, a **reflecting telescope** uses a convex lens and two mirrors to make an object appear larger. (Figure 13.20.) Light is collected by the primary mirror, which is large and concave. Parallel rays travelling toward this mirror are reflected and focused to a point. The secondary plane mirror is placed within the focal length of the primary mirror. This changes the direction of the light. A final eyepiece lens diverges the rays so that they are parallel when they reach your eye.

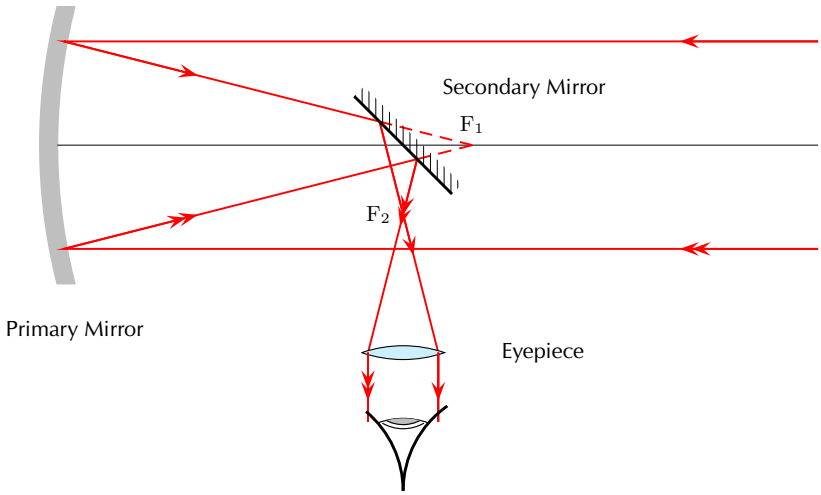


Figure 13.20: Lenses and mirrors in a reflecting telescope.

Southern African Large Telescope

ESBGB

The Southern African Large Telescope (SALT) is the largest single optical telescope in the southern hemisphere, with a hexagonal mirror array 11 metres across. SALT is located in Sutherland in the Northern Cape. SALT is able to record images of distant stars, galaxies and quasars a billion times too faint to be seen with the unaided eye. This is equivalent to a person being able to see a candle flame on the moon.

SALT was completed in 2005 and is a truly international initiative, because the money to build it came from South Africa, the United States, Germany, Poland, the United Kingdom and New Zealand.

Activity:	*SALT*

Investigate what the South African Astronomical Observatory (SAAO) does. SALT is part of SAAO. Write your investigation as a short 5-page report. Include images of the instrumentation used.

13.5 Microscopes

ESBGC

We have seen how lenses and mirrors are combined to magnify objects that are far away using a telescope. Lenses can also be used to make very small objects appear bigger.

Figure 13.10 shows that when an object is placed at a distance less than f from the lens, the image formed is virtual, upright and is larger than the object. This set-up is a simple magnifier.

If you want to look at something very small, two lenses may work better than one. Microscopes and telescopes often use two lenses to make an image large enough to see.

A **compound microscope** uses two lenses to achieve high magnification (Figure 13.21). Both lenses are convex, or converging. Light from the object first passes through the **objective lens**. The lens that you look through is called the **eyepiece**. The focus of the system can be adjusted by changing the length of the tube between the lenses.

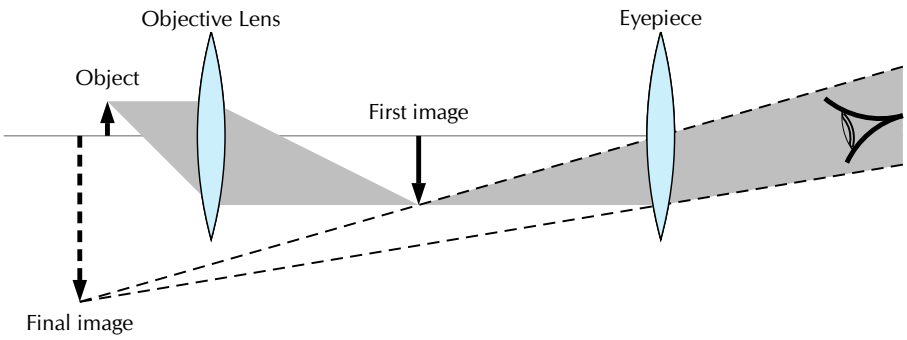


Figure 13.21: Compound microscope

Drawing a Ray Diagram for a Two-Lens System
You already have all the tools to analyse a two-lens system. Just consider one lens at a time.

1. Use ray tracing or the lens equation to find the image for the first lens.
2. Use the image of the first lens as the object of the second lens.
3. To find the magnification, multiply: $m_{total} = m_1 \times m_2 \times m_3 \times \cdots$

Example 5: *The Compound Microscope*

QUESTION

A compound microscope consists of two convex lenses. The eyepiece has a focal length of 10 cm. The objective lens has a focal length of 6 cm. The two lenses are 30 cm apart. A 2 cm-tall object is placed 8 cm from the objective lens.

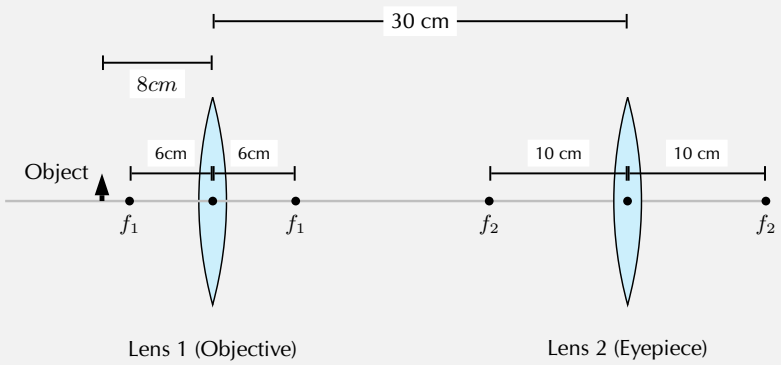
1. *Where is the final image?*
2. *Is the final image real or virtual?*

SOLUTION

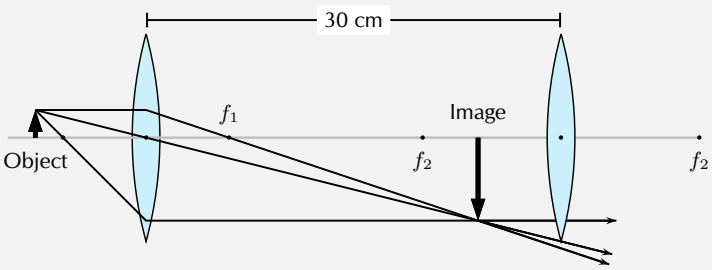
We can use ray tracing to follow light rays through the microscope, one lens at a time.

Step 1 : ***Set up the system***

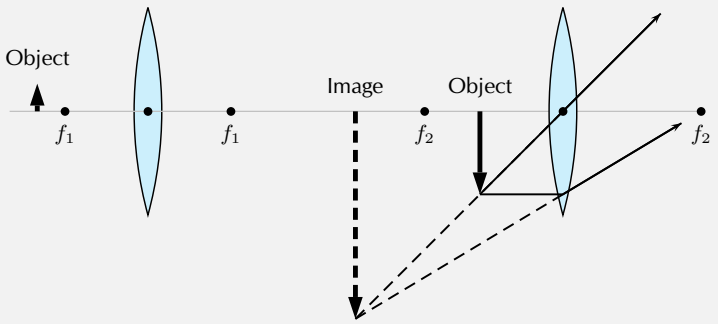
To prepare to trace the light rays, make a diagram. In the diagram here, we place the image on the left side of the microscope. Since the light will pass through the objective lens first, we'll call this Lens 1. The eyepiece will be called Lens 2. Be sure to include the focal points of both lenses in your diagram.



Step 2 : ***Find the image for the objective lens.***



Step 3 : ***Find the image for the eyepiece.***
The image we just found becomes the object for the second lens.



Chapter 13 — Summary

See the summary presentation (▶ Presentation: VPknd at www.everythingscience.co.za)

1. A lens is any transparent material that is shaped in such a way that it will converge parallel incident rays to a point or diverge incident rays from a point.
2. Converging lenses are thicker in the middle than on the edge and will bend incoming light rays towards the principal axis.
3. Diverging lenses are thinner in the middle than on the edge and will bend incoming light rays away from the principal axis.
4. The principal axis of a lens is the horizontal line through the centre of the lens.
5. The centre of the lens is called the optical centre.
6. The focus or focal point is a point on the principal axis where parallel rays converge through or diverge from.
7. The focal length is the distance between the focus and the optical centre.
8. Ray diagrams are used to determine the position and height of an image formed by a lens. The properties of images formed by converging and diverging lenses are summarised in Table 13.1.
9. The human eye consists of a lens system that focuses images on the retina where the optic nerve transfers the messages to the brain.
10. Defects of vision include short-sightedness, long-sightedness and astigmatism.
11. Massive astronomical bodies, such as galaxies, act as gravitational lenses that can change the apparent positions of the images of stars.
12. Microscopes and telescopes use systems of lenses to create magnified images of very small or very distant objects.

Chapter 13 End of Chapter Exercises

1. Select the correct answer from the options given:
   (a) A . . . . . (*convex/concave*) lens is thicker in the centre than on the edges.
   (b) When used individually, a (*diverging/converging*) lens usually forms real images.
   (c) When formed by a single lens, a . . . . . (*real/virtual*) image is always inverted.
   (d) When formed by a single lens, a . . . . . (*real/virtual*) image is always upright.
   (e) Virtual images formed by converging lenses are . . . . . (*bigger/the same size/smaller*) compared to the object.
   (f) A . . . . . (*real/virtual*) image can be projected onto a screen.
   (g) A . . . . . (*real/virtual*) image is said to be "trapped" in the lens.
   (h) A ray that starts from the top of an object and runs parallel to the axis of the lens, would then pass through the . . . . . (*principal focus of the lens/centre of the lens/secondary focus of the lens*).
   (i) A ray that starts from the top of an object and passes through the . . . . . (*principal focus of the lens/centre of the lens/secondary focus of the lens*) would leave the lens running parallel to its axis.
   (j) For a converging lens, its . . . . . (*principal focus/centre/secondary focus*) is located on the same side of the lens as the object.
   (k) After passing through a lens, rays of light travelling parallel to a lens' axis are refracted to the lens' . . . . . (*principal focus/centre/secondary focus*).
   (l) Real images are formed by . . . . . (*converging/parallel/diverging*) rays of light that have passed through a lens.
   (m) Virtual images are formed by . . . . . (*converging/parallel/diverging*) rays of light that have passed through a lens.
   (n) Images which are closer to the lens than the object are . . . . . (*bigger/the same size/smaller*) than the object.
   (o) . . . . . (*Real/Virtual*) images are located on the same side of the lens as the object - that is, by looking in one direction, the observer can see both the image and the object.
   (p) . . . . . (*Real/Virtual*) images are located on the opposite side of the lens as the object.
   (q) When an object is located greater than two focal lengths in front of a converging lens, the image it produces will be . . . . . (*real and enlarged/virtual and enlarged/real and reduced/virtual and reduced*).
2. An object 1 cm high is placed 1,8 cm in front of a converging lens with a focal length of 0,5 cm. Draw a ray diagram to show where the image is formed. Is the final image real or virtual?
3. An object 1 cm high is placed 2,10 cm in front of a diverging lens with a focal length of 1,5 cm. Draw a ray diagram to show where the image is formed. Is the final image real or virtual?
4. An object 1 cm high is placed 0,5 cm in front of a converging lens with a focal length of 0,5 cm. Draw a ray diagram to show where the image is formed. Is the final image real or virtual?

5. An object is at right angles to the principal axis of a convex lens. The object is 2 cm high and is 5 cm from the centre of the lens, which has a focal length of 10 cm. Find the distance of the image from the centre of the lens, and its height. Is it real or virtual?
6. A convex lens of focal length 15 cm produces a real image of height 4 cm at 45 cm from the centre of the lens. Find the distance of the object from the lens and its height.
7. An object is 20 cm from a concave lens. The virtual image formed is three times smaller than the object. Find the focal length of the lens.
8. A convex lens produces a virtual image which is four times larger than the object. The image is 15 cm from the lens. What is the focal length of the lens?
9. A convex lens is used to project an image of a light source onto a screen. The screen is 30 cm from the light source, and the image is twice the size of the object. What focal length is required, and how far from the source must it be placed?
10. An object 6 cm high is place 20 cm from a converging lens of focal length 8 cm. Find by scale drawing the position, size and nature of the image produced. (Advanced: check your answer by calculation).
11. An object is placed in front of a converging lens of focal length 12 cm. By scale diagram, find the nature, position and magnification of the image when the object distance is
    (a) 16 cm
    (b) 8 cm
12. A concave lens produces an image three times smaller than the object. If the object is 18 cm away from the lens, determine the focal length of the lens by means of a scale diagram. (Advanced: check your answer by calculation).
13. You have seen how the human eye works, how telescopes work and how microscopes work. Using what you have learnt, describe how you think a camera works.
14. Describe 3 common defects of vision and discuss the various methods that are used to correct them.

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(1. a. - j.) 00rx (1. k. - q.) 00ry (2.) 00rz (3.) 00s0 (4.) 00s1 (5.) 00s2
(6.) 00s3 (7.) 00s4 (8.) 00s5 (9.) 00s6 (10.) 00s7 (11.) 00s8
(12.) 00s9 (13.) 00sa (14.) 00sb

Longitudinal Waves 14

14.1 Introduction

ESBGD

In Grade 10 we studied pulses and waves. We looked at transverse waves more closely. In this chapter we look at another type of wave called *longitudinal* waves. In transverse waves, the motion of the particles in the medium were perpendicular to the direction of the wave. In longitudinal waves, the particles in the medium move *parallel* (in the *same* direction as) to the motion of the wave. Examples of transverse waves are water waves or light waves. An example of a longitudinal wave is a sound wave.

See introductory video: VPkqn at www.everythingscience.co.za

14.2 What is a longitudinal wave?

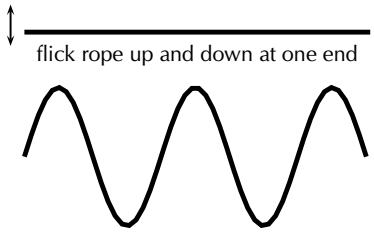
ESBGE

> *DEFINITION: Longitudinal waves*
>
> A longitudinal wave is a wave where the particles in the medium move parallel to the direction of propagation of the wave.

When we studied transverse waves we looked at two different motions: the motion of the particles of the medium and the motion of the wave itself. We will do the same for longitudinal waves.

The question is how do we construct such a wave?

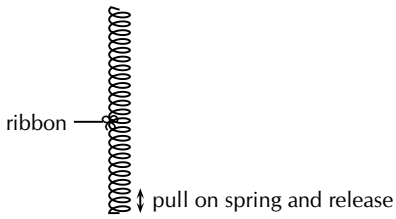
To create a transverse wave, we flick the end of for example a rope up and down. The particles move up and down and return to their equilibrium position. The wave moves from left to right and will be displaced.



A longitudinal wave is seen best in a spring that is hung from a ceiling. Do the following investigation to find out more about longitudinal waves.

Activity:	*Investigating longitudinal waves*

1. Take a spring and hang it from the ceiling. Pull the free end of the spring and release it. Observe what happens.



2. In which direction does the disturbance move?
3. What happens when the disturbance reaches the ceiling?
4. Tie a ribbon to the middle of the spring. Watch carefully what happens to the ribbon when the free end of the spring is pulled and released. Describe the motion of the ribbon.

From the investigation you will have noticed that the disturbance moves parallel to the direction in which the spring was pulled. The spring was pulled down and the wave moved up and down. The ribbon in the investigation represents one particle in the medium. The particles in the medium move in the same direction as the wave. The ribbon moves from rest upwards, then back to its original position, then down and then back to its original position.

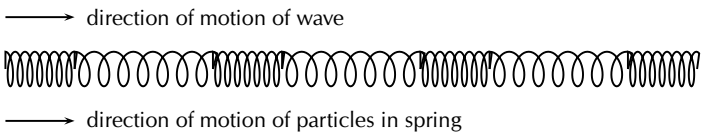


Figure 14.1: Longitudinal wave through a spring

14.3 Characteristics of Longitudinal Waves

ESBGF

As in the case of transverse waves the following properties can be defined for longitudinal waves: wavelength, amplitude, period, frequency and wave speed. However instead of peaks and troughs, longitudinal waves have *compressions* and *rarefactions*.

DEFINITION: Compression

A **compression** is a region in a longitudinal wave where the particles are closest together.

DEFINITION: Rarefaction

A **rarefaction** is a region in a longitudinal wave where the particles are furthest apart.

Compression and Rarefaction

ESBGG

As seen in Figure 14.2, there are regions where the medium is compressed and other regions where the medium is spread out in a longitudinal wave.

The region where the medium is compressed is known as a **compression** and the region where the medium is spread out is known as a **rarefaction**.

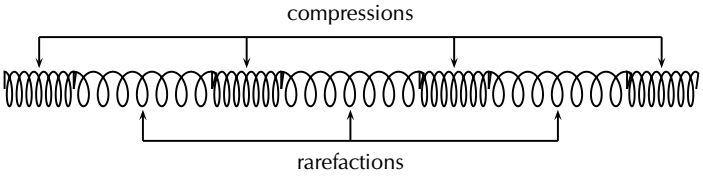


Figure 14.2: Compressions and rarefactions on a longitudinal wave

Wavelength and Amplitude

ESBGH

DEFINITION: Wavelength

The **wavelength** in a longitudinal wave is the distance between two consecutive points that are in phase.

The wavelength in a longitudinal wave refers to the distance between two consecutive compressions or between two consecutive rarefactions.

DEFINITION: Amplitude

The **amplitude** is the maximum displacement from a position of rest.

The amplitude is the distance from the equilibrium position of the medium to a compression or a rarefaction.

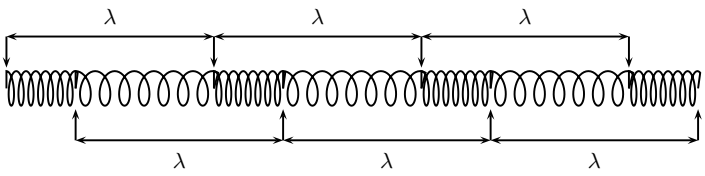


Figure 14.3: Wavelength on a longitudinal wave

Period and Frequency

ESBGI

> *DEFINITION: Period*
>
> The **period** of a wave is the time taken by the wave to move one wavelength.

> *DEFINITION: Frequency*
>
> The **frequency** of a wave is the number of wavelengths per second.

The *period* of a longitudinal wave is the time taken by the wave to move one wavelength. As for transverse waves, the symbol T is used to represent period and period is measured in seconds (s).

The *frequency* f of a wave is the number of wavelengths per second. Using this definition and the fact that the period is the time taken for 1 wavelength, we can define:

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

or alternately,

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

Speed of a Longitudinal Wave

ESBGJ

The speed of a longitudinal wave is defined as:

$$v = f \cdot \lambda$$

where
v = speed in m.s^{-1}
f = frequency in Hz
λ = wavelength in m

Example 1: *Speed of longitudinal waves*

QUESTION

The musical note A is a sound wave. The note has a frequency of 440 Hz and a wavelength of 0,784 m. Calculate the speed of the musical note.

SOLUTION

Step 1 : ***Determine what is given and what is required***

$$\begin{aligned} f &= 440\ \text{Hz} \\ \lambda &= 0{,}784\ \text{m} \end{aligned}$$

We need to calculate the speed of the musical note "A".

Step 2 : ***Determine how to approach based on what is given***
We are given the frequency and wavelength of the note. We can therefore use:

$$v = f \cdot \lambda$$

Step 3 : ***Calculate the wave speed***

$$\begin{aligned} v &= f \cdot \lambda \\ &= (440\ \text{Hz})(0{,}784\,\text{m}) \\ &= 345\,\text{m} \cdot \text{s}^{-1} \end{aligned}$$

Step 4 : ***Write the final answer***
The musical note "A" travels at 345 m·s^{-1}.

Example 2: *Speed of longitudinal waves*

QUESTION

A longitudinal wave travels into a medium in which its speed increases. How does this affect its... (write only increases, decreases, stays the same).

1. *period?*
2. *wavelength?*

SOLUTION

Step 1 : ***Determine what is required***
We need to determine how the period and wavelength of a longitudinal wave change when its speed increases.

Step 2 : ***Determine how to approach based on what is given***
We need to find the link between period, wavelength and wave speed.

Step 3 : ***Discuss how the period changes***
We know that the frequency of a longitudinal wave is dependent on the frequency of the vibrations that lead to the creation of the longitudinal wave. Therefore, the frequency is always unchanged, irrespective of any changes in speed. Since the period is the inverse of the frequency, the period remains the same.

Step 4 : ***Discuss how the wavelength changes***
The frequency remains unchanged. According to the wave equation

$$v = f\lambda$$

if f remains the same and v increases, then λ, the wavelength, must also increase.

14.4 Graphs of Particle Position, Displacement, Velocity and Acceleration

ESBGK

Tip

A particle in the medium **only** moves back and forth when a longitudinal wave moves through the medium.

When a longitudinal wave moves through the medium, the particles in the medium **only** move back and forth relative to the direction of motion of the wave. We can see this in Figure 14.4 which shows the motion of the particles in a medium as a longitudinal wave moves through the medium.

We can draw a graph of the particle's change in position from its starting point as a function of time. For the wave shown in Figure 14.4, we can draw the graph shown in Figure 14.5 for particle 0. The graph for each of the other particles will be identical.

Tip

A sound wave is produced by an oscillating object while a light wave is not. Also, because a sound wave is a mechanical wave (i.e. that it needs a medium) it

The graph of the particle's velocity as a function of time is obtained by taking the gradient of the position vs. time graph. The graph of velocity vs. time for the position vs. time graph shown in Figure 14.5 is shown is Figure 14.6.

The graph of the particle's acceleration as a function of time is obtained by taking the gradient of the velocity vs. time graph. The graph of acceleration vs. time for the position vs. time graph shown in Figure 14.5 is shown is Figure 14.7.

14.5 Sound Waves

ESBGL

Sound waves coming from a tuning fork are caused by the vibrations of the tuning fork which push against the air particles in front of it. As the air particles are pushed together a compression is formed. The particles behind the compression move further apart causing a rarefaction. As the particles continue to push against each other, the sound wave travels through the air. Due to this motion of the particles, there is a constant variation in the pressure in the air. Sound waves are therefore pressure waves. This means that in media where the particles are closer together, sound waves will travel quicker.

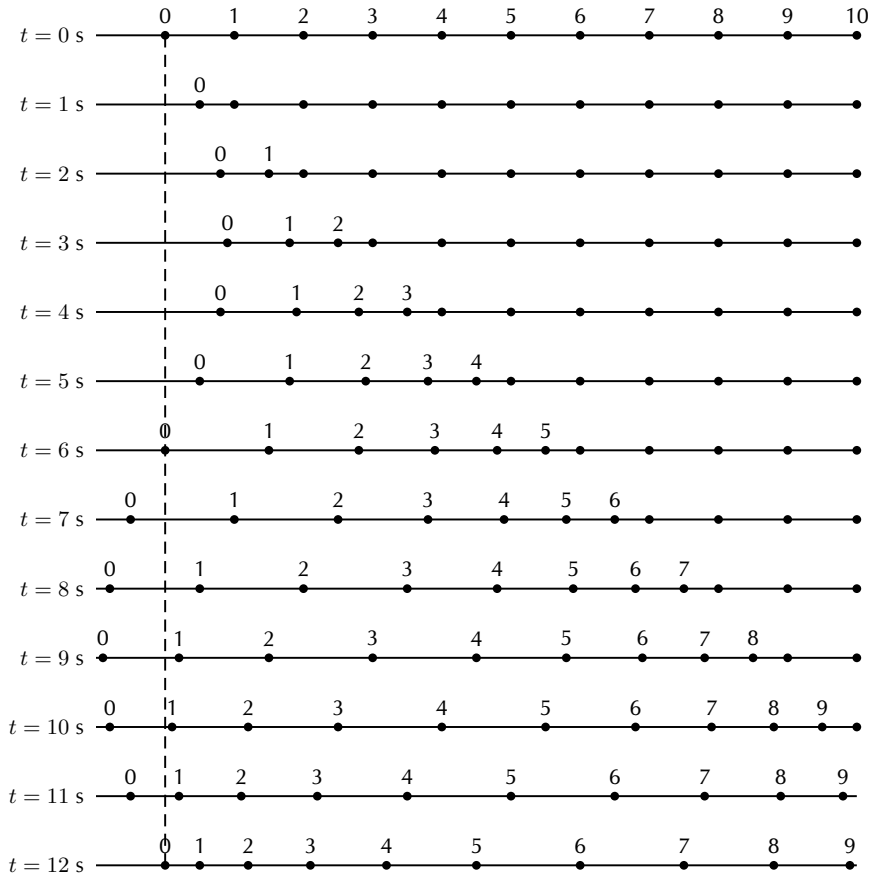


Figure 14.4: Positions of particles in a medium at different times as a longitudinal wave moves through it. The wave moves to the right. The dashed line shows the equilibrium position of particle 0.

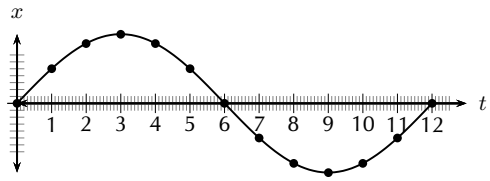


Figure 14.5: Graph of particle displacement as a function of time for the longitudinal wave shown in Figure 14.4.

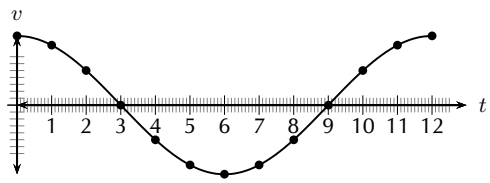


Figure 14.6: Graph of velocity as a function of time.

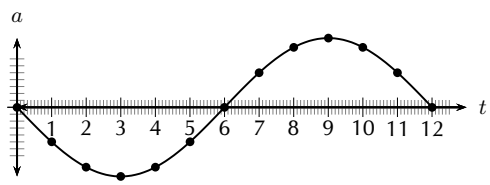


Figure 14.7: Graph of acceleration as a function of time.

Sound waves travel faster through liquids, like water, than through the air because water is denser than air (the particles are closer together). Sound waves travel faster in solids than in liquids.

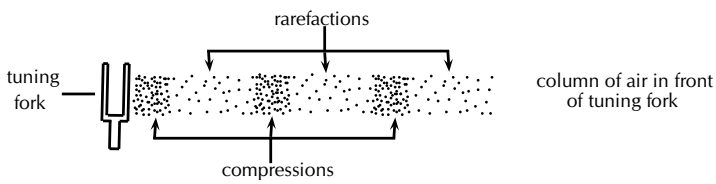


Figure 14.8: Sound waves are pressure waves and need a medium through which to travel.

A sound wave is a pressure wave. This means that regions of high pressure (compressions) and low pressure (rarefactions) are created as the sound source vibrates. These compressions and rarefactions arise because the source vibrates longitudinally and the longitudinal motion of air produces pressure fluctuations.

Sound will be studied in more detail in Chapter 15.

14.6 Seismic Waves

ESBGM

Seismic waves are waves from vibrations in the Earth (core, mantle, oceans). Seismic waves also occur on other planets, for example the moon and can be natural (due to earthquakes, volcanic eruptions or meteor strikes) or man-made (due to explosions or anything that hits the earth hard). Seismic P-waves (P for pressure) are longitudinal waves which can travel through solid and liquid.

Chapter 14 — Summary

See the summary presentation (Presentation: VPkvv at www.everythingscience.co.za)

- A longitudinal wave is a wave where the particles in the medium move parallel to the direction in which the wave is travelling.
- Longitudinal waves consist of areas of higher pressure, where the particles in the medium are closest together (compressions) and areas of lower pressure, where the particles in the medium are furthest apart (rarefactions).
- The wavelength of a longitudinal wave is the distance between two consecutive compressions, or two consecutive rarefactions.
- The relationship between the period (T) and frequency (f) is given by

$$T = \frac{1}{f} \text{ or } f = \frac{1}{T}.$$

- The relationship between wave speed (v), frequency (f) and wavelength (λ) is given by

$$v = f\lambda.$$

- Graphs of position vs time, velocity vs time and acceleration vs time can be drawn and are summarised in figures
- Sound waves are examples of longitudinal waves. The speed of sound depends on the medium, temperature and pressure. Sound waves travel faster in solids than in liquids, and faster in liquids than in gases. Sound waves also travel faster at higher temperatures and higher pressures.

Chapter 14 End of Chapter Exercises

1. Which of the following is not a longitudinal wave?
   (a) seismic P-wave
   (b) light
   (c) sound

(d) ultrasound

2. Which of the following media can sound not travel through?
   (a) solid
   (b) liquid
   (c) gas
   (d) vacuum
3. Select a word from Column B that best fits the description in Column A:

Column A	**Column B**
A. waves in the air caused by vibrations	longitudinal waves
B. waves that move in one direction, but medium moves in another	frequency
D. waves and medium that move in the same direction	white noise
E. the distance between consecutive points of a wave which are in phase	amplitude
F. how often a single wavelength goes by	sound waves
G. half the difference between high points and low points of waves	standing waves
H. the distance a wave covers per time interval	transverse waves
I. the time taken for one wavelength to pass a point	wavelength
	music
	sounds
	wave speed

4. A longitudinal wave has a crest to crest distance of 10 m. It takes the wave 5 s to pass a point.
   (a) What is the wavelength of the longitudinal wave?
   (b) What is the speed of the wave?
5. A flute produces a musical sound travelling at a speed of 320 m.s^{-1}. The frequency of the note is 256 Hz. Calculate:
   (a) the period of the note
   (b) the wavelength of the note
6. A person shouts at a cliff and hears an echo from the cliff 1 s later. If the speed of sound is 344 m·s^{-1}, how far away is the cliff?
7. A wave travels from one medium to another and the speed of the wave decreases. What will the effect be on the ... (write only *increases, decreases* or *remains the same*)
   (a) wavelength?
   (b) period?

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(1.) 00sc (2.) 00sd (3.) 00se (4.) 00sf (5.) 00sg (6.) 00sh
(7.) 00si

Sound 15

15.1 Introduction

ESBGN

Now that we have studied the basics of longitudinal waves, we are ready to study sound waves in detail.

Have you ever thought about how amazing your sense of hearing is? It is actually pretty remarkable. There are many types of sounds: a car horn, a laughing baby, a barking dog, and somehow your brain can sort it all out. Though it seems complicated, it is rather simple to understand once you learn a very simple fact. Sound is a wave. So you can use everything you know about waves to explain sound.

See introductory video: VPkxk at www.everythingscience.co.za

15.2 Characteristics of a Sound Wave

ESBGO

Since sound is a wave, we can relate the properties of sound to the properties of a wave. The basic properties of sound are: pitch, loudness and tone.

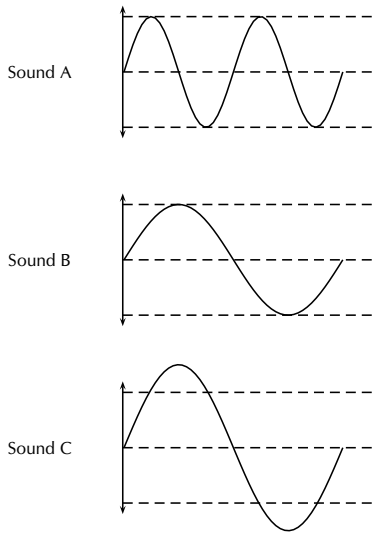


Figure 15.1: Pitch and loudness of sound. Sound B has a *lower* pitch (lower frequency) than Sound A and is *softer* (smaller amplitude) than Sound C.

Pitch

ESBGP

The frequency of a sound wave is what your ear understands as pitch. A higher frequency sound has a higher pitch, and a lower frequency sound has a lower pitch. In Figure 15.1 sound A has a higher pitch than sound B. For instance, the chirp of a bird would have a high pitch, but the roar of a lion would have a low pitch.

The human ear can detect a wide range of frequencies. Frequencies from 20 to 20 000 Hz are audible to the human ear. Any sound with a frequency below 20 Hz is known as an **infrasound** and any sound with a frequency above 20 000 Hz is known as an **ultrasound**.

Table 15.1 lists the ranges of some common animals compared to humans.

Table 15.1: Range of frequencies

	lower frequency (Hz)	upper frequency (Hz)
Humans	20	20 000
Dogs	50	45 000
Cats	45	85 000
Bats	20	120 000
Dolphins	0,25	200 000
Elephants	5	10 000

Activity: *Range of Wavelengths*

Using the information given in Table 15.1, calculate the lower and upper wavelengths that each species can hear. Assume the speed of sound in air is 344 $m{\cdot}s^{-1}$.

Loudness

ESBGQ

The amplitude of a sound wave determines its loudness or volume. A larger amplitude means a louder sound, and a smaller amplitude means a softer sound. In Figure 15.1 sound C is louder than sound B. The vibration of a source sets the amplitude of a wave. It transmits energy into the medium through its vibration. More energetic vibration corresponds to larger amplitude. The molecules move back and forth more vigorously.

The loudness of a sound is also determined by the sensitivity of the ear. The human ear is more sensitive to some frequencies than to others. The volume we receive thus depends on both the amplitude of a sound wave and whether its frequency lies in a region where the ear is more or less sensitive.

Tone

ESBGR

Tone is a measure of the quality of the sound wave. For example, the quality of the sound produced in a particular musical instruments depends on which harmonics are superposed and in which

proportions. The harmonics are determined by the standing waves that are produced in the instrument. Chapter 16 will explain the physics of music in greater detail.

The quality (timbre) of the sound heard depends on the pattern of the incoming vibrations, i.e. the *shape* of the sound wave. The more irregular the vibrations, the more jagged is the shape of the sound wave and the harsher is the sound heard.

15.3 Speed of Sound

ESBGS

The speed of sound depends on the medium the sound is travelling in. Sound travels faster in solids than in liquids, and faster in liquids than in gases. This is because the density of solids is higher than that of liquids which means that the particles are closer together. Sound can be transmitted more easily.

The speed of sound also depends on the temperature of the medium. The hotter the medium is, the faster its particles move and therefore the quicker the sound will travel through the medium. When we heat a substance, the particles in that substance have more kinetic energy and vibrate or move faster. Sound can therefore be transmitted more easily and quickly in hotter substances.

Sound waves are pressure waves. The speed of sound will therefore be influenced by the pressure of the medium through which it is travelling. At sea level the air pressure is higher than high up on a mountain. Sound will travel faster at sea level where the air pressure is higher than it would at places high above sea level.

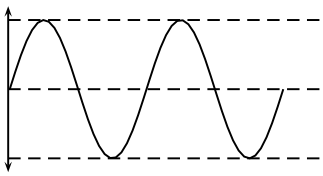
DEFINITION: Speed of sound

The speed of sound in air, at sea level, at a temperature of 21°C and under normal atmospheric conditions, is 344 $m \cdot s^{-1}$.

Exercise 15 - 1

Study the following diagram representing a musical note. Redraw the diagram for a note

1. with a higher pitch
2. that is louder
3. that is softer



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(1.) 00sj (2.) 00sk (3.) 00sm
See video: VPkxq at www.everythingscience.co.za

15.4 Physics of the Ear and Hearing

ESBGT

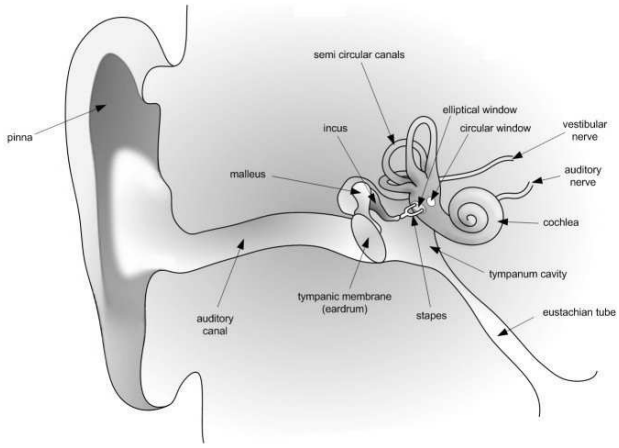


Figure 15.2: Diagram of the human ear.

The human ear is divided into three main sections: the outer, middle, and inner ear. Let's follow the journey of a sound wave from the pinna (outermost part) to the auditory nerve (innermost part) which transmits a signal to the brain. The pinna is the part of the ear we typically think of when we refer to the ear. Its main function is to collect and focus an incident sound wave. The wave then travels through the ear canal until it meets the eardrum. The pressure fluctuations of the sound wave make the eardrum vibrate. The three very small bones of the middle ear, the malleus (hammer), the incus (anvil), and the stapes (stirrup), transmit the signal through to the elliptical window. The elliptical window is the beginning of the inner ear. From the elliptical window the sound waves are transmitted through the liquid in the inner ear and interpreted as sounds by the brain. The inner ear, made of the semicircular canals, the cochlea, and the auditory nerve, is filled with fluid. The fluid allows the body to detect quick movements and maintain balance. The snail-shaped cochlea is covered in nerve cells. There are more than 25 000 hairlike nerve cells. Different nerve cells vibrate with different frequencies. When a nerve cell vibrates, it releases electrical impulses to the auditory nerve. The impulses are sent to the brain through the auditory nerve and understood as sound.

Intensity of Sound

ESBGU

Intensity is one indicator of amplitude. Intensity is the energy transmitted over a unit of area each second.

Extension:	*Intensity*

Intensity is defined as:

$$\text{Intensity} = \frac{\text{energy}}{\text{time} \times \text{area}} = \frac{\text{power}}{\text{area}}$$

By the definition of intensity, we can see that the units of intensity are

$$\frac{\text{Joules}}{\text{s} \cdot \text{m}^2} = \frac{\text{Watts}}{\text{m}^2}$$

The unit of intensity is the **decibel** (symbol: dB). This reduces to an SI equivalent of $\text{W} \cdot \text{m}^{-2}$.

The average threshold of hearing is $10^{-12}\ \text{W} \cdot \text{m}^{-2}$. Below this intensity, the sound is too soft for the ear to hear. The threshold of pain is $1.0\ \text{W} \cdot \text{m}^{-2}$. Above this intensity a sound is so loud it becomes uncomfortable for the ear.

Notice that there is a factor of 10^{12} between the thresholds of hearing and pain. This is one reason we define the decibel (dB) scale.

Extension:	*dB Scale*

The intensity in dB of a sound of intensity I, is given by:

$$\beta = 10\ \log \frac{I}{I_o} \qquad I_o = 10^{-12}\ \text{W} \cdot \text{m}^{-2} \tag{15.1}$$

In this way we can compress the whole hearing intensity scale into a range from 0 dB to 120 dB.

Table 15.2: Examples of sound intensities.

Source	**Intensity** (dB)	**Times greater than hearing threshold**
Rocket Launch	180	10^{18}
Jet Plane	140	10^{14}
Threshold of Pain	120	10^{12}
Rock Band	110	10^{11}
Subway Train	90	10^{9}
Factory	80	10^{8}
City Traffic	70	10^{7}
Normal Conversation	60	10^{6}
Library	40	10^{4}
Whisper	20	10^{2}
Threshold of hearing	0	0

Notice that there are sounds which exceed the threshold of pain. Exposure to these sounds can cause immediate damage to hearing. In fact, exposure to sounds from 80 dB and above can damage hearing over time. Measures can be taken to avoid damage, such as wearing earplugs or ear muffs. Limiting exposure time and increasing distance between you and the source are also important steps for protecting your hearing.

Activity:	*Importance of Safety Equipment*

Working in groups of 5, discuss the importance of safety equipment such as ear protectors for workers in loud environments, e.g. those who use jack hammers or direct aeroplanes to

their parking bays. Write up your conclusions in a one page report. Some prior research into the importance of safety equipment might be necessary to complete this group discussion.

See simulation: Vpkyl at www.everythingscience.co.za)

15.5 Ultrasound

ESBGV

Ultrasound is sound with a frequency that is higher than 20 kHz. Some animals, such as dogs, dolphins, and bats, have an upper limit that is greater than that of the human ear and can hear ultrasound.

The most common use of ultrasound is to create images, and has industrial and medical applications. The use of ultrasound to create images is based on the reflection and transmission of a wave at a boundary. When an ultrasound wave travels inside an object that is made up of different materials such as the human body, each time it encounters a boundary, e.g. between bone and muscle, or muscle and fat, part of the wave is reflected and part of it is transmitted. The reflected rays are detected and used to construct an image of the object.

FACT

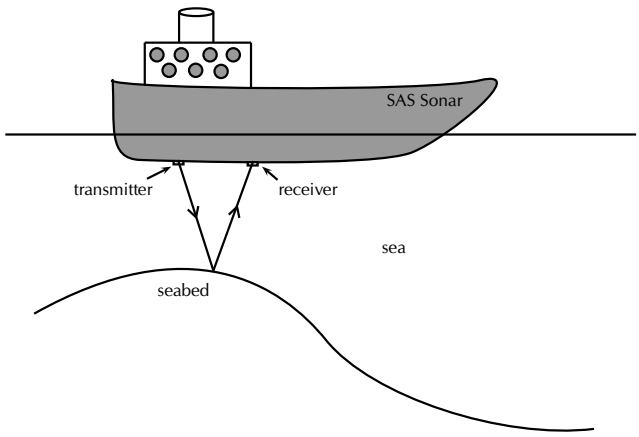
Ultrasound generator/speaker systems are sold with claims that they frighten away rodents and insects, but there is no scientific evidence that the devices work; controlled tests have shown that rodents quickly learn that the speakers are harmless.

Ultrasound in medicine can visualise muscle and soft tissue, making them useful for scanning the organs, and is commonly used during pregnancy. Ultrasound is a safe, non-invasive method of looking inside the human body. Ultrasound sources may be used to generate local heating in biological tissue, with applications in physical therapy and cancer treatment. Focused ultrasound sources may be used to break up kidney stones.

Ultrasonic cleaners, sometimes called supersonic cleaners, are used at frequencies from 20-40 kHz for jewellery, lenses and other optical parts, watches, dental instruments, surgical instruments and industrial parts. These cleaners consist of containers with a fluid in which the object to be cleaned is placed. Ultrasonic waves are then sent into the fluid. The main mechanism for cleaning action in an ultrasonic cleaner is actually the energy released from the collapse of millions of microscopic bubbles occurring in the liquid of the cleaner.

15.6 SONAR

ESBGW



Ships on the ocean make use of the reflecting properties of sound waves to determine the depth of the ocean. A sound wave is transmitted and bounces off the seabed. Because the speed of sound is

known and the time lapse between sending and receiving the sound can be measured, the distance from the ship to the bottom of the ocean can be determined, This is called sonar, which stands from **So**und **N**avigation **A**nd **R**anging.

Echolocation

ESBGX

Animals like dolphins and bats make use of sounds waves to find their way. Just like ships on the ocean, bats use sonar to navigate. Ultrasound waves that are sent out are reflected off the objects around the animal. Bats, or dolphins, then use the reflected sounds to form a "picture" of their surroundings. This is called echolocation.

Example 1: SONAR

QUESTION

A ship sends a signal to the bottom of the ocean to determine the depth of the ocean. The speed of sound in sea water is 1450 $\mathrm{m.s^{-1}}$ *If the signal is received 1,5 seconds later, how deep is the ocean at that point?*

SOLUTION

Step 1 : ***Identify what is given and what is being asked:***

$$\begin{aligned} s &= 1450\ \mathrm{m.s^{-1}} \\ t &= 1{,}5\ \mathrm{s\ there\ and\ back} \\ \therefore t &= 0{,}75\ \mathrm{s\ one\ way} \\ d &= ? \end{aligned}$$

Step 2 : ***Calculate the distance:***

$$\begin{aligned} \mathrm{Distance} &= \mathrm{speed} \times \mathrm{time} \\ d &= s \times t \\ &= 1450 m.s^{-1} \times 0{,}75 s \\ &= 1087{,}5\ \mathrm{m} \end{aligned}$$

Chapter 15 — Summary

See the summary presentation (▶ Presentation: VPkza at www.everythingscience.co.za)

- Sound waves are longitudinal waves
- The **frequency** of a sound is an indication of how high or low the *pitch* of the sound is.
- The human ear can hear frequencies from 20 to 20 000 Hz.
  Infrasound waves have frequencies lower than 20 Hz.
  Ultrasound waves have frequencies higher than 20 000 Hz.
- The **amplitude** of a sound determines its *loudness* or volume.
- The **tone** is a measure of the *quality* of a sound wave.
- The speed of sound in air is around 340 $m.s^{-1}$. It is dependent on the temperature, height above sea level and the phase of the medium through which it is travelling.
- Sound travels faster when the medium is hot.
- Sound travels faster in a solid than a liquid and faster in a liquid than in a gas.
- Sound travels faster at sea level where the air pressure is higher.
- The intensity of a sound is the energy transmitted over a certain area. Intensity is a measure of frequency.
- Ultrasound can be used to form pictures of things we cannot see, like unborn babies or tumours.
- Echolocation is used by animals such as dolphins and bats to "see" their surroundings by using ultrasound.
- Ships use sonar to determine how deep the ocean is or to locate shoals of fish.

Chapter 15 End of Chapter Exercises

1. Choose a word from column B that best describes the concept in column A.

Column A	Column B
pitch of sound	amplitude
loudness of sound	frequency
quality of sound	speed
	waveform

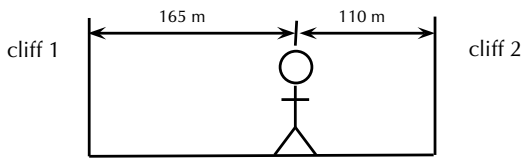
2. A tuning fork, a violin string and a loudspeaker are producing sounds. This is because they are all in a state of:
   a. compression
   b. rarefaction
   c. rotation
   d. tension
   e. vibration
3. What would a drummer do to make the sound of a drum give a note of lower pitch?
   a. hit the drum harder

b. hit the drum less hard
c. hit the drum near the edge
d. loosen the drum skin
e. tighten the drum skin

4. What is the approximate range of audible frequencies for a healthy human?
   a. 0.2 Hz → 200 Hz
   b. 2 Hz → 2 000 Hz
   c. 20 Hz → 20 000 Hz
   d. 200 Hz → 200 000 Hz
   e. 2 000 Hz → 2 000 000 Hz
5. X and Y are different wave motions. In air, X travels much faster than Y but has a much shorter wavelength. Which types of wave motion could X and Y be?

	X	Y
a)	microwaves	red light
b)	radio	infra red
c)	red light	sound
d)	sound	ultraviolet
e)	ultraviolet	radio

6. Astronauts are in a spaceship orbiting the moon. They see an explosion on the surface of the moon. Why can they not hear the explosion?
   a. explosions do not occur in space
   b. sound cannot travel through a vacuum
   c. sound is reflected away from the spaceship
   d. sound travels too quickly in space to affect the ear drum
   e. the spaceship would be moving at a supersonic speed
7. A man stands between two cliffs as shown in the diagram and claps his hands once.



   Assuming that the velocity of sound is 330 m.s^{-1}, what will be the time interval between the two loudest echoes?
   a. $\frac{1}{6}$ s
   b. $\frac{5}{6}$ s
   c. $\frac{1}{3}$ s
   d. 1 s
   e. $\frac{2}{3}$ s
8. A dolphin emits an ultrasonic wave with frequency of 0,15 MHz. The speed of the ultrasonic wave in water is 1 500 m.s^{-1}. What is the wavelength of this wave in water?
   a. 0.1 mm
   b. 1 cm
   c. 10 cm
   d. 10 m
   e. 100 m
9. The amplitude and frequency of a sound wave are both increased. How are the loudness and pitch of the sound affected?

	loudness	pitch
a)	increased	raised
b)	increased	unchanged
c)	increased	lowered
d)	decreased	raised
e)	decreased	lowered

10. A jet fighter travels slower than the speed of sound. Its speed is said to be:
    a. Mach 1
    b. supersonic
    c. isosonic
    d. hypersonic
    e. infrasonic
11. A sound wave is different from a light wave in that a sound wave is:
    a. produced by a vibrating object and a light wave is not.
    b. not capable of travelling through a vacuum.
    c. not capable of diffracting and a light wave is.
    d. capable of existing with a variety of frequencies and a light wave has a single frequency.
12. At the same temperature, sound waves have the fastest speed in:
    a. rock
    b. milk
    c. oxygen
    d. sand
13. Two sound waves are travelling through a container of nitrogen gas. The first wave has a wavelength of 1,5 m, while the second wave has a wavelength of 4,5 m. The velocity of the second wave must be:
    a. $\frac{1}{9}$ the velocity of the first wave.
    b. $\frac{1}{3}$ the velocity of the first wave.
    c. the same as the velocity of the first wave.
    d. three times larger than the velocity of the first wave.
    e. nine times larger than the velocity of the first wave.
14. Sound travels at a speed of 340 m·s^{-1}. A straw is 0,25 m long. The standing wave set up in such a straw with one end closed has a wavelength of 1,0 m. The standing wave set up in such a straw with both ends open has a wavelength of 0,50 m.
    a. calculate the frequency of the sound created when you blow across the straw with the bottom end closed.
    b. calculate the frequency of the sound created when you blow across the straw with the bottom end open.
15. A lightning storm creates both lightning and thunder. You see the lightning almost immediately since light travels at $3 \times 10^8\ \mathrm{m \cdot s^{-1}}$. After seeing the lightning, you count 5 s and then you hear the thunder. Calculate the distance to the location of the storm.
16. A person is yelling from a second story window to another person standing at the garden gate, 50 m away. If the speed of sound is 344 m·s^{-1}, how long does it take the sound to reach the person standing at the gate?
17. A piece of equipment has a warning label on it that says, "Caution! This instrument produces 140 decibels." What safety precaution should you take before you turn on the instrument?
18. What property of sound is a measure of the amount of energy carried by a sound wave?
19. How is intensity related to loudness?
20. Person 1 speaks to person 2. Explain how the sound is created by person 1 and how it is possible for person 2 to hear the conversation.
21. Sound cannot travel in space. Discuss what other modes of communication astronauts can use when they are outside the space shuttle?
22. An automatic focus camera uses an ultrasonic sound wave to focus on objects. The camera sends out sound waves which are reflected off distant objects and return to the camera. A sensor detects the time it takes for the waves to return and then determines the distance an object is from the camera. If a sound wave (speed = 344 m·s^{-1}) returns to the camera 0,150 s after leaving the camera, how far away is the object?

23. Calculate the frequency (in Hz) and wavelength of the annoying sound made by a mosquito when it beats its wings at the average rate of 600 wing beats per second. Assume the speed of the sound waves is 344 $m{\cdot}s^{-1}$.
24. How does halving the frequency of a wave source affect the speed of the waves?
25. Humans can detect frequencies as high as 20 000 Hz. Assuming the speed of sound in air is 344 $m{\cdot}s^{-1}$, calculate the wavelength of the sound corresponding to the upper range of audible hearing.
26. An elephant trumpets at 10 Hz. Assuming the speed of sound in air is 344 $m{\cdot}s^{-1}$, calculate the wavelength of this infrasonic sound wave made by the elephant.
27. A ship sends a signal out to determine the depth of the ocean. The signal returns 2,5 seconds later. If sound travels at 1450 $m.s^{-1}$ in sea water, how deep is the ocean at that point?

More practice video solutions or help at
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(1.) 00sn	(2.) 00sp	(3.) 00sq	(4.) 00sr	(5.) 00ss	(6.) 00st
(7.) 00su	(8.) 00sv	(9.) 00sw	(10.) 00sx	(11.) 00sy	(12.) 00sz
(13.) 00t0	(14.) 00t1	(15.) 00t2	(16.) 00t3	(17.) 01xi	(18.) 01xj
(19.) 01xk	(20.) 01xm	(21.) 01xn	(22.) 01xp	(23.) 01xq	(24.) 01xr
(25.) 01xs	(26.) 01xt	(27.) 01xu			

The Physics of Music 16

16.1 Introduction

ESBGY

What is your favourite musical instrument? How do you play it? Do you pluck a string, like a guitar? Do you blow through it, like a flute? Do you hit it, like a drum? All musical instruments work by making standing waves. Each instrument has a unique sound because of the special waves made in it. These waves could be in the strings of a guitar or violin. They could also be in the skin of a drum or a tube of air in a trumpet. These waves are picked up by the air and later reach your ear as sound.
In Grade 10, you learned about standing waves and boundary conditions. We saw a rope that was:

- fixed at both ends
- fixed at one end and free at the other

We also saw a pipe that was:

- closed at both ends
- open at both ends
- open at one end, closed at the other

String and wind instruments are good examples of standing waves on strings and pipes.

One way to describe standing waves is to count nodes. Recall that a node is a point on a string that does not move as the wave changes. The anti-nodes are the highest and lowest points on the wave. There is a node at each end of a fixed string. There is also a node at the closed end of a pipe. But an open end of a pipe has an anti-node.

What causes a standing wave? There are incident and reflected waves travelling back and forth on our string or pipe. For some frequencies, these waves combine in just the right way so that the whole wave appears to be standing still. These special cases are called harmonic frequencies, or **harmonics**. They depend on the length and material of the medium.

See introductory video: VPkzh at www.everythingscience.co.za

> *DEFINITION: Harmonic*
>
> A **harmonic** frequency is a frequency at which standing waves can be made in a particular object or on a particular instrument.

16.2 Standing Waves in String Instruments

ESBGZ

Let us look at a basic "instrument": a string pulled tight and fixed at both ends. When you pluck the string, you hear a certain pitch. This pitch is made by a certain frequency. What causes the string to emit sounds at this pitch?

You have learned that the frequency of a standing wave depends on the length of the wave. The wavelength depends on the nodes and anti-nodes. The longest wave that can "fit" on the string is shown in Figure 16.1. This is called the **fundamental** or **natural frequency** of the string. The string has nodes at both ends. The wavelength of the fundamental is twice the length of the string.

Now put your finger on the centre of the string. Hold it down gently and pluck it. The standing wave now has a node in the middle of the string. There are three nodes. We can fit a whole wave between the ends of the string. This means the wavelength is equal to the length of the string. This wave is called the first harmonic. As we add more nodes, we find the second harmonic, third harmonic, and so on. We must keep the nodes equally spaced or we will lose our standing wave.

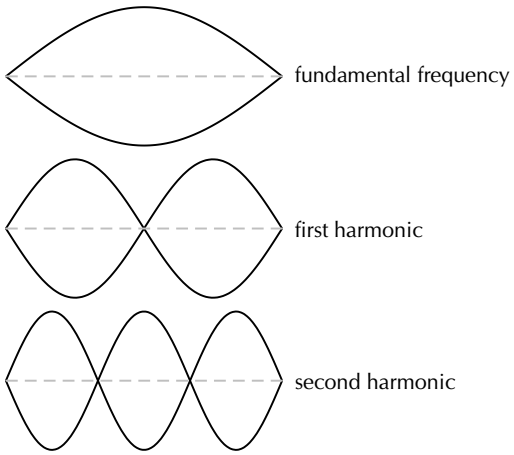


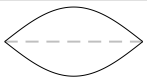
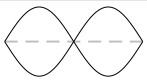
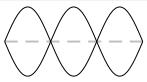
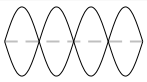
Figure 16.1: Harmonics on a string fixed at both ends.

Activity: *Waves on a String Fixed at Both Ends*

This chart shows various waves on a string. The string length L is the dashed line.

1. Fill in the:
   - number of nodes
   - number of anti-nodes
   - wavelength in terms of L

   The first and last waves are done for you.

Wave	Nodes	Antinodes	Wavelength
	2	1	$2L$
			
			
	5	4	$\frac{L}{2}$

2. Use the chart to find a formula for the wavelength in terms of the number of nodes.

You should have found this formula:

$$\lambda = \frac{2L}{n-1}$$

Here, n is the number of nodes. L is the length of the string. The frequency f is:

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

Here, v is the velocity of the wave. This may seem confusing. The wave is a *standing* wave, so how can it have a velocity? But one standing wave is made up of many waves that travel back and forth on the string. Each of these waves has the same velocity. This speed depends on the mass and tension of the string.

Example 1: *Harmonics on a String*

QUESTION

We have a standing wave on a string that is 65 cm long. The wave has a velocity of 143 m.s^{-1}. Find the frequencies of the fundamental, first, second, and third harmonics.

SOLUTION

Step 1 : ***Identify what is given and what is asked:***

$$\begin{aligned} \mathrm{L} &= 65\ \mathrm{cm} = 0.65\ \mathrm{m} \\ v &= 143\ \mathrm{m.s^{-1}} \\ f &= ? \end{aligned}$$

To find the frequency we will use $f = \frac{v}{\lambda}$

Step 2 : ***Find the wavelength for each harmonic:***
To find f we need the wavelength of each harmonic ($\lambda = \frac{2L}{n-1}$). The wavelength is then substituted into $f = \frac{v}{\lambda}$ to find the harmonics. The table below shows the calculations.

	Nodes	**Wavelength** $\lambda = \frac{2L}{n-1}$	**Frequency** $f = \frac{v}{\lambda}$
Fundamental frequency f_o	2	$\frac{2(0{,}65)}{2-1}$ = 1,3	$\frac{143}{1{,}3}$ = 110 Hz
First harmonic f_1	3	$\frac{2(0{,}65)}{3-1} = 0{,}65$	$\frac{143}{0{,}65}$ = 220 Hz
Second harmonic f_2	4	$\frac{2(0{,}65)}{4-1} = 0{,}43$	$\frac{143}{0{,}43} = 330$ Hz
Third harmonic f_3	5	$\frac{2(0{,}65)}{5-1} = 0{,}33$	$\frac{143}{0{,}33} = 440$ Hz

110 Hz is the natural frequency of the A string on a guitar. The third harmonic, at 440 Hz, is the note that orchestras use for tuning.

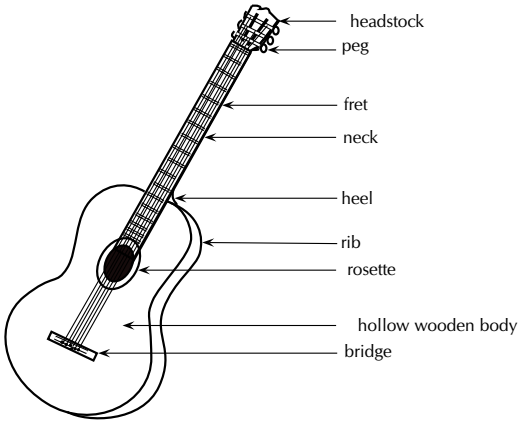
Extension:	*Guitar*

Guitars use strings with high tension. The length, tension and mass of the strings affect the pitches you hear. High tension and short strings make high frequencies; low tension and long strings make low frequencies. When a string is first plucked, it vibrates at many frequencies. All of these except the harmonics are quickly filtered out. The harmonics make up the tone we hear.

The body of a guitar acts as a large wooden soundboard. Here is how a soundboard works: the body picks up the vibrations of the strings. It then passes these vibrations to the air. A sound hole allows the soundboard of the guitar to vibrate more freely. It also helps sound waves to get out of the body.

The neck of the guitar has thin metal bumps on it called frets. Pressing a string against a fret shortens the length of that string. This raises the natural frequency and the pitch of that string.

Most guitars use an "equal tempered" tuning of 12 notes per octave. A 6 string guitar has a range of 4 $\frac{1}{2}$ octaves with pitches from 82.407 Hz (low E) to 2093 kHz (high C). Harmonics may reach over 20 kHz, in the inaudible range.

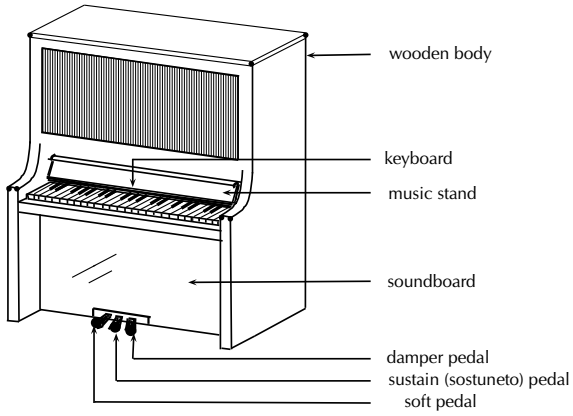


Extension:	*Piano*

Let us look at another stringed instrument: the piano. The piano has strings that you cannot see. When a key is pressed, a felt-tipped hammer hits a string inside the piano. The pitch depends on the length, tension and mass of the string. But there are many more strings than keys on a piano. This is because the short and thin strings are not as loud as the long and heavy strings. To make up for this, the higher keys have groups of two to four strings each.

The soundboard in a piano is a large cast iron plate. It picks up vibrations from the strings. This heavy plate can withstand over 200 tons of pressure from string tension! Its mass also allows the piano to sustain notes for long periods of time.

The piano has a wide frequency range, from 27,5 Hz (low A) to 4186,0 Hz (upper C). But these are just the fundamental frequencies. A piano plays complex, rich tones with over 20 harmonics per note. Some of these are out of the range of human hearing. Very low piano notes can be heard mostly because of their higher harmonics.



16.3 Standing Waves in Wind Instruments

ESBHA

A wind instrument is an instrument that is usually made with a pipe or thin tube. Examples of wind instruments are recorders, clarinets, flutes, organs etc.

When one plays a wind instrument, the air that is pushed through the pipe vibrates and standing waves are formed. Just like with strings, the wavelengths of the standing waves will depend on the length of the pipe and whether it is open or closed at each end. Let's consider each of the following situations:

- A pipe with both ends open, like a flute or organ pipe.
- A pipe with one end open and one closed, like a clarinet.

If you blow across a small hole in a pipe or reed, it makes a sound. If both ends are open, standing waves will form according to figure 16.2. You will notice that there is an anti-node at each end. In the next activity you will find how this affects the wavelengths.

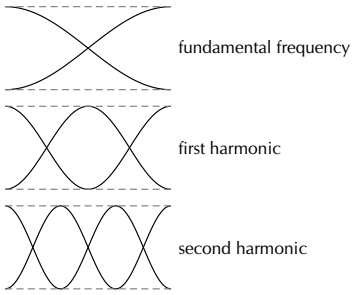


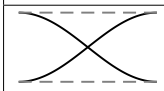
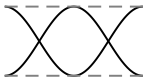
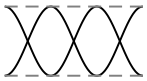
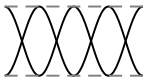
Figure 16.2: Harmonics in a pipe open at both ends.

Activity:	*Waves in a Pipe Open at Both Ends*

This chart shows some standing waves in a pipe open at both ends. The pipe (shown with dashed lines) has length L.

1. Fill in the:
   - number of nodes
   - number of anti-nodes
   - wavelength in terms of L

   The first and last waves are done for you.

Wave	Nodes	Antinodes	Wavelength
	1	2	$2L$
			
			
	4	5	$\frac{L}{2}$

2. Use the chart to find a formula for the wavelength in terms of the number of nodes.

The formula is different because there are more anti-nodes than nodes. The right formula is:

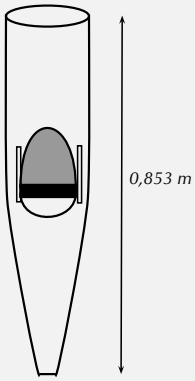
$$\lambda_n = \frac{2L}{n}$$

Here, n is still the number of nodes.

Example 2: *The Organ Pipe*

QUESTION

An open organ pipe is 0,853 m long. The speed of sound in air is 345 m.s^{-1}. Can this pipe play middle C? (Middle C has a frequency of about 262 Hz)



SOLUTION

The main frequency of a note is the fundamental frequency. The fundamental frequency of the open pipe has one node.

Step 1 : ***To find the frequency we will use the equation:***

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

We need to find the wavelength first.

$$\begin{aligned} \lambda &= \frac{2L}{n} \\ &= \frac{2(0{,}853)}{1} \\ &= 1{,}706 \text{ m} \end{aligned}$$

Step 2 : ***Now we can calculate the frequency:***

$$\begin{aligned} f &= \frac{v}{\lambda} \\ &= \frac{345}{1{,}706} \\ &= 202 \text{ Hz} \end{aligned}$$

This is lower than 262 Hz, so this pipe will not play middle C. We will need a shorter pipe for a higher pitch.

Example 3: *The Flute*

QUESTION

A flute can be mode led as a metal pipe open at both ends. (One end looks closed but the flute has an embouchure, or hole for the player to blow across. This hole is large enough for air to escape on that side as well.) If the fundamental note of a flute is middle C (262 Hz) , how long is the flute? The speed of sound in air is 345 m.s^{-1}.

SOLUTION

We can calculate the length of the flute from $\lambda = \frac{2L}{n}$ but

Step 1 : ***We need to calculate the wavelength first:***

$$\begin{aligned} f &= \frac{v}{\lambda} \\ 262 &= \frac{345}{\lambda} \\ \lambda &= \frac{345}{262} = 1{,}32 \text{ m} \end{aligned}$$

Step 2 : ***Using the wavelength, we can now solve for L:***

$$\begin{aligned} \lambda &= \frac{2L}{n} \\ &= \frac{2L}{1} \\ L &= \frac{1{,}32}{2} = 0{,}66 \text{ m} \end{aligned}$$

Now let's look at a pipe that is open on one end and closed on the other. This pipe has a node at one end and an antinode at the other. An example of a musical instrument that has a node at one end and an antinode at the other is a clarinet. In the activity you will find out how the wavelengths are affected.

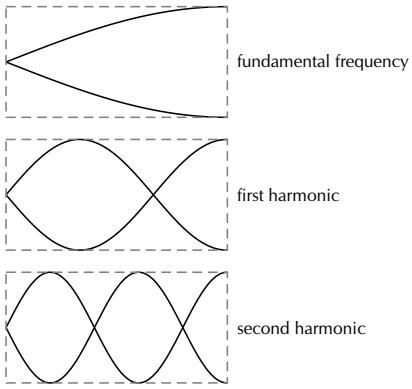


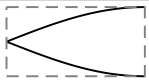
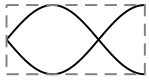
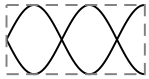
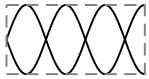
Figure 16.3: Harmonics in a pipe open at one end.

Activity: *Waves in a Pipe open at One End*

This chart shows some standing waves in a pipe open at *one* end. The pipe (shown as dashed lines) has length L.

1. Fill in the:
   - number of nodes
   - number of anti-nodes
   - wavelength in terms of L

   The first and last waves are done for you.

Wave	Nodes	Antinodes	Wavelength
	1	1	$4L$
			
			
	4	4	$\frac{4L}{7}$

2. Use the chart to find a formula for the wavelength in terms of the number of nodes.

The right formula for this pipe is:

$$\lambda_n = \frac{4L}{2n-1}$$

A long wavelength has a low frequency and low pitch. If you took your pipe from the last example and covered one end, you should hear a much lower note! Also, the wavelengths of the harmonics for this tube are *not* integer multiples of each other.

Example 4: *The Clarinet*

QUESTION

A clarinet can be modelled as a wooden pipe closed on one end and open on the other. The player blows into a small slit on one end. A reed then vibrates in the mouthpiece. This makes the standing wave in the air. What is the fundamental frequency of a clarinet 60 cm long? The speed of sound in air is 345 m.s^{-1}.

SOLUTION

Step 1 : ***Identify what is given and what is asked:***
We are given:

$$\begin{aligned} L &= 60 \text{ cm} \\ v &= 345 \text{ m.s}^{-1} \\ f &= ? \end{aligned}$$

Step 2 : ***To find the frequency we will use the equation $f = \frac{v}{\lambda}$ but we need to find the wavelength first:***

$$\begin{aligned} \lambda &= \frac{4L}{2n-1} \\ &= \frac{4(0{,}60)}{2(1)-1} \\ &= 2{,}4 \text{ m} \end{aligned}$$

Step 3 : ***Now, using the wavelength you have calculated, find the frequency:***

$$\begin{aligned} f &= \frac{v}{\lambda} \\ &= \frac{345}{2{,}4} \\ &= 144 \text{ Hz} \end{aligned}$$

This is closest to the D below middle C. This note is one of the lowest notes on a clarinet.

Extension: *Musical Scale*

The 12 tone scale popular in Western music took centuries to develop. This scale is also called the 12-note Equal Tempered scale. It has an octave divided into 12 steps. (An **octave** is the main interval of most scales. If you double a frequency, you have raised the note one octave.) All steps have equal ratios of frequencies. But this scale is not perfect. If the octaves are in tune, all the other intervals are slightly mistuned. No interval is badly out of tune. But none is perfect.

For example, suppose the base note of a scale is a frequency of 110 Hz (a low A). The first harmonic is 220 Hz. This note is also an A, but is one octave higher. The second harmonic is at 330 Hz (close to an E). The third is 440 Hz (also an A). But not all the notes have such simple ratios. Middle C has a frequency of about 262 Hz. This is not a simple multiple of 110 Hz. So the interval between C and A is a little out of tune.

Many other types of tuning exist. Just Tempered scales are tuned so that all intervals are simple ratios of frequencies. There are also equal tempered scales with more or less notes per octave. Some scales use as many as 31 or 53 notes.

16.4 Resonance

ESBHB

Resonance is the tendency of a system to vibrate at a maximum amplitude at the natural frequency of the system.

Resonance takes place when a system is made to vibrate at its natural frequency as a result of vibrations that are received from another source of the same frequency. In the following investigation you will measure the speed of sound using resonance.

General experiment: *Using resonance to measure the speed of sound*

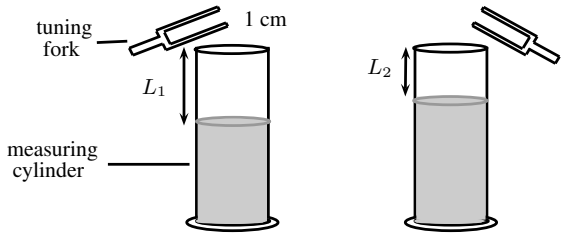
Aim: To measure the speed of sound using resonance
Apparatus:

- one measuring cylinder
- a high frequency (512 Hz) tuning fork
- some water
- a ruler or tape measure

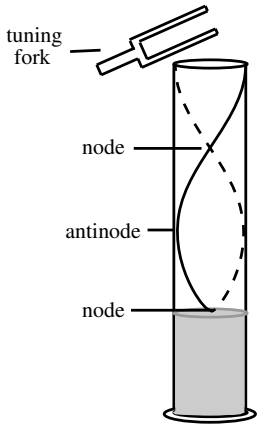
Method:

1. Make the tuning fork vibrate by hitting it on the sole of your shoe or something else that has a rubbery texture. A hard surface is not ideal as you can more easily damage the tuning fork. Be careful to hold the tuning fork by its handle. Don't touch the fork because it will damp the vibrations.
2. Hold the vibrating tuning fork about 1 cm above the cylinder mouth and start adding water to the cylinder at the same time. Keep doing this until the first resonance occurs. Pour out or add a little water until you find the level at which the loudest sound (i.e. the resonance) is made.
3. When the water is at the resonance level, use a ruler or tape measure to measure the distance (L_A) between the top of the cylinder and the water level.
4. Repeat the steps **??** above, this time adding more water until you find the next resonance. Remember to hold the tuning fork at the same height of about 1 cm above the cylinder mouth and adjust the water level to get the loudest sound.
5. Use a ruler or tape measure to find the new distance (L_B) from the top of the cylinder to the new water level.

Conclusions: The difference between the two resonance water levels (i.e. $L = L_A - L_B$) is half a wavelength, or the same as the distance between a compression and rarefaction. Therefore, since you know the wavelength, and you know the frequency of the tuning fork, it is easy to calculate the speed of sound!



From the investigation you will notice that the column of air will make a sound at a certain length. This is where resonance takes place.



FACT

Soldiers march out of time on bridges to avoid stimulating the bridge to vibrate at its natural frequency.

Example 5: *Resonance*

QUESTION

A 512 Hz tuning fork can produce a resonance in a cavity where the air column is 18,2 cm long. It can also produce a second resonance when the length of the air column is 50,1 cm. What is the speed of sound in the cavity?

SOLUTION

Step 1 : ***Identify what is given and what is asked:***

$$\begin{aligned} L_1 &= 18{,}2 \text{ cm} \\ L_2 &= 50{,}3 \text{ cm} \\ f &= 512 \text{ Hz} \\ v &= ? \end{aligned}$$

Remember that:

$$v = f \times \lambda$$

We have values for f and so to calculate v, we need to first find λ. You know that the difference in the length of the air column between two resonances is half a wavelength.

Step 2 : ***Calculate the difference in the length of the air column between the two resonances:***

$$L_2 - L_1 = 32{,}1 \text{ cm}$$

Therefore 32,1 cm = $\frac{1}{2} \times \lambda$
So,

$$\begin{aligned} \lambda &= 2 \times 32{,}1 \text{ cm} \\ &= 64{,}2 \text{ cm} \\ &= 0{,}642 \text{ m} \end{aligned}$$

Step 3 : ***Now you can substitute into the equation for v to find the speed of sound:***

$$\begin{aligned} v &= f \times \lambda \\ &= 512 \times 0{,}642 \\ &= 328{,}7 \text{ m.s}^{-1} \end{aligned}$$

16.5 Music and Sound Quality

ESBHC

In the sound chapter, we referred to the quality of sound as its tone. What makes the tone of a note played on an instrument? When you pluck a string or vibrate air in a tube, you hear mostly the fundamental frequency. Higher harmonics are present, but are fainter. These are called **overtones**. The tone of a note depends on its mixture of overtones. Different instruments have different mixtures of overtones. This is why the same note sounds different on a flute and a piano.

Let us see how overtones can change the shape of a wave:

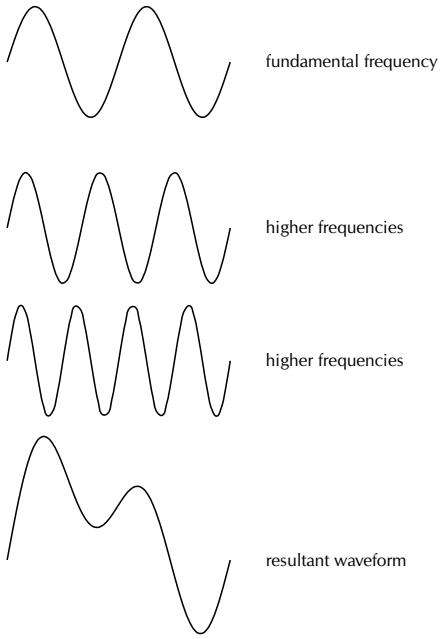


Figure 16.4: The quality of a tone depends on its mixture of harmonics.

The resultant waveform is very different from the fundamental frequency. Even though the two waves have the same main frequency, they do not sound the same!

Chapter 16 — Summary

See the summary presentation (▶ Presentation: VPkzl at www.everythingscience.co.za)

1. Instruments produce sound because they form standing waves in strings or pipes.
2. The fundamental frequency of a string or a pipe is its natural frequency. The wavelength of the fundamental frequency is twice the length of the string or pipe when both ends are fixed or both ends are open. It is four times the length of the pipe when one end is closed and one end is open.
3. When the string is fixed at both ends, or the pipe is open at both ends the first harmonic is formed when the standing wave forms one whole wavelength in the string or pipe. The second harmonic is formed when the standing wave forms $1\frac{1}{2}$ wavelengths in the string or pipe.
4. When a pipe is open at one end and closed at the other, the first harmonic is formed when the standing wave forms $\frac{11}{3}$ wavelengths in the pipe.
5. The frequency of a wave can be calculated with the equation $f = \frac{v}{\lambda}$.
6. The wavelength of a standing wave in a string fixed at both ends can be calculated using $\lambda_n = \frac{2L}{n-1}$.
7. The wavelength of a standing wave in a pipe with both ends open can be calculated using $\lambda_n = \frac{2L}{n}$.

8. The wavelength of a standing wave in a pipe with one end open can be calculated using $\lambda_n = \frac{4L}{2n-1}$.

9. Resonance takes place when a system is made to vibrate at its natural frequency as a result of vibrations received from another source of the same frequency.

Extension:	*Waveforms*

Below are some examples of the waveforms produced by a flute, clarinet and saxophone for different frequencies (i.e. notes):

Flute waveform
B_4, 247 Hz

Clarinet waveform
$E_\flat$, 156 Hz

Saxophone waveform
C_4, 256 Hz

Chapter 16 End of Chapter Exercises

1. A guitar string with a length of 70 cm is plucked. The speed of a wave in the string is 400 $m \cdot s^{-1}$. Calculate the frequency of the first, second, and third harmonics.
2. A pitch of Middle D (first harmonic = 294 Hz) is sounded out by a vibrating guitar string. The length of the string is 80 cm. Calculate the speed of the standing wave in the guitar string.
3. The frequency of the first harmonic for a guitar string is 587 Hz (pitch of D5). The speed of the wave is 600 $m \cdot s^{-1}$. Find the length of the string.
4. Two notes which have a frequency ratio of 2:1 are said to be separated by an octave. A note which is separated by an octave from middle C (256 Hz) is
   (a) 254 Hz
   (b) 128 Hz
   (c) 258 Hz
   (d) 512 Hz
5. Playing a middle C on a piano keyboard generates a sound at a frequency of 256 Hz. If the speed of sound in air is 345 $m \cdot s^{-1}$, calculate the wavelength of the sound corresponding to the note of middle C.
6. What is resonance? Explain how you would demonstrate what resonance is if you have a measuring cylinder, tuning fork and water available.
7. A tuning fork with a frequency of 256 Hz produced resonance in an air column of length 25,2 cm and at 89,5 cm. Calculate the speed of sound in the air column.

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(1.) 00t4 (2.) 00t5 (3.) 00t6 (4.) 00t7 (5.) 00t8 (6.) 00t9
(7.) 00ta

Electrostatics 17

17.1 Introduction

ESBHD

In Grade 10, you learnt about the force between charges. In this chapter you will learn exactly how to determine this force and about a basic law of electrostatics.
See introductory video: VPlbc at www.everythingscience.co.za

17.2 Forces between charges - Coulomb's Law

ESBHE

Like charges repel each other while opposite charges attract each other. If the charges are at rest then the force between them is known as the **electrostatic force**. The electrostatic force between charges increases when the magnitude of the charges increases or the distance between the charges decreases. The electrostatic force was first studied in detail by Charles Coulomb around 1784. Through his observations he was able to show that the electrostatic force between two point-like charges is inversely proportional to the square of the distance between the objects. He also discovered that the force is proportional to the product of the charges on the two objects. That is:

$$F \propto \frac{Q_1 Q_2}{r^2},$$

where Q_1 is the charge on the one point-like object, Q_2 is the charge on the second, and r is the distance between the two. The magnitude of the electrostatic force between two point-like charges is given by *Coulomb's Law*.

DEFINITION: Coulomb's Law

Coulomb's Law states that the magnitude of the electrostatic force between two point charges is directly proportional to the magnitudes of each charge and inversely proportional to the square of the distance between the charges:

$$F = k\frac{Q_1 Q_2}{r^2}$$

The proportionality constant k is called the *electrostatic constant* and has the value:

$$k = 8{,}99 \times 10^9 \mathrm{N} \cdot \mathrm{m}^2 \cdot \mathrm{C}^{-2}.$$

Similarity of Coulomb's Law to Newton's Universal Law of Gravitation.

Notice how similar Coulomb's Law is to the form of Newton's Universal Law of Gravitation between two point-like particles:

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

where m_1 and m_2 are the masses of the two particles, r is the distance between them, and G is the gravitational constant.

Both laws represent the force exerted by particles (masses or charges) on each other that interact by means of a field.

See video: VPldz at www.everythingscience.co.za

Example 1: *Coulomb's Law I*

QUESTION

Two point-like charges carrying charges of $+3 \times 10^{-9}\mathrm{C}$ and $-5 \times 10^{-9}\mathrm{C}$ are $2\,\mathrm{m}$ apart. Determine the magnitude of the force between them and state whether it is attractive or repulsive.

SOLUTION

Step 1 : ***Determine what is required***
We are required to find the force between two point charges given the charges and the distance between them.

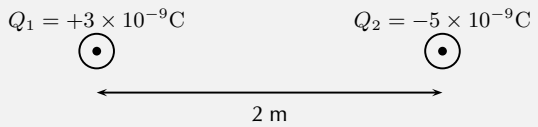
Step 2 : ***Determine how to approach the problem***
We can use Coulomb's Law to find the force.

$$F = k\frac{Q_1 Q_2}{r^2}$$

Step 3 : ***Determine what is given***
We are given:

- $Q_1 = +3 \times 10^{-9}\mathrm{C}$
- $Q_2 = -5 \times 10^{-9}\mathrm{C}$
- $r = 2\,\mathrm{m}$

We know that $k = 8{,}99 \times 10^9 \mathrm{N} \cdot \mathrm{m}^2 \cdot \mathrm{C}^{-2}$.
We can draw a diagram of the situation.



Step 4 : ***Check units***
All quantities are in SI units.

Step 5 : ***Determine the magnitude of the force***
Using Coulomb's Law we have

$$\begin{aligned} F &= k\frac{Q_1 Q_2}{r^2} \\ &= (8{,}99 \times 10^9 \mathrm{N} \cdot \mathrm{m}^2/\mathrm{C}^2)\frac{(3 \times 10^{-9}\mathrm{C})(5 \times 10^{-9}\mathrm{C})}{(2\mathrm{m})^2} \\ &= 3{,}37 \times 10^{-8}\mathrm{N} \end{aligned}$$

Thus the *magnitude* of the force is $3{,}37 \times 10^{-8}\text{N}$. However since both point charges have opposite signs, the force will be attractive.

Next is another example that demonstrates the difference in magnitude between the gravitational force and the electrostatic force.

Example 2: *Coulomb's Law II*

QUESTION

Determine the electrostatic force and gravitational force between two electrons 10^{-10}m apart (i.e. the forces felt inside an atom).

SOLUTION

Step 1 : ***Determine what is required***

We are required to calculate the electrostatic and gravitational forces between two electrons, a given distance apart.

Step 2 : ***Determine how to approach the problem***

We can use:

$$F_e = k\frac{Q_1 Q_2}{r^2}$$

to calculate the electrostatic force and

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

to calculate the gravitational force.

Step 3 : ***Determine what is given***

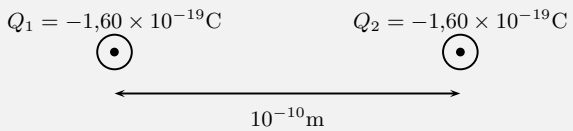
- $Q_1 = Q_2 = 1{,}6 \times 10^{-19}$ C(The charge on an electron)
- $m_1 = m_2 = 9{,}1 \times 10^{-31}$ kg(The mass of an electron)
- $r = 1 \times 10^{-10}\text{m}$

We know that:

- $k = 8{,}99 \times 10^{9}\ \text{N} \cdot \text{m}^2 \cdot \text{C}^{-2}$
- $G = 6{,}67 \times 10^{-11}\ \text{N} \cdot \text{m}^2 \cdot \text{kg}^{-2}$

All quantities are in SI units.

We can draw a diagram of the situation.



Step 4 : ***Calculate the electrostatic force***

$$\begin{aligned} F_e &= k\frac{Q_1Q_2}{r^2} \\ &= (8{,}99 \times 10^9)\frac{(-1{,}60 \times 10^{-19})(-1{,}60 \times 10^{-19})}{(10^{-10})^2} \\ &= 2{,}30 \times 10^{-8}\ \mathrm{N} \end{aligned}$$

Hence the *magnitude* of the electrostatic force between the electrons is $2{,}30 \times 10^{-8}$N. Since electrons carry the same charge, the force is repulsive.

Step 5 : ***Calculate the gravitational force***

$$\begin{aligned} F_g &= G\frac{m_1m_2}{r^2} \\ &= (6{,}67 \times 10^{-11}\mathrm{N}\cdot\mathrm{m}^2/\mathrm{kg}^2)\frac{(9.11 \times 10^{-31}\mathrm{C})(9.11 \times 10^{-31}\mathrm{kg})}{(10^{-10}\mathrm{m})^2} \\ &= 5{,}54 \times 10^{-51}\mathrm{N} \end{aligned}$$

The magnitude of the gravitational force between the electrons is $5{,}54 \times 10^{-51}$N. This is an attractive force.

Notice that the gravitational force between the electrons is much smaller than the electrostatic force. For this reason, the gravitational force is usually neglected when determining the force between two charged objects.

Tip

We can apply Newton's Third Law to charges because, two charges exert forces of equal magnitude on one another in opposite directions.

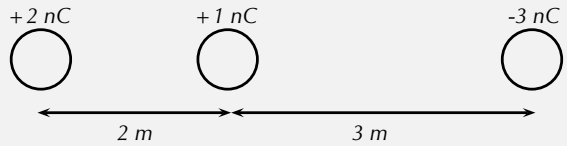
Example 3: *Coulomb's Law III*

Tip

When substituting into the Coulomb's Law equation, one may choose a positive direction thus making it unnecessary to include the signs of the charges. Instead, select a positive direction. Those forces that tend to move the charge in this direction are added, while forces acting in the opposite direction are subtracted.

QUESTION

Three point charges are in a straight line. Their charges are $Q_1 = +2 \times 10^{-9}$C, $Q_2 = +1 \times 10^{-9}$C and $Q_3 = -3 \times 10^{-9}$C. The distance between Q_1 and Q_2 is 2×10^{-2}m and the distance between Q_2 and Q_3 is 4×10^{-2}m. What is the net electrostatic force on Q_2 from the other two charges?



SOLUTION

Step 1 : ***Determine what is required***

We are needed to calculate the net force on Q_2. This force is the sum of the two electrostatic forces - the forces between Q_1 on Q_2 and Q_3 on Q_2.

Step 2 : ***Determine how to approach the problem***

- We need to calculate the two electrostatic forces on Q_2, using Coulomb's Law.
- We then need to add up the two forces using our rules for adding vector quantities,

because force is a vector quantity.

Step 3 : ***Determine what is given***
We are given all the charges and all the distances.

Step 4 : ***Calculate the forces.***
Force of Q_1 on Q_2:

$$\begin{aligned} F &= k\frac{Q_1Q_2}{r^2} \\ &= (8{,}99 \times 10^9)\frac{(2 \times 10^{-9})(1 \times 10^{-9})}{(2 \times 10^{-4})} \\ &= 4{,}5 \times 10^{-5}\text{N} \end{aligned}$$

Force of Q_3 on Q_2:

$$\begin{aligned} F &= k\frac{Q_2Q_3}{r^2} \\ &= (8{,}99 \times 10^9)\frac{(1 \times 10^{-9})(3 \times 10^{-9})}{(4 \times 10^{-4}} \\ &= 1{,}69 \times 10^{-5}\text{N} \end{aligned}$$

Both forces act in the same direction because the force between Q_1 and Q_2 is repulsive (like charges) and the force between Q_2 and Q_3 is attractive (unlike charges).

Therefore,

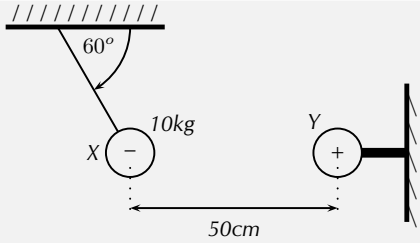
$$\begin{aligned} F_{tot} &= 4{,}50 \times 10^{-5} + 4{,}50 \times 10^{-5} \\ &= 6{,}19 \times 10^{-5}\text{N} \end{aligned}$$

We mentioned in Chapter **??** that charge placed on a spherical conductor spreads evenly along the surface. As a result, if we are far enough from the charged sphere, electrostatically, it behaves as a point-like charge. Thus we can treat spherical conductors (e.g. metallic balls) as point-like charges, with all the charge acting at the centre.

Example 4: *Coulomb's Law: challenging question*

QUESTION

In the picture below, X is a small negatively charged sphere with a mass of 10kg. It is suspended from the roof by an insulating rope which makes an angle of $60°$ with the roof. Y is a small positively charged sphere which has the same magnitude of charge as X. Y is fixed to the wall by means of an insulating bracket. Assuming the system is in equilibrium, what is the magnitude of the charge on X?

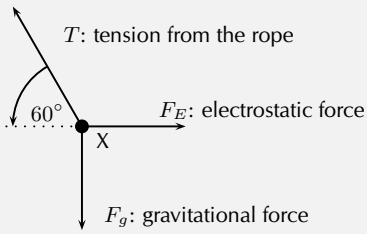


SOLUTION

How are we going to determine the charge on X? Well, if we know the force between X and Y we can use Coulomb's Law to determine their charges as we know the distance between them. So, firstly, we need to determine the magnitude of the electrostatic force between X and Y.

Step 1 :
Is everything in S.I. units? The distance between X and Y is $50\text{cm} = 0{,}5\text{m}$, and the mass of X is 10kg.

Step 2 : ***Draw a force diagram***
Draw the forces on X (with directions) and label.



Step 3 : ***Calculate the magnitude of the electrostatic force,*** F_E
Since nothing is moving (system is in equilibrium) the vertical and horizontal components of the gravitational force must cancel the vertical and horizontal components of the electrostatic force. Thus

$$F_E = T\cos(60^\circ); \qquad F_g = T\sin(60^\circ).$$

The only force we know is the gravitational force $F_g = mg$. Now we can calculate the magnitude of T from above:

$$T = \frac{F_g}{\sin(60^\circ)} = \frac{(10)(10)}{\sin(60^\circ)} = 115{,}5\text{N}.$$

Which means that F_E is:

$$F_E = T\cos(60^\circ) = 115{,}5 \cdot \cos(60^\circ) = 57{,}75\text{N}$$

Step 4 : ***Write the final answer***
Now that we know the magnitude of the electrostatic force between X and Y, we can calculate their charges using Coulomb's Law. Don't forget that the

magnitudes of the charges on X and Y are the same: $Q_{\mathrm{X}} = Q_{\mathrm{Y}}$. The magnitude of the electrostatic force is

$$\begin{aligned} F_E &= k\frac{Q_{\mathrm{X}}Q_{\mathrm{Y}}}{r^2} = k\frac{Q_{\mathrm{X}}^2}{r^2} \\ Q_{\mathrm{X}} &= \sqrt{\frac{F_E r^2}{k}} \\ &= \sqrt{\frac{(57.75)(0.5)^2}{8.99 \times 10^9}} \\ &= 5.66 \times 10^{-5}\mathrm{C} \end{aligned}$$

Thus the charge on X is $-5.66 \times 10^{-5}\mathrm{C}$.

Exercise 17 - 1

1. Calculate the electrostatic force between two charges of $+6\mathrm{nC}$ and $+1\mathrm{nC}$ if they are separated by a distance of $2\mathrm{mm}$.

2. Calculate the distance between two charges of $+4\mathrm{nC}$ and $-3\mathrm{nC}$ if the electrostatic force between them is $0{,}005\mathrm{N}$.

3. Calculate the charge on two identical spheres that are similarly charged if they are separated by $20\mathrm{cm}$ and the electrostatic force between them is $0{,}06\mathrm{N}$.

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(1.) 00tb (2.) 00tc (3.) 00td

17.3 Electric field around charges

ESBHF

We have learnt that objects that carry charge feel forces from all other charged objects. It is useful to determine what the effect from a charge would be at every point surrounding it. To do this we need some sort of reference. We know that the force that one charge feels due to another depends on both charges (Q_1 and Q_2). How then can we talk about forces if we only have one charge? The solution to this dilemma is to introduce a *test charge*. We then determine the force that would be exerted on it if we placed it at a certain location. If we do this for every point surrounding a charge we know what would happen if we put a test charge at any location.
This map of what would happen at any point is called an electric field map. It is a map of the electric field *due to* a charge. It tells us, at each point in space, how large the force on a test charge would be and in what direction the force would be. Our map consists of the vectors that describe the force on the test charge if it were placed there.

DEFINITION: Electric field

A collection of electric charges gives rise to a 'field of vectors' in the surrounding region of space, called an **electric field**. The direction of the electric field at a point is the direction that a positive test charge would move if placed at that point.

Electric field lines

ESBHG

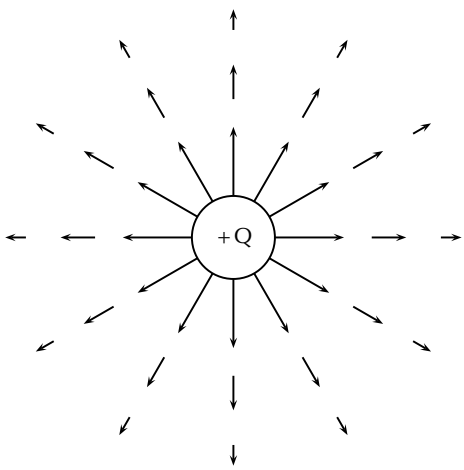
The electric field maps depend very much on the charge or charges that the map is being made for. We will start off with the simplest possible case. Take a single positive charge with no other charges around it. First, we will look at what effects it would have on a test charge at a number of points. Electric field lines, like the magnetic field lines that were studied in Grade 10, are a way of representing the electric field at a point.

- Arrows on the field lines indicate the direction of the field, i.e. the direction a positive test charge would move.
- Electric field lines therefore point away from positive charges and towards negative charges.
- Field lines are drawn closer together where the field is stronger.

Positive charge acting on a test charge

ESBHH

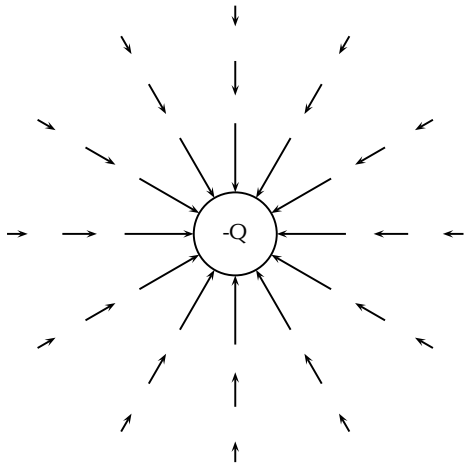
At each point we calculate the force on a test charge, q, and represent this force by a vector.



We can see that at every point the positive test charge, q, would experience a force pushing it away from the charge, Q. This is because both charges are positive and so they repel. Also notice that at points further away the vectors are shorter. That is because the force is smaller if you are further away.

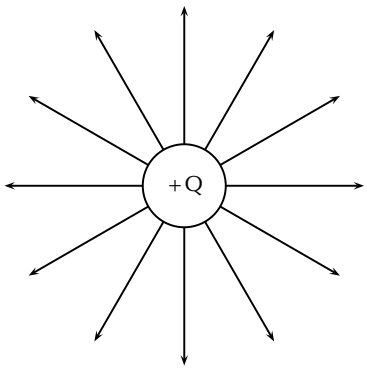
Negative charge acting on a test charge

If the charge, Q, were negative we would have the following result.



Notice that it is **almost** identical to the positive charge case. This is important – the arrows are the same length because the magnitude of the charge is the same and so is the magnitude of the test charge. Thus the **magnitude** (size) of the force is the same. The arrows point in the opposite direction because the charges now have opposite sign and so the positive test charge is **attracted** to the charge. Now, to make things simpler, we draw continuous lines showing the path that the test charge would travel. This means we don't have to work out the magnitude of the force at many different points.

Electric field map due to a positive charge



Some important points to remember about electric fields:

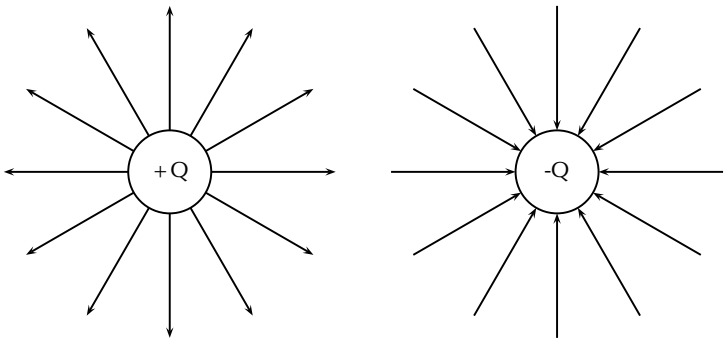
- There is an electric field at **every point** in space surrounding a charge.
- Field lines are merely a **representation** – they are not real. When we draw them, we just pick convenient places to indicate the field in space.
- Field lines usually start at a **right-angle** (90°) to the charged object causing the field.
- Field lines **never** cross.

Combined charge distributions

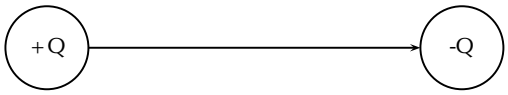
ESBHI

We will now look at the field of a positive charge and a negative charge placed next to each other. The net resulting field would be the addition of the fields from each of the charges. To start off with let us sketch the field maps for each of the charges separately.

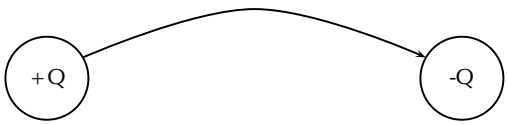
Electric field of a negative and a positive charge in isolation



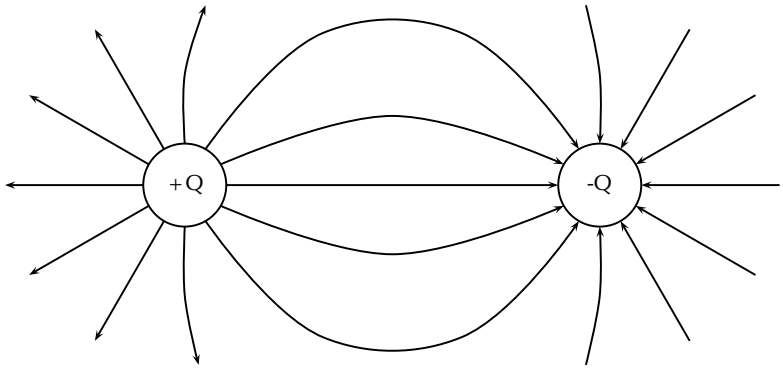
Notice that a test charge starting off directly between the two would be pushed away from the positive charge and pulled towards the negative charge in a straight line. The path it would follow would be a straight line between the charges.



Now let's consider a test charge starting off a bit higher than directly between the charges. If it starts closer to the positive charge the force it feels from the positive charge is greater, but the negative charge also attracts it, so it would experience a force away from the positive charge with a tiny force attracting it towards the negative charge. If it were a bit further from the positive charge the force from the negative and positive charges change and in fact they would be equal in magnitude if the forces were at equal distances from the charges. After that point the negative charge starts to exert a stronger force on the test charge. This means that the test charge would move towards the negative charge with only a small force away from the positive charge.

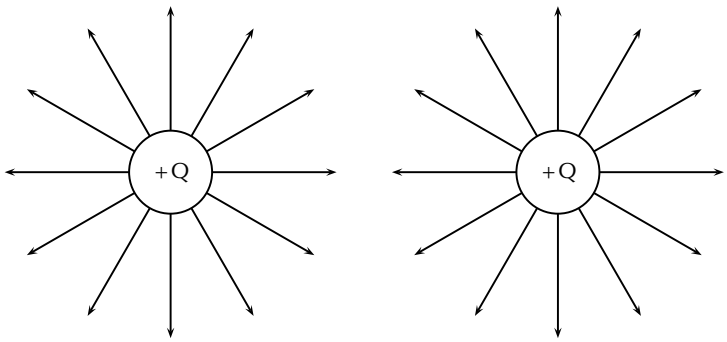


Now we can fill in the other lines quite easily using the same ideas. The resulting field map is:

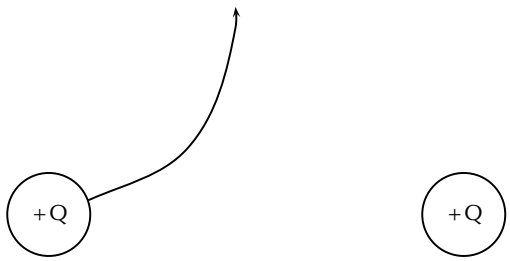


Two like charges : both positive

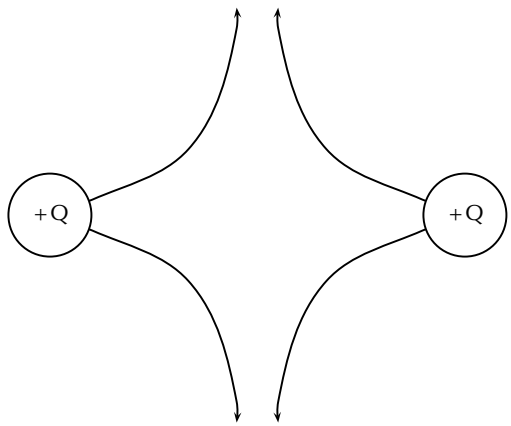
For the case of two positive charges things look a little different. We can't just turn the arrows around the way we did before. In this case the test charge is repelled by both charges. This tells us that a test charge will never cross half way because the force of repulsion from both charges will be equal in magnitude.



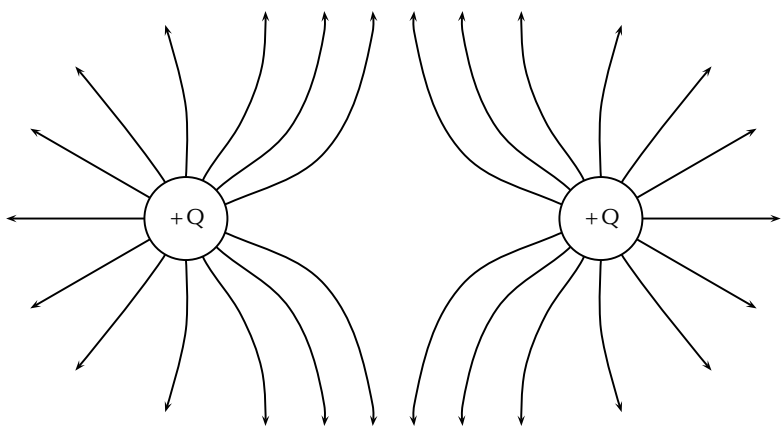
The field directly between the charges cancels out in the middle. The force has equal magnitude and opposite direction. Interesting things happen when we look at test charges that are not on a line directly between the two.



We know that a charge the same distance below the middle will experience a force along a reflected line, because the problem is symmetric (i.e. if we flipped vertically it would look the same). This is also true in the horizontal direction. So we use this fact to easily draw in the next four lines.

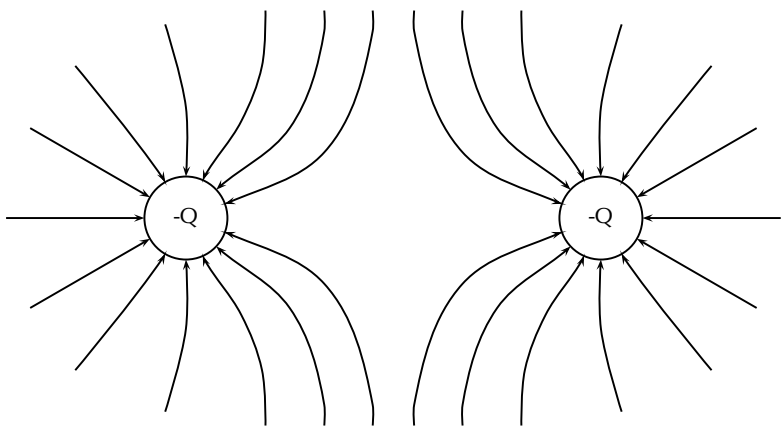


Working through a number of possible starting points for the test charge we can show the electric field map to be:



Two like charges : both negative

We can use the fact that the direction of the force is reversed for a test charge if you change the sign of the charge that is influencing it. If we change to the case where both charges are negative we get the following result:

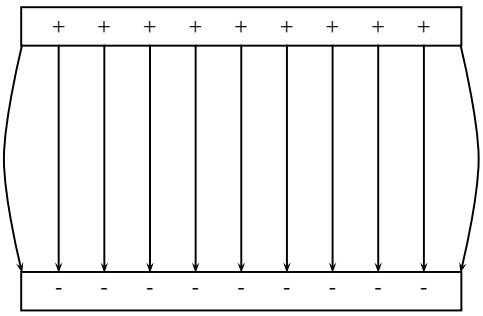


Parallel plates

ESBHJ

One very important example of electric fields which is used extensively is the electric field between two charged parallel plates. In this situation the electric field is constant. This is used for many practical purposes and later we will explain how Millikan used it to measure the charge on the electron.

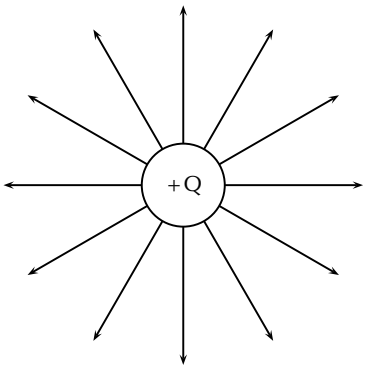
Field map for oppositely charged parallel plates



This means that the force that a test charge would feel at any point between the plates would be identical in magnitude and direction. The fields on the edges exhibit fringe effects, *i.e. they bulge outwards*. This is because a test charge placed here would feel the effects of charges only on one side (either left or right depending on which side it is placed). Test charges placed in the middle experience the effects of charges on both sides so they balance the components in the horizontal direction. This is clearly not the case on the edges.

Strength of an electric field

When we started making field maps we drew arrows to indicate the strength of the field and the direction. When we moved to lines you might have asked "Did we forget about the field strength?". We did not. Consider the case for a single positive charge again:



Notice that as you move further away from the charge the field lines become more spread out. In field map diagrams, the closer together field lines are, the stronger the field. Therefore, the electric field is stronger closer to the charge (the electric field lines are closer together) and weaker further from the charge (the electric field lines are further apart).

The magnitude of the electric field at a point as the force per unit charge. Therefore,

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

E and F are vectors. From this we see that the force on a charge q is simply:

$$F = E \cdot q$$

The force between two electric charges is given by:

$$F = k\frac{Qq}{r^2}.$$

(if we make the one charge Q and the other q.) Therefore, the electric field can be written as:

$$E = k\frac{Q}{r^2}$$

The electric field is the force per unit of charge and hence has units of newtons per coulomb.

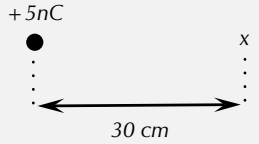
As with Coulomb's law calculations, do not substitute the sign of the charge into the equation for electric field. Instead, choose a positive direction, and then either add or subtract the contribution to the electric field due to each charge depending upon whether it points in the positive or negative direction, respectively. ▶ See video: VPlno at www.everythingscience.co.za

▶ See simulation: VPlnv at www.everythingscience.co.za)

Example 5: *Electric field 1*

QUESTION

Calculate the electric field strength 30cm *from a* 5nC *charge.*



SOLUTION

Step 1 : ***Determine what is required***
We need to calculate the electric field a distance from a given charge.

Step 2 : ***Determine what is given***
We are given the magnitude of the charge and the distance from the charge.

Step 3 : ***Determine how to approach the problem***
We will use the equation:

$$E = k\frac{Q}{r^2}.$$

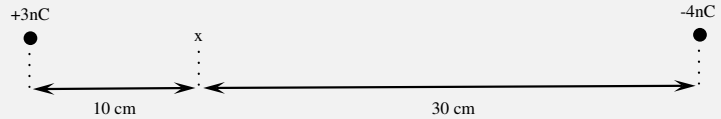
Step 4 : ***Solve the problem***

$$\begin{aligned} E &= k\frac{Q}{r^2} \\ &= \frac{(8.99 \times 10^9)(5 \times 10^{-9})}{(0{,}3)^2} \\ &= 4{,}99 \times 10^2 \mathrm{N.C}^{-1} \end{aligned}$$

Example 6: *Electric field 2*

QUESTION

Two charges of $Q_1 = +3\mathrm{nC}$ and $Q_2 = -4\mathrm{nC}$ are separated by a distance of $50\mathrm{cm}$. What is the electric field strength at a point that is $20\mathrm{cm}$ from Q_1 and $50\mathrm{cm}$ from Q_2? The point lies between Q_1 and Q_2.



SOLUTION

Step 1 : ***Determine what is required***
We need to calculate the electric field a distance from two given charges.

Step 2 : ***Determine what is given***
We are given the magnitude of the charges and the distances from the charges.

Step 3 : ***Determine how to approach the problem***
We will use the equation:

$$E = k\frac{Q}{r^2}.$$

We need to work out the electric field for each charge separately and then add them to get the resultant field.

Step 4 : ***Solve the problem***
We first solve for Q_1:

$$\begin{aligned} E &= k\frac{Q}{r^2} \\ &= \frac{(8.99 \times 10^9)(3 \times 10^{-9})}{(0{,}2)^2} \\ &= 6{,}74 \times 10^2 \mathrm{N.C}^{-1} \end{aligned}$$

Then for Q_2:

$$\begin{aligned} E &= k\frac{Q}{r^2} \\ &= \frac{(8.99 \times 10^9)(4 \times 10^{-9})}{(0{,}3)^2} \\ &= 2{,}70 \times 10^2 \mathrm{N.C}^{-1} \end{aligned}$$

We need to add the two electric fields because both are in the same direction. The field is away from Q_1 and towards Q_2. Therefore,
$E_{total} = 6{,}74 \times 102 + 2{,}70 \times 10^2 = 9{,}44 \times 102 \mathrm{N.C}^{-1}$

17.4 Electrical potential energy and potential

ESBHK

The *electrical potential energy* of a charge is the energy it has because of its position relative to other charges that it interacts with. The potential energy of a charge Q_1 relative to a charge Q_2 a distance r away is calculated by:

$$U = \frac{kQ_1Q_2}{r}$$

See video: VPlsc at www.everythingscience.co.za

Example 7: *Electrical potential energy 1*

QUESTION

What is the electric potential energy of a $7\mathrm{nC}$ charge that is 2 cm from a $20\mathrm{nC}$ charge?

SOLUTION

Step 1 : ***Determine what is required***
We need to calculate the electric potential energy (U).

Step 2 : ***Determine what is given***
We are given both charges and the distance between them.

Step 3 : ***Determine how to approach the problem***
We will use the equation:

$$U = \frac{kQ_1Q_2}{r}$$

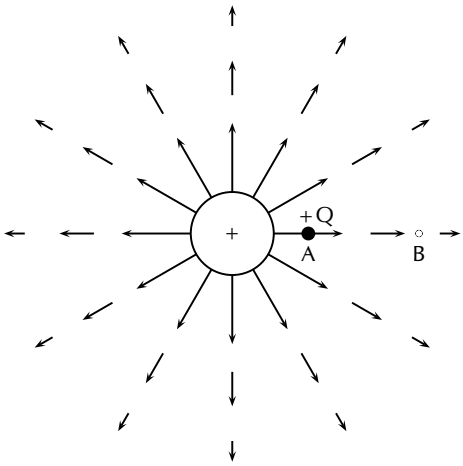
Step 4 : ***Solve the problem***

$$\begin{aligned} U &= \frac{kQ_1Q_2}{r} \\ &= \frac{(8.99 \times 10^9)(7 \times 10^{-9})(20 \times 10^{-9})}{(0{,}02)} \\ &= 6{,}29 \times 10{-}5\text{J} \end{aligned}$$

Electrical potential

ESBHL

The electrical potential at a point is the electrical potential energy per unit charge, i.e. the potential energy a positive test charge would have if it were placed at that point.
Consider a positive test charge $+Q$ placed at A in the electric field of another positive point charge.



The test charge moves towards B under the influence of the electric field of the other charge. In the process the test charge loses electrical potential energy and gains kinetic energy. Thus, at A, the test charge has more potential energy than at B – **A is said to have a higher electrical potential than B**. The potential energy of a charge at a point in a field is defined as the work required to move that charge from infinity to that point.

DEFINITION: Potential difference

The **potential difference between two points** in an electric field is defined as the **work required to move a unit positive test charge from the point of lower potential to that of higher potential**.

If an amount of work W is required to move a charge Q from one point to another, then the potential difference between the two points is given by,

$$V = \frac{W}{Q} \qquad \text{unit : J.C}^{-1} \text{ or V (the volt)}$$

From this equation we can define the volt.

DEFINITION: The Volt

One volt is the potential difference between two points in an electric field if one joule of work is done in moving one coulomb of charge from the one point to the other.

Example 8: *Potential difference*

QUESTION

What is the potential difference between two points in an electric field if it takes 600J *of energy to move a charge of* 2C *between these two points?*

SOLUTION

Step 1 : ***Determine what is required***
We need to calculate the potential difference (V) between two points in an electric field.

Step 2 : ***Determine what is given***
We are given both the charges and the energy or work done to move the charge between the two points.

Step 3 : ***Determine how to approach the problem***
We will use the equation:

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

Step 4 : ***Solve the problem***

$$\begin{aligned} V &= \frac{W}{Q} \\ &= \frac{600}{2} \\ &= 300\text{V} \end{aligned}$$

Real-world application: lightning

ESBHM

Lightning is an atmospheric discharge of electricity, usually, but not always, during a rain storm. An understanding of lightning is important for power transmission lines as engineers need to know about lightning in order to adequately protect lines and equipment.

Extension:	*Formation of lightning*

1. **Charge separation**
   The first process in the generation of lightning is charge separation. The mechanism by which charge separation happens is still the subject of research. One theory is that opposite charges are driven apart and energy is stored in the electric field between them. Cloud electrification appears to require strong updrafts which carry water droplets upward, supercooling them to -10 to -20 °C. These collide with ice crystals to form a soft ice-water mixture called graupel. The collisions result in a slight positive charge being transferred to ice crystals, and a slight negative charge to the graupel. Updrafts drive lighter ice crystals upwards, causing the cloud top to accumulate increasing positive charge. The heavier negatively charged graupel falls towards the middle and lower portions of the cloud, building up an increasing negative charge. Charge separation and accumulation continue until the electrical potential becomes sufficient to initiate lightning discharges, which occurs when the gathering of positive and negative charges forms a sufficiently strong electric field.
2. **Leader formation**
   As a thundercloud moves over the Earth's surface, an equal but opposite charge is induced in the Earth below, and the induced ground charge follows the movement of the cloud. An initial bipolar discharge, or path of ionised air, starts from a negatively charged mixed water and ice region in the thundercloud. The discharge ionised channels are called leaders. The negative charged leaders, called a "stepped leader", proceed generally downward in a number of quick jumps, each up to 50 metres long. Along the way, the stepped leader may branch into a number of paths as it continues to descend. The progression of stepped leaders takes a comparatively long time (hundreds of milliseconds) to approach the ground. This initial phase involves a relatively small electric current (tens or hundreds of amperes), and the leader is almost invisible compared to the subsequent lightning channel. When a step leader approaches the ground, the presence of opposite charges on the ground enhances the electric field. The electric field is highest on trees and tall buildings. If the electric field is strong enough, a conductive discharge (called a positive streamer) can develop from these points. As the field increases, the positive streamer may evolve into a hotter, higher current leader which eventually connects to the descending stepped leader from the cloud. It is also possible for many streamers to develop from many different objects at the same time, with only one connecting with the leader and forming the main discharge path. Photographs have been taken on which non-connected streamers are clearly visible. When the two leaders meet, the electric current greatly increases. The region of high current propagates back up the positive stepped leader into the cloud with a "return stroke" that is the most luminous part of the lightning discharge.
3. **Discharge** When the electric field becomes strong enough, an electrical discharge (the bolt of lightning) occurs within clouds or between clouds and the ground. During the strike, successive portions of air become a conductive discharge channel as the electrons and positive ions of air molecules are pulled away from each other and forced to flow in opposite directions. The electrical discharge rapidly superheats the discharge channel, causing the air to expand rapidly and produce a shock wave heard as thunder. The

rolling and gradually dissipating rumble of thunder is caused by the time delay of sound coming from different portions of a long stroke.

Estimating distance of a lightning strike. The flash of a lightning strike and resulting thunder occur at roughly the same time. But light travels at 300 000 kilometres in a second, almost a million times the speed of sound. Sound travels at the slower speed of 330 m/s in the same time, so the flash of lightning is seen before thunder is heard. By counting the seconds between the flash and the thunder and dividing by 3, you can estimate your distance from the strike and initially the actual storm cell (in kilometres).

17.5 Capacitance and the parallel plate capacitor

ESBHN

Capacitors and capacitance

ESBHO

A parallel plate capacitor is a device that consists of two oppositely charged conducting plates separated by a small distance, which stores charge. When voltage is applied to the capacitor, usually by connecting it to an energy source (e.g. a battery) in a circuit, electric charge of equal magnitude, but opposite polarity, builds up on each plate.

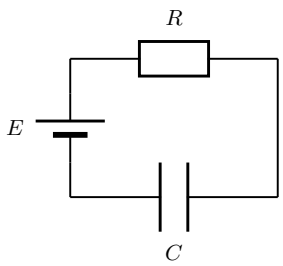


Figure 17.1: A capacitor (C) connected in series with a resistor (R) and an energy source (E).

DEFINITION: Capacitance

Capacitance is the charge stored per volt and is measured in Farads (F).

Mathematically, capacitance is the ratio of the charge on a single plate to the voltage across the plates of the capacitor:

$$C = \frac{Q}{V}.$$

Capacitance is measured in Farads (F). Since capacitance is defined as $C = \frac{Q}{V}$, the units are in terms of charge over potential difference. The unit of charge is the coulomb and the unit of the potential difference is the volt. One farad is therefore the capacitance if one coulomb of charge was stored on a capacitor for every volt applied.

Tip

Q is the magnitude of the charge stored on either plate, not on both plates added together. Since one plate stores positive charge and the other stores negative charge, the total charge on the two plates is zero.

1 C of charge is a very large amount of charge. So, for a small amount of voltage applied, a 1 F capacitor can store a enormous amount of charge. Therefore, capacitors are often denoted in terms of microfarads (1×10^{-6}), nanofarads (1×10^{-9}), or picofarads (1×10^{-12}).

Example 9: *Capacitance*

QUESTION

Suppose that a 5 V battery is connected in a circuit to a 5 pF capacitor. After the battery has been connected for a long time, what is the charge stored on each of the plates?

SOLUTION

To begin remember that after a voltage has been applied for a long time the capacitor is fully charged. The relation between voltage and the maximum charge of a capacitor is found in equation **??**.

$$CV = Q$$

Inserting the given values of $C = 5\text{F}$ and $V = 5\text{V}$, we find that:

$$\begin{aligned} Q &= CV \\ &= (5 \times 10^{-12} F)(5V) \\ &= 2{,}5 \times 10^{-11} C \end{aligned}$$

Dielectrics

ESBHP

The electric field between the plates of a capacitor is affected by the substance between them. The substance between the plates is called a dielectric. Common substances used as dielectrics are mica, perspex, air, paper and glass.
When a dielectric is inserted between the plates of a parallel plate capacitor the dielectric becomes polarised so an electric field is induced in the dielectric that opposes the field between the plates. When the two electric fields are superposed, the new field between the plates becomes smaller. Thus the voltage between the plates decreases so the capacitance increases.
In every capacitor, the dielectric stops the charge on one plate from travelling to the other plate. However, each capacitor is different in how much charge it allows to build up on the electrodes per voltage applied. When scientists started studying capacitors they discovered the property that the voltage applied to the capacitor was proportional to the maximum charge that would accumulate on the electrodes. The constant that made this relation into an equation was called the capacitance, C. The capacitance was different for different capacitors. But, it stayed constant no matter how much voltage was applied. So, it predicts how much charge will be stored on a capacitor when different voltages are applied.

Physical properties of the capacitor and capacitance

ESBHQ

The capacitance of a capacitor is proportional to the surface area of the conducting plate and inversely proportional to the distance between the plates. It also depends on the dielectric between the plates. We say that it is proportional to the permittivity of the *dielectric*. The dielectric is the non-conducting substance that separates the plates. As mentioned before, dielectrics can be air, paper, mica, perspex or glass.
The capacitance of a parallel-plate capacitor is given by:

$$C = \epsilon_0 \frac{A}{d}$$

where ϵ_0 is, in this case, the permittivity of air, A is the area of the plates and d is the distance between the plates.

Example 10: *Capacitance*

QUESTION

What is the capacitance of a capacitor in which the dielectric is air, the area of the plates is $0{,}001\text{m}^2$ *and the distance between the plates is* $0{,}02\text{m}$*?*

SOLUTION

Step 1 : ***Determine what is required***
We need to determine the capacitance of the capacitor.

Step 2 : ***Determine how to approach the problem***
We can use the formula:

$$C = \epsilon_0 \frac{A}{d}$$

Step 3 : ***Determine what is given.***
We are given the area of the plates, the distance between the plates and that the dielectric is air.

Step 4 : ***Determine the capacitance***

$$C = \epsilon_0 \frac{A}{d} \tag{17.1}$$

$$= \frac{(8{,}9 \times 10^{-12})(0{,}001)}{0{,}02} \tag{17.2}$$

$$= 4{,}45 \times 10^{-13}\text{F} \tag{17.3}$$

Electric field in a capacitor

ESBHR

The electric field strength between the plates of a capacitor can be calculated using the formula:
$E = \frac{V}{d}$
where E is the electric field in $\mathrm{J.C^{-1}}$, V is the potential difference in volts (V) and d is the distance between the plates in metres (m).

Example 11: *Electric field in a capacitor*

QUESTION

What is the strength of the electric field in a capacitor which has a potential difference of $300\mathrm{V}$ *between its parallel plates that are* $0{,}02\mathrm{m}$ *apart?*

SOLUTION

Step 1 : ***Determine what is required***
We need to determine the electric field between the plates of the capacitor.

Step 2 : ***Determine how to approach the problem***
We can use the formula:
$E = \frac{V}{d}$

Step 3 : ***Determine what is given.***
We are given the potential difference and the distance between the plates.

Step 4 : ***Determine the electric field***

$$\begin{aligned} E &= \frac{V}{d} \\ &= \frac{300}{0{,}02} \\ &= 1{,}50 \times 10^{4}\mathrm{J.C^{-1}} \end{aligned}$$

Exercise 17 - 2

1. Determine the capacitance of a capacitor which stores $9 \times 10^{-9}\mathrm{C}$ when a potential difference of 12 V is applied to it.
2. What charge will be stored on a $5\mu\mathrm{F}$ capacitor if a potential difference of $6\mathrm{V}$ is maintained between its plates?

3. What is the capacitance of a capacitor that uses air as its dielectric if it has an area of $0{,}004\text{m}^2$ and a distance of $0{,}03\text{m}$ between its plates?

4. What is the strength of the electric field between the plates of a charged capacitor if the plates are 2mm apart and have a potential difference of 200V across them?

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(1.) 00te (2.) 00tf (3.) 00tg (4.) 00th

See simulation: VPlsh at www.everythingscience.co.za)

17.6 A capacitor as a circuit device ESBHS

A capacitor in a circuit ESBHT

When a capacitor is connected in a DC circuit, current will flow until the capacitor is fully charged. After that, no further current will flow. If the charged capacitor is connected to another circuit with no source of emf in it, the capacitor will discharge through the circuit, creating a potential difference for a short time. This is useful, for example, in a camera flash.
Initially, the electrodes have no net charge. A voltage source is applied to charge a capacitor. The voltage source creates an electric field, causing the electrons to move. The charges move around the circuit stopping at the left electrode. Here they are unable to travel across the dielectric, since electrons cannot travel through an insulator. The charge begins to accumulate, and an electric field forms pointing from the left electrode to the right electrode. This is the opposite direction of the electric field created by the voltage source. When this electric field is equal to the electric field created by the voltage source, the electrons stop moving. The capacitor is then fully charged, with a positive charge on the left electrode and a negative charge on the right electrode.
If the voltage is removed, the capacitor will discharge. The electrons begin to move because in the absence of the voltage source, there is now a net electric field. This field is due to the imbalance of charge on the electrodes–the field across the dielectric. Just as the electrons flowed to the positive electrode when the capacitor was being charged, during discharge, the electrons flow to negative electrode. The charges cancel, and there is no longer an electric field across the dielectric.

Real-world applications: capacitors ESBHU

Capacitors are used in many different types of circuitry. In car speakers, capacitors are often used to aid the power supply when the speakers require more power than the car battery can provide. Capacitors are also used in processing electronic signals in circuits, such as smoothing voltage spikes due to inconsistent voltage sources. This is important for protecting sensitive electronic components in a circuit.

Chapter 17 — Summary

See the summary presentation (▶ Presentation: VPltf at www.everythingscience.co.za)

- Objects can be **positively**, **negatively** charged or **neutral**.
- Charged objects feel a force with a magnitude. This is known as Coulomb's law:

$$F = k\frac{Q_1 Q_2}{r^2}$$

- The electric field due to a point charge is given by the equation:

$$E = \frac{kQ}{r^2}$$

- The force is attractive for unlike charges and repulsive for like charges.
- Electric fields start on positive charges and end on negative charges.
- A charge in an electric field, just like a mass under gravity, has potential energy which is related to the work to move it.
- A capacitor is a device that stores charge in a circuit.
- The electrical potential energy between two point charges is given by:

$$U = \frac{kQ_1 Q_2}{r^2}$$

- Potential difference is measured in volts and is given by the equation:

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

- The electric field is constant between equally charged parallel plates. The electric field is given by:

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

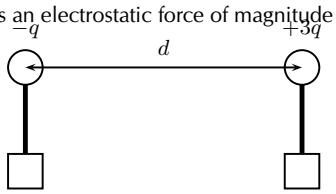
- The capacitance of a capacitor can be calculated as

$$C = \frac{Q}{V} = \frac{\epsilon_0 A}{d}$$

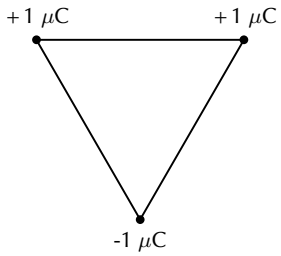
Chapter 17 End of Chapter Exercises

1. Two charges of $+3\text{nC}$ and -5nC are separated by a distance of 40cm. What is the electrostatic force between the two charges?
2. Two insulated metal spheres carrying charges of $+6\text{nC}$ and -10nC are separated by a distance of 20 mm.
   (a) What is the electrostatic force between the spheres?
   (b) The two spheres are touched and then separated by a distance of 60mm. What are the new charges on the spheres?
   (c) What is new electrostatic force between the spheres at this distance?

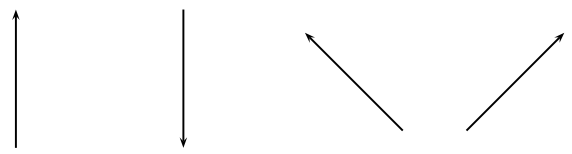
3. The electrostatic force between two charged spheres of $+3\text{nC}$ and $+4\text{nC}$ respectively is $0{,}04\text{N}$. What is the distance between the spheres?
4. Calculate the potential difference between two parallel plates if it takes 5000J of energy to move 25C of charge between the plates?
5. Draw the electric field pattern lines between:
   (a) two equal positive point charges.
   (b) two equal negative point charges.
6. Calculate the electric field between the plates of a capacitor if the plates are 20mm apart and the potential difference between the plates is 300V.
7. Calculate the electrical potential energy of a 6nC charge that is 20cm from a 10nC charge.
8. What is the capacitance of a capacitor if it has a charge of $0{,}02\text{C}$ on each of its plates when the potential difference between the plates is 12V?
9. [SC 2003/11] Two small identical metal spheres, on insulated stands, carry charges -q and $+3q$ respectively. When the centres of the spheres are separated by a distance d the one exerts an electrostatic force of magnitude F on the other.



   The spheres are now made to touch each other and are then brought back to the same distance d apart. What will be the magnitude of the electrostatic force which one sphere now exerts on the other?
   (a) $\frac{1}{4}F$
   (b) $\frac{1}{3}F$
   (c) $\frac{1}{2}F$
   (d) $3F$
10. [SC 2003/11] Three point charges of magnitude $+1\ \mu$C, $+1\ \mu$C and -1 μC respectively are placed on the three corners of an equilateral triangle as shown.



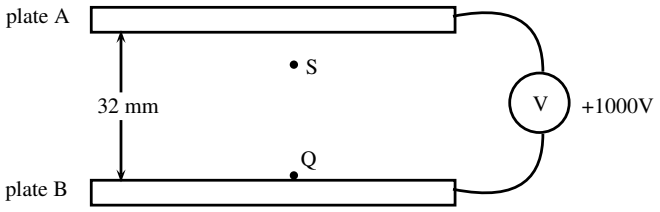
   Which vector best represents the direction of the resultant force acting on the -1 μC charge as a result of the forces exerted by the other two charges?



   (a) (b) (c) (d)
11. [IEB 2003/11 HG1 - Force Fields]
   (a) Write a statement of Coulomb's law.

(b) Calculate the magnitude of the force exerted by a point charge of $+2$ nC on another point charge of -3 nC separated by a distance of 60 mm.
(c) Sketch the electric field between two point charges of $+2$ nC and -3 nC, respectively, placed 60 mm apart from each other.

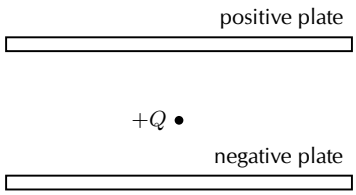
12. [IEB 2003/11 HG1 - Electrostatic Ping-Pong]
Two charged parallel metal plates, X and Y, separated by a distance of 60 mm, are connected to a DC supply of emf 2 000 V in series with a microammeter. An initially uncharged conducting sphere (a graphite-coated ping pong ball) is suspended from an insulating thread between the metal plates as shown in the diagram.



When the ping pong ball is moved to the right to touch the positive plate, it acquires a charge of $+9$ nC. It is then released. The ball swings to and fro between the two plates, touching each plate in turn.

(a) How many electrons have been removed from the ball when it acquires a charge of $+9$ nC?
(b) Explain why a current is established in the circuit.
(c) Determine the current if the ball takes 0,25 s to swing from Y to X.
(d) Using the same graphite-coated ping pong ball, and the same two metal plates, give TWO ways in which this current could be increased.
(e) Sketch the electric field between the plates X and Y.
(f) How does the electric force exerted on the ball change as it moves from Y to X?

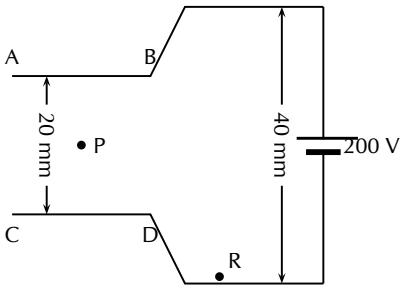
13. [IEB 2005/11 HG] A positive charge Q is released from rest at the centre of a uniform electric field.



How does Q move immediately after it is released?

(a) It accelerates uniformly.
(b) It moves with an increasing acceleration.
(c) It moves with constant speed.
(d) It remains at rest in its initial position.

14. [SC 2002/03 HG1] The sketch below shows two sets of parallel plates which are connected together. A potential difference of 200 V is applied across both sets of plates. The distances between the two sets of plates are 20 mm and 40 mm respectively.



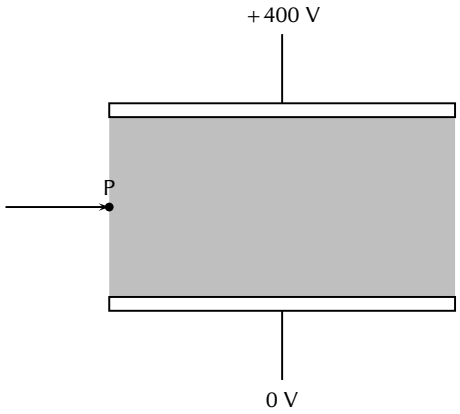
When a charged particle Q is placed at point R, it experiences a force of magnitude F. Q is now moved to point P, halfway between plates AB and CD. Q now experiences a force of magnitude .

(a) $\frac{1}{2}F$
(b) F
(c) $2F$
(d) $4F$

15. [SC 2002/03 HG1] The electric field strength at a distance x from a point charge is E. What is the magnitude of the electric field strength at a distance $2x$ away from the point charge?

(a) $\frac{1}{4}E$
(b) $\frac{1}{2}E$
(c) $2E$
(d) $4E$

16. [IEB 2005/11 HG1]
An electron (mass 9,11 $\times$ 10^{-31} kg) travels horizontally in a vacuum. It enters the shaded regions between two horizontal metal plates as shown in the diagram below.



A potential difference of 400 V is applied across the places which are separated by 8 mm.
The electric field intensity in the shaded region between the metal plates is uniform. Outside this region, it is zero.

(a) Explain what is meant by the phrase **"the electric field intensity is uniform"**.
(b) Copy the diagram and draw the following:
   i. The electric field between the metal plates.
   ii. An arrow showing the direction of the electrostatic force on the electron when it is at **P**.
(c) Determine the magnitude of the electric field intensity between the metal plates.
(d) Calculate the magnitude of the electrical force on the electron during its passage through the electric field between the plates.
(e) Calculate the magnitude of the acceleration of the electron (due to the electrical force on it) during its passage through the electric field between the plates.
(f) After the electron has passed through the electric field between these plates, it collides with phosphorescent paint on a TV screen and this causes the paint to glow. What energy transfer takes place during this collision?

17. [IEB 2004/11 HG1] A positively-charged particle is placed in a uniform electric field. Which of the following pairs of statements correctly describes the potential energy of the charge, and the force which the charge experiences in this field?
Potential energy — Force

(a) Greatest near the negative plate — Same everywhere in the field
(b) Greatest near the negative plate — Greatest near the positive and negative plates
(c) Greatest near the positive plate — Greatest near the positive and negative plates
(d) Greatest near the positive plate — Same everywhere in the field

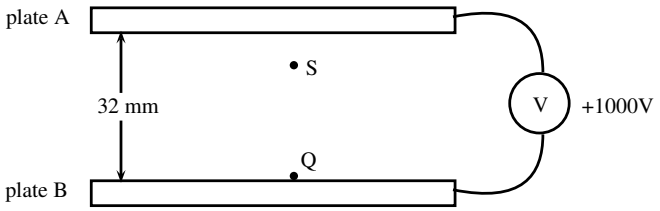
18. [IEB 2004/11 HG1 - TV Tube]
A speck of dust is attracted to a TV screen. The screen is negatively charged, because this is where the electron beam strikes it. The speck of dust is neutral.

(a) What is the name of the electrostatic process which causes dust to be attracted to a TV screen?
(b) Explain why a neutral speck of dust is attracted to the negatively-charged TV screen?
(c) Inside the TV tube, electrons are accelerated through a uniform electric field. Determine the magnitude of the electric force exerted on an electron when it accelerates through a potential difference of 2 000 V over a distance of 50 mm.
(d) How much kinetic energy (in J) does one electron gain while it accelerates over this distance?
(e) The TV tube has a power rating of 300 W. Estimate the maximum number of electrons striking the screen per second.

19. [IEB 2003/11 HG1] A point charge is held stationary between two charged parallel plates that are separated by a distance d. The point charge experiences an electrical force F due to the electric field E between the parallel plates.
What is the electrical force on the point charge when the plate separation is increased to 2d?

(a) $\frac{1}{4}$ F
(b) $\frac{1}{2}$ F
(c) 2 F
(d) 4 F

20. [IEB 2001/11 HG1] - **Parallel Plates**
A distance of 32 mm separates the horizontal parallel plates A and B.
B is at a potential of $+1\,000$ V.



(a) Draw a sketch to show the electric field lines between the plates A and B.
(b) Calculate the magnitude of the electric field intensity (strength) between the plates.
A tiny charged particle is stationary at S, 8 mm below plate A that is at zero electrical potential. It has a charge of $3{,}2 \times 10^{-12}$ C.
(c) State whether the charge on this particle is positive or negative.
(d) Calculate the force due to the electric field on the charge.
(e) Determine the mass of the charged particle.
The charge is now moved from S to Q.
(f) What is the magnitude of the force exerted by the electric field on the charge at Q?
(g) Calculate the work done when the particle is moved from S to Q.

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(1.) 00ti	(2.) 00tj	(3.) 00tk	(4.) 00tm	(5.) 00tn	(6.) 00tp
(7.) 00tq	(8.) 00tr	(9.) 00ts	(10.) 00tt	(11.) 00tu	(12.) 00tv
(13.) 00tw	(14.) 00tx	(15.) 00ty	(16.) 00tz	(17.) 00u0	(18.) 00u1
(19.) 00u2	(20.) 00u3				

Electromagnetism 18

18.1 Introduction

ESBHV

Electromagnetism describes the interaction between charges, currents and the electric and magnetic fields which they give rise to. An electric current creates a magnetic field and a changing magnetic field will create a flow of charge. This relationship between electricity and magnetism has resulted in the invention of many devices which are useful to humans.

See introductory video: VPlwi at www.everythingscience.co.za

18.2 Magnetic field associated with a current

ESBHW

If you hold a compass near a wire through which current is flowing, the needle on the compass will be deflected.

Since compasses work by pointing along magnetic field lines, this means that there must be a magnetic field near the wire through which the current is flowing.

The magnetic field produced by an electric current is always oriented perpendicular to the direction of the current flow. When we are drawing directions of magnetic fields and currents, we use the symbols $\odot$ and $\otimes$. The symbol

$$\odot$$

represents an arrow that is coming out of the page and the symbol

$$\otimes$$

represents an arrow that is going into the page. It is easy to remember the meanings of the symbols if you think of an arrow with a head and a tail.

When the arrow is coming out of the page, you see the point of the arrow ($\odot$). When the arrow is going into the page, you see the tail of the arrow ($\otimes$).

The direction of the magnetic field around the current carrying conductor is shown in Figure 18.1.

FACT

The Danish physicist Hans Christian Oersted was lecturing one day in 1820 on the possibility of electricity and magnetism being related to one another, and in the process demonstrated it conclusively by experiment in front of his whole class. By passing an electric current through a metal wire suspended above a magnetic compass, Oersted was able to produce a definite motion of the compass needle in response to the current. What began as a guess at the start of the class session was confirmed as fact at the end. Needless to say, Oersted had to revise his lecture notes for future classes. His discovery paved the way for a whole new branch of science - electromagnetism.

Figure 18.1: Magnetic field around a conductor when you look at the conductor from one end. (a) Current flows out of the page and the magnetic field is counter clockwise. (b) Current flows into the page and the magnetic field is clockwise.

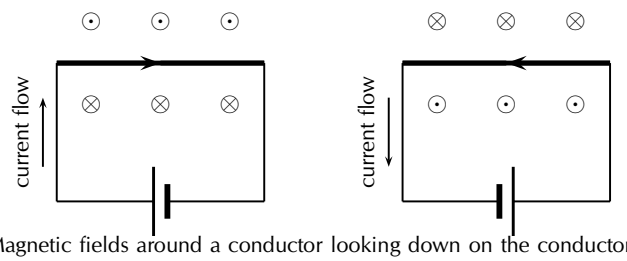
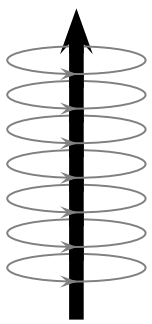


Figure 18.2: Magnetic fields around a conductor looking down on the conductor. (a) Current flows clockwise. (b) current flows counter clockwise.

Activity:	*Direction of a magnetic field*

Using the directions given in Figure 18.1 and Figure 18.2 try to find a rule that easily tells you the direction of the magnetic field.

Hint: Use your fingers. Hold the wire in your hands and try to find a link between the direction of your thumb and the direction in which your fingers curl.



The magnetic field around a current carrying conductor.

There is a simple method of finding the relationship between the direction of the current flowing in a conductor and the direction of the magnetic field around the same conductor. The method is called the *Right Hand Rule*. Simply stated, the right hand rule says that the magnetic field lines produced by a current-carrying wire will be oriented in the same direction as the curled fingers of a person's right hand (in the "hitchhiking" position), with the thumb pointing in the direction of the current flow.

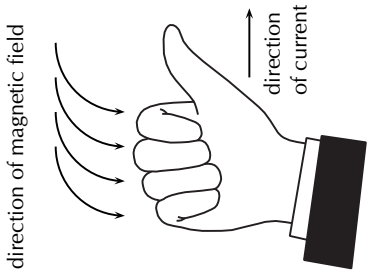
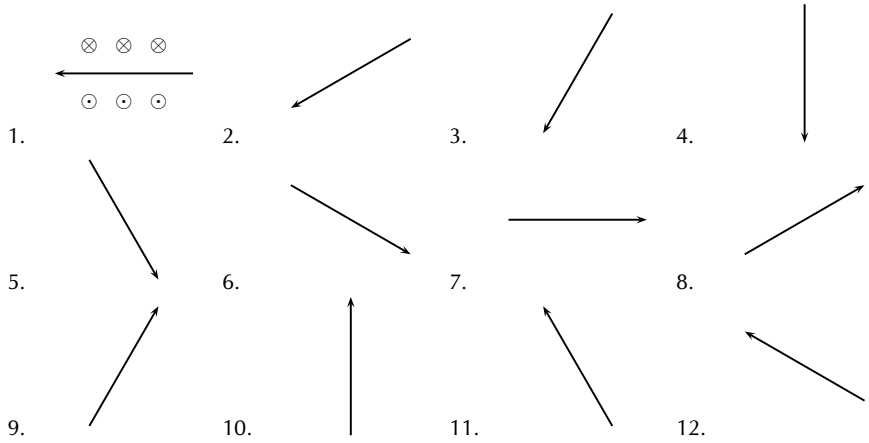


Figure 18.3: The Right Hand Rule.

Activity: *The Right Hand Rule*

Use the Right Hand Rule to draw in the directions of the magnetic fields for the following conductors with the currents flowing in the directions shown by the arrows. The first problem has been completed for you.



General experiment: *Magnetic field around a current carrying conductor*

Apparatus:

1. one 9V battery with holder
2. two hookup wires with alligator clips
3. compass
4. stop watch

Method:

1. Connect your wires to the battery leaving one end of each wire unconnected so that the circuit is not closed.

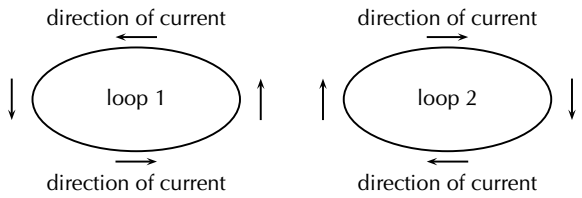
2. One student should be in charge of limiting the current flow to 10 seconds. This is to preserve battery life as well as to prevent overheating of the wires and battery contacts.
3. Place the compass close to the wire.
4. Close the circuit and observe what happens to the compass.
5. Reverse the polarity of the battery and close the circuit. Observe what happens to the compass.

Conclusions:
Use your observations to answer the following questions:

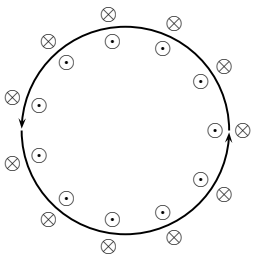
1. Does a current flowing in a wire generate a magnetic field?
2. Is the magnetic field present when the current is not flowing?
3. Does the direction of the magnetic field produced by a current in a wire depend on the direction of the current flow?
4. How does the direction of the current affect the magnetic field?

Activity: *Magnetic field around a loop of conductor*

Consider two loops made from a conducting material, which carry currents (in opposite directions) and are placed in the plane of the page. By using the Right Hand Rule, draw what you think the magnetic field would look like at different points around each of the two loops. Loop 1 has the current flowing in a counter-clockwise direction, while loop 2 has the current flowing in a clockwise direction.



If you make a loop of current carrying conductor, then the direction of the magnetic field is obtained by applying the Right Hand Rule to different points in the loop.



The directions of the magnetic field around a loop of current carrying conductor with the current flowing in a counter-clockwise direction is shown.

If we now add another loop with the current in the same direction, then the magnetic field around each loop can be added together to create a stronger magnetic field. A coil of many such loops is called a *solenoid*. The magnetic field pattern around a solenoid is similar to the magnetic field pattern around the bar magnet that you studied in Grade 10, which had a definite north and south pole.

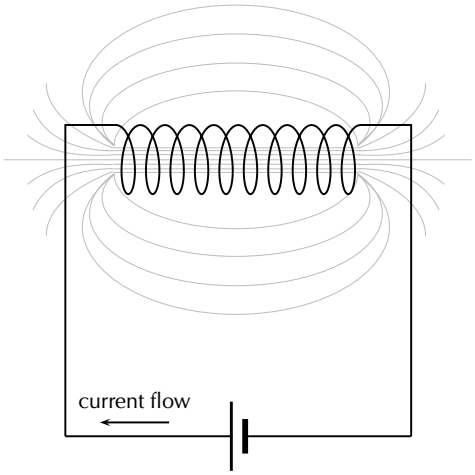


Figure 18.4: Magnetic field around a solenoid.

Real-world applications

ESBHX

Electromagnets

An *electromagnet* is a piece of wire intended to generate a magnetic field with the passage of electric current through it. Though all current-carrying conductors produce magnetic fields, an electromagnet is usually constructed in such a way as to maximise the strength of the magnetic field it produces for a special purpose. Electromagnets are commonly used in research, industry, medical, and consumer products. An example of a commonly used electromagnet is in security doors, e.g. on shop doors which open automatically.

As an electrically-controllable magnet, electromagnets form part of a wide variety of "electromechanical" devices: machines that produce a mechanical force or motion through electrical power. Perhaps the most obvious example of such a machine is the *electric motor* which will be described in detail in Grade 12. Other examples of the use of electromagnets are electric bells, relays, loudspeakers and scrapyard cranes.

General experiment: *Electromagnets*

Aim: A magnetic field is created when an electric current flows through a wire. A single wire does not produce a strong magnetic field, but a wire coiled around an iron core does. We will investigate this behaviour.

Apparatus:

1. a battery and holder
2. a length of wire
3. a compass
4. a few nails

Method:

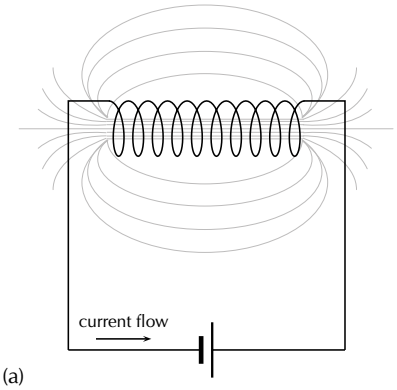
1. If you have not done the previous experiment in this chapter do it now.
2. Bend the wire into a series of coils before attaching it to the battery. Observe what happens to the deflection of the needle on the compass. Has the deflection of the compass grown stronger?
3. Repeat the experiment by changing the number and size of the coils in the wire. Observe what happens to the deflection on the compass.
4. Coil the wire around an iron nail and then attach the coil to the battery. Observe what happens to the deflection of the compass needle.

Conclusions:

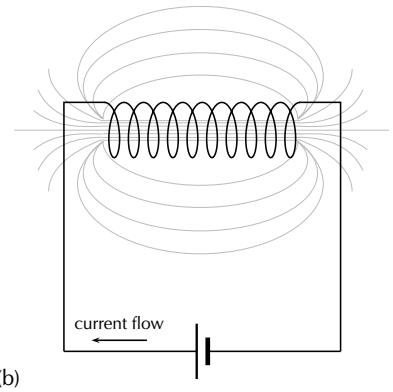
1. Does the number of coils affect the strength of the magnetic field?
2. Does the iron nail increase or decrease the strength of the magnetic field?

Exercise 18 - 1

1. Give evidence for the existence of a magnetic field near a current carrying wire.
2. Describe how you would use your right hand to determine the direction of a magnetic field around a current carrying conductor.
3. Use the Right Hand Rule to determine the direction of the magnetic field for the following situations:

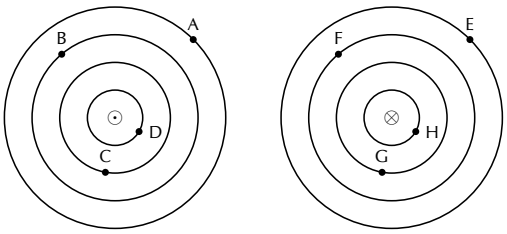


(a)



(b)

4. Use the Right Hand Rule to find the direction of the magnetic fields at each of the points labelled A - H in the following diagrams.



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(1.) 01hb (2.) 01hc (3.) 01hd (4.) 01he

18.3 Current induced by a changing magnetic field

ESBHY

While Oersted's surprising discovery of electromagnetism paved the way for more practical applications of electricity, it was Michael Faraday who gave us the key to the practical generation of electricity: **electromagnetic induction**.

Faraday discovered that a voltage was generated across a length of wire while moving a magnet nearby, such that the distance between the two changed. This meant that the wire was exposed to a magnetic field flux of changing intensity. Furthermore, the voltage also depended on the orientation of the magnet; this is easily understood again in terms of the magnetic flux. The flux will be at its maximum as the magnet is aligned perpendicular to the wire. The magnitude of the changing flux and the voltage are linked. In fact, if the lines of flux are parallel to the wire, there will be no induced voltage.

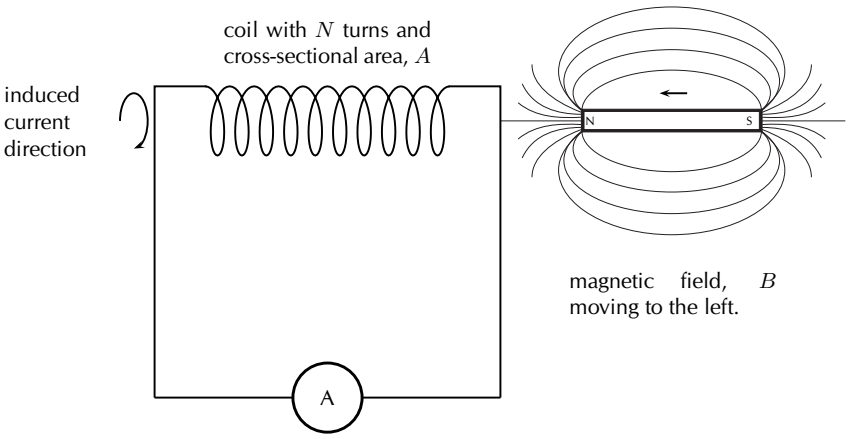
DEFINITION: Faraday's Law

The emf, ϵ, produced around a loop of conductor is proportional to the rate of change of the magnetic flux, ϕ, through the area, A, of the loop. This can be stated mathematically as:

$$\epsilon = -N\frac{\Delta\phi}{\Delta t}$$

where $\phi = B \cdot A$ and B is the strength of the magnetic field.

Faraday's Law relates induced emf to the rate of change of flux, which is the product of the magnetic field and the cross-sectional area the field lines pass through.



When the north pole of a magnet is pushed into a solenoid, the flux in the solenoid increases so the induced current will have an associated magnetic field pointing out of the solenoid (opposite to the magnet's field). When the north pole is pulled out, the flux decreases, so the induced current will have an associated magnetic field pointing into the solenoid (same direction as the magnet's field) to try to oppose the change. The directions of currents and associated magnetic fields can all be found using only the Right Hand Rule. When the fingers of the right hand are pointed in the direction of the magnetic field, the thumb points in the direction of the current. When the thumb is pointed in the direction of the magnetic field, the fingers point in the direction of the current.

The induced current generates a magnetic field. The induced magnetic field is in a direction that tends to cancel out the change in the magnetic field in the loop of wire. So, you can use the Right Hand Rule to find the direction of the induced current by remembering that the induced magnetic field is opposite in direction to the change in the magnetic field.

Electromagnetic induction is put into practical use in the construction of electrical generators, which use mechanical power to move a magnetic field past coils of wire to generate voltage. However, this is by no means the only practical use for this principle.

If we recall that the magnetic field produced by a current-carrying wire is always perpendicular to the wire, and that the flux intensity of this magnetic field varies with the amount of current which passes through it, we can see that a wire is capable of inducing a voltage *along its own length* if the current is changing. This effect is called *self-induction*. Self-induction is when a changing magnetic field is produced by changes in current through a wire, inducing a voltage along the length of that same wire.

If the magnetic flux is enhanced by bending the wire into the shape of a coil, and/or wrapping that coil around a material of high permeability, this effect of self-induced voltage will be more intense. A device constructed to take advantage of this effect is called an *inductor*, and will be discussed in greater detail in the next chapter.

Tip

An easy way to create a magnetic field of changing intensity is to move a permanent magnet next to a wire or coil of wire. The magnetic field must increase or decrease in intensity *perpendicular* to the wire (so that the magnetic field lines "cut across" the conductor), or else no voltage will be induced.

Tip

Finding the direction of the induced current

Extension:	*Lenz's Law*

The induced current will create a magnetic field that opposes the change in the magnetic flux.

Example 1: *Faraday's Law*

QUESTION

Consider a flat square coil with 5 turns. The coil is 0,50 m on each side, and has a magnetic field of 0,5 T passing through it. The plane of the coil is perpendicular to the magnetic field: the field points out of the page. Use Faraday's Law to calculate the induced emf, if the magnetic field is increases uniformly from 0,5 T to 1 T in 10 s. Determine the direction of the induced current.

SOLUTION

Step 1 : ***Identify what is required***
We are required to use Faraday's Law to calculate the induced emf.

Step 2 : ***Write Faraday's Law***

$$\epsilon = -N\frac{\Delta\phi}{\Delta t}$$

Step 3 : ***Solve Problem***

$$\begin{aligned}
\epsilon &= -N\frac{\Delta\phi}{\Delta t} \\
&= -N\frac{\phi_f - \phi_i}{\Delta t} \\
&= -N\frac{B_f \cdot A - B_i \cdot A}{\Delta t} \\
&= -N\frac{A(B_f - B_i)}{\Delta t} \\
&= -(5)\frac{(0{,}5)^2(1 - 0{,}5)}{10} \\
&= -0{,}0625 \text{ V}
\end{aligned}$$

The induced current is anti-clockwise as viewed from the direction of the increasing magnetic field.

Real-life applications

ESBHZ

The following devices use Faraday's Law in their operation.

- induction stoves
- tape players
- metal detectors
- transformers

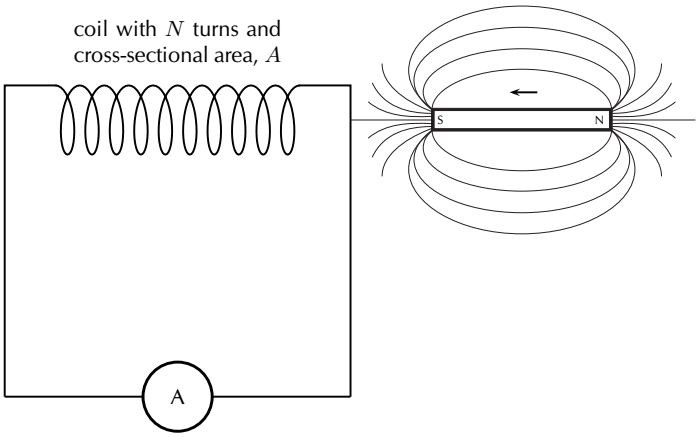
Activity: *Real-life applications of Faraday's Law*

Choose one of the following devices and do some research on the internet or in a library how your device works. You will need to refer to Faraday's Law in your explanation.

- induction stoves
- tape players
- metal detectors
- transformers

Exercise 18 - 2

1. State Faraday's Law in words and write down a mathematical relationship.
2. Describe what happens when a bar magnet is pushed into or pulled out of a solenoid connected to an ammeter. Draw pictures to support your description.
3. Use the Right Hand Rule to determine the direction of the induced current in the solenoid below.



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(1.) 00u9 (2.) 00ua (3.) 00ub

18.4 Transformers

ESBIA

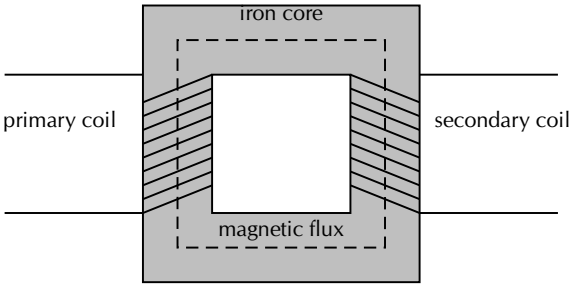
One of the real-world applications of Faraday's Law is in a *transformer*.

Eskom generates electricity at around 22 000 V. When you plug in a toaster, the mains voltage is 220 V. A transformer is used to *step-down* the high voltage to the lower voltage that is used as mains voltage.

DEFINITION: Transformer

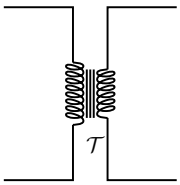
A transformer is an electrical device that uses the principle of induction between the primary coil and the secondary coil to either step-up or step-down the voltage.

The essential features of a transformer are two coils of wire, called the primary coil and the secondary coil, which are wound around different sections of the same iron core.



When an alternating voltage is applied to the primary coil it creates an alternating current in that coil, which induces an alternating magnetic field in the iron core. The changing magnetic flux through the secondary coil induces an emf, which creates a current in this secondary coil.

The circuit symbol for a transformer is:



By choosing the number of coils in the secondary solenoid relative to the number of coils in the primary solenoid, we can choose how much bigger or smaller the induced secondary current is by comparison to the current in the primary solenoid (so by how much the current is stepped up or down.)

This ability to transform voltage and current levels according to a simple ratio, determined by the ratio of input and output coil turns is a very useful property of transformers and accounts for the name. We can derive a mathematical relationship by using Faraday's law.

Assume that an alternating voltage V_p is applied to the primary coil (which has N_p turns) of a transformer. The current that results from this voltage generates a changing magnetic flux ϕ_p. We can then describe the emf in the primary coil by:

$$V_p = N_p \frac{\Delta\phi_p}{\Delta t}$$

Similarly, for the secondary coil,

$$V_s = N_s \frac{\Delta\phi_s}{\Delta t}$$

If we assume that the primary and secondary windings are perfectly coupled, then:

$$\phi_p = \phi_s$$

which means that:

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

Example 2: *Transformer specifications*

QUESTION

Calculate the voltage on the secondary coil if the voltage on the primary coil is 120 V and the ratio of primary windings to secondary windings is 10:1.

SOLUTION

Step 1 : ***Determine how to approach the problem***

Use

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

with

- $V_p = 120$
- $\frac{N_p}{N_s} = \frac{10}{1}$

Step 2 : ***Rearrange equation to solve for*** V_s

$$\begin{aligned} \frac{V_p}{V_s} &= \frac{N_p}{N_s} \\ \frac{1}{V_s} &= \frac{N_p}{N_s}\frac{1}{V_p} \\ \therefore V_s &= \frac{1}{\frac{N_p}{N_s}}V_p \end{aligned}$$

Step 3 : ***Substitute values and solve for*** V_s

$$\begin{aligned} V_s &= \frac{1}{\frac{N_p}{N_s}}V_p \\ &= \frac{1}{\frac{10}{1}}120 \\ &= 12\text{ V} \end{aligned}$$

A transformer designed to output more voltage than it takes in across the input coil is called a *step-up* transformer. A step-up transformer has more windings on the secondary coil than on the primary coil. This means that:

$$N_s > N_p$$

Similarly, a transformer designed to output less than it takes in across the input coil is called a *step-down* transformer. A step-down transformer has more windings on the primary coil than on the primary coil. This means that:

$$N_p > N_s$$

We use a step-up transformer to increase the voltage from the primary coil to the secondary coil. It is used at power stations to increase the voltage for the transmission lines. A step-down transformer decreases the voltage from the primary coil to the secondary coil. It is particularly used to decrease the voltage from the transmission lines to a voltage which can be used in factories and in homes.

Transformer technology has made long-range electric power distribution practical. Without the ability to efficiently step voltage up and down, it would be cost-prohibitive to construct power systems for anything but close-range (within a few kilometres) use.

As useful as transformers are, they only work with AC, not DC. This is because the phenomenon of mutual inductance relies on *changing* magnetic fields, and direct current (DC) can only produce steady magnetic fields, transformers simply will not work with direct current.

Of course, direct current may be interrupted (pulsed) through the primary winding of a transformer to create a changing magnetic field (as is done in automotive ignition systems to produce high-voltage spark plug power from a low-voltage DC battery), but pulsed DC is not that different from AC. Perhaps more than any other reason, this is why AC finds such widespread application in power systems. See simulation: VPlxa at www.everythingscience.co.za)

Real-world applications

ESBIB

Transformers are very important in the supply of electricity nationally. In order to reduce energy losses due to heating, electrical energy is transported from power stations along power lines at high voltage and low current. Transformers are used to step the voltage up from the power station to the power lines, and step it down from the power lines to buildings where it is needed.

Exercise 18 - 3

1. Draw a sketch of the main features of a transformer
2. Use Faraday's Law to explain how a transformer works in words and pictures.
3. Use the equation for Faraday's Law to derive an expression involving the ratios of the voltages and the number of windings in the primary and secondary coils.
4. If we have $N_p = 100$ and $N_s = 50$, and we connect the primary winding to a 230 V, 50Hz supply, then calculate the voltage on the secondary winding.
5. State the difference between a step-up and a step-down transformer in both structure and function.
6. Give an example of the use of transformers.

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(1.) 01hf (2.) 01hg (3.) 01hh (4.) 01hi (5.) 01hj (6.) 01hk

18.5 Motion of a charged particle in a magnetic field

ESBIC

When a charged particle moves through a magnetic field it experiences a force. For a particle that is moving at right angles to the magnetic field, the force is given by:

$$F = qvB$$

where q is the charge on the particle, v is the velocity of the particle and B is the magnetic field through which the particle is moving. This force is called the Lorentz force.

Tip

The direction of the force exerted on a charged particle moving through a magnetic field is determined by using the Right Hand Rule.
Point your first finger (index finger) in the direction of the velocity of the charge, your second finger (middle finger) in the direction of the magnetic field and then your thumb will point in the direction of the force exerted on the charge. If the charge is negative, the direction of the force will be opposite to the direction of your thumb.

Example 3: *Charged particle moving in a magnetic field*

QUESTION

An electron travels at 150m.s^{-1} at right angles to a magnetic field of 80 000 T. What force is exerted on the electron?

SOLUTION

Step 1 : ***Determine what is required***
We are required to determine the force on a moving charge in a magnetic field

Step 2 : ***Determine how to approach the problem***
We can use the formula:

$$F = qvB$$

Step 3 : ***Determine what is given***
We are given

- $q = 1{,}6 \times 10^{-19}\text{C}$ (The charge on an electron)
- $v = 150\text{m.s}^{-1}$
- $B = 80\ 000\text{T}$

Step 4 : ***Determine the force***

$$\begin{aligned} F &= qvB \\ &= (1{,}6 \times 10^{-19}\text{C})(150\text{m.s}^{-1})(80\ 000\text{T}) \\ &= 1{,}92 \times 10^{-12}\text{N} \end{aligned}$$

Real-world applications

ESBID

The following devices use the movement of charge in a magnetic field

- old televisions (cathode ray tubes)
- oscilloscope

Activity: *Real-life applications of charges moving in a magnetic field*

Choose one of the following devices and do some research on the internet or in a library how your device works.

- oscilloscope
- television

Exercise 18 - 4

1. What happens to a charged particle when it moves through a magnetic field?
2. Explain how you would use the Right Hand Rule to determine the direction of the force experienced by a charged particle as it moves in a magnetic field.

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(1.) 00uc (2.) 00ud

Chapter 18 — Summary

See the summary presentation (Presentation: VPmbf at www.everythingscience.co.za)

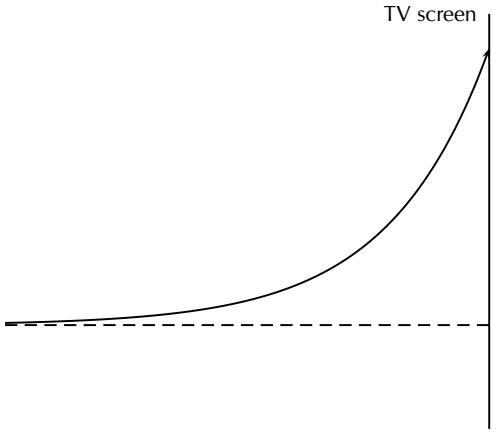
1. Electromagnetism is the study of the properties and relationship between electric currents and magnetism.
2. A current-carrying conductor will produce a magnetic field around the conductor.
3. The direction of the magnetic field is found by using the Right Hand Rule.
4. Electromagnets are temporary magnets formed by current-carrying conductors.
5. Electromagnetic induction occurs when a changing magnetic field induces a voltage in a current-carrying conductor.
6. Transformers use electromagnetic induction to alter the voltage.

7. A moving charged particle will experience a force in a magnetic field.

Chapter 18 End of Chapter Exercises

1. State the Right Hand Rule to determine the direction of a magnetic field around a current carrying wire and the Right Hand Rule to determine the direction of the force experienced by a moving charged particle in a magnetic field.
2. What did Hans Oersted discover about the relationship between electricity and magnetism?
3. List two uses of electromagnetism.
4. Draw a labelled diagram of an electromagnet and show the poles of the electromagnet on your sketch.
5. Transformers are useful electrical devices.
   (a) What is a transformer?
   (b) Draw a sketch of a step-down transformer.
   (c) What is the difference between a step-down and step-up transformer?
   (d) When would you use a step-up transformer?
6. Calculate the voltage on the secondary coil of a transformer if the voltage on the primary coil is 22 000 V and the ratio of primary windings to secondary windings is 500:1.
7. You find a transformer with 1000 windings on the primary coil and 200 windings on the secondary coil.
   (a) What type of transformer is it?
   (b) What will be the voltage on the secondary coil if the voltage on the primary coil is 400 V?

IEB 2005/11 HG An electron moving horizontally in a TV tube enters a region where there is a uniform magnetic field. This causes the electron to move along the path (shown by the solid line) because the magnetic field exerts a constant force on it. What is the direction of this magnetic field?



(a) upwards (towards the top of the page)
(b) downwards (towards the bottom of the page)
(c) into the page

(d) out of the page

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(1.) 00ue	(2.) 00uf	(3.) 00ug	(4.) 00uh	(5.) 00ui	(6.) 00uj
(7.) 00uk	(8.) 00um	(9.) 00un	(10.) 00up	(11.) 00uq	(12.) 00ur

Electric Circuits 19

19.1 Introduction

ESBIE

The study of electrical circuits is essential to understand the technology that uses electricity in the real-world. This includes electricity being used for the operation of electronic devices like computers.

See introductory video: VPmbu at www.everythingscience.co.za

19.2 Ohm's Law

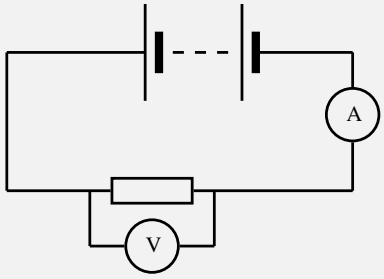
ESBIF

Definition of Ohm's Law

ESBIG

General experiment: *Ohm's Law*

Aim: In this experiment we will look at the relationship between the current going through a resistor and the potential difference (voltage) across the same resistor.



Method:

1. Set up the circuit according to the circuit diagram, starting with just one cell.
2. Draw the following table in your lab book.

Voltage, V (V)	Current, I (A)
1,5	
3,0	
4,5	
6,0	

3. Get your teacher to check the circuit before turning the power on.
4. Measure the current.
5. Add one more 1,5 V cell to the circuit and measure the current again.
6. Repeat until you have four cells and you have completed your table.
7. Draw a graph of voltage versus current.

Results:

1. Does your experimental results verify Ohm's Law? Explain.
2. How would you go about finding the resistance of an unknown resistor using only a power supply, a voltmeter and a known resistor R_0?

Activity: *Ohm's Law*

If you do not have access to the equipment necessary for the Ohm's Law experiment, you can do this activity.

Voltage, V (V)	Current, I (A)
3,0	0,4
6,0	0,8
9,0	1,2
12,0	1,6

1. Plot a graph of voltage (on the x-axis) and current (on the y-axis).

Conclusions:

1. What type of graph do you obtain (straight line, parabola, other curve)
2. Calculate the gradient of the graph.
3. Do your experimental results verify Ohm's Law? Explain.
4. How would you go about finding the resistance of an unknown resistor using only a power supply, a voltmeter and a known resistor R_0?

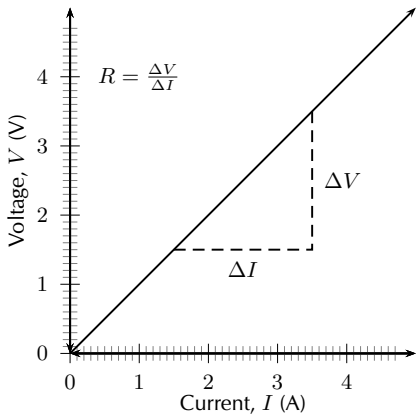
An important relationship between the current, voltage and resistance in a circuit was discovered by Georg Simon Ohm and is called **Ohm's Law**.

DEFINITION: Ohm's Law

The amount of electric current through a metal conductor, at a constant temperature, in a circuit is proportional to the voltage across the conductor. Mathematically, Ohm's Law is written:

$$V = R \cdot I.$$

Ohm's Law tells us that if a conductor is at a constant temperature, the current flowing through the conductor is proportional to the voltage across it. This means that if we plot voltage on the x-axis of a graph and current on the y-axis of the graph, we will get a straight-line. The gradient of the straight-line graph is related to the resistance of the conductor.



See simulation: VPmdo at www.everythingscience.co.za)

Ohmic and non-ohmic conductors

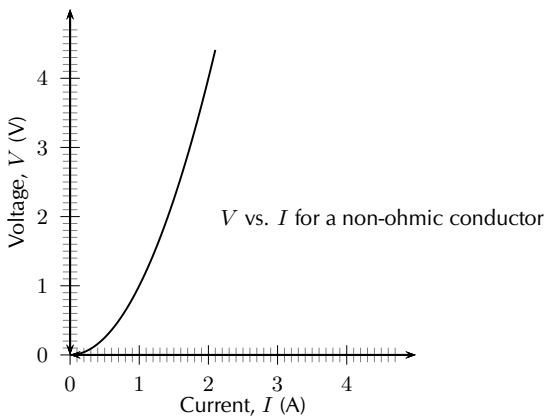
ESBIH

As you have seen, there is a mention of *constant temperature* when we talk about Ohm's Law. This is because the resistance of some conductors changes as their temperature changes. These types of conductors are called *non-ohmic* conductors, because they do not obey Ohm's Law. As can be expected, the conductors that obey Ohm's Law are called *ohmic* conductors. A light bulb is a common example of a non-ohmic conductor. Nichrome wire is an ohmic conductor.

In a light bulb, the resistance of the filament wire will increase dramatically as it warms from room temperature to operating temperature. If we increase the supply voltage in a real lamp circuit, the resulting increase in current causes the filament to increase in temperature, which increases its resistance. This effectively limits the increase in current. In this case, voltage and current do not obey Ohm's Law.

The phenomenon of resistance changing with variations in temperature is one shared by almost all metals, of which most wires are made. For most applications, these changes in resistance are small enough to be ignored. In the application of metal lamp filaments, which increase a lot in temperature (up to about 1000°C, and starting from room temperature) the change is quite large.

In general non-ohmic conductors have plots of voltage against current that are curved, indicating that the resistance is not constant over all values of voltage and current.



Activity: *Ohmic and non-ohmic conductors*

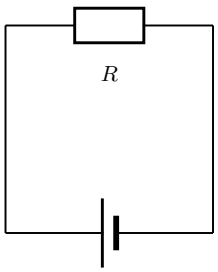
Repeat the experiment as described in the previous section. In this case use a light bulb as a resistor. Compare your results to the ohmic resistor.

Using Ohm's Law

ESBII

We are now ready to see how Ohm's Law is used to analyse circuits.

Consider the circuit with an ohmic resistor, R. If the resistor has a resistance of 5 Ω and voltage across the resistor is 5 V, then we can use Ohm's law to calculate the current flowing through the resistor.



Ohm's law is:

$$V = R \cdot I$$

which can be rearranged to:

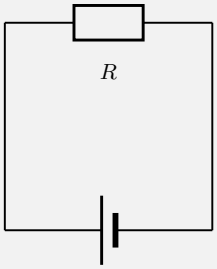
$$I = \frac{V}{R}$$

The current flowing through the resistor is:

$$\begin{aligned} I &= \frac{V}{R} \\ &= \frac{5\ \text{V}}{5\ \Omega} \\ &= 1\ \text{A} \end{aligned}$$

Example 1: *Ohm's Law*

QUESTION



The resistance of the above resistor is 10 Ω and the current going through the resistor is 4 A. What is the potential difference (voltage) across the resistor?

SOLUTION

Step 1 : ***Determine how to approach the problem***
It is an Ohm's Law problem. So we use the equation:

$$V = R \cdot I$$

Step 2 : ***Solve the problem***

$$\begin{aligned} V &= R \cdot I \\ &= (10)(4) \\ &= 40\ V \end{aligned}$$

Step 3 : ***Write the final answer***
The voltage across the resistor is 40 V.

Exercise 19 - 1

1. Calculate the resistance of a resistor that has a potential difference of 8 V across it when a current of 2 A flows through it.
2. What current will flow through a resistor of 6 Ω when there is a potential difference of 18 V across its ends?
3. What is the voltage across a 10 Ω resistor when a current of 1,5 A flows though it?

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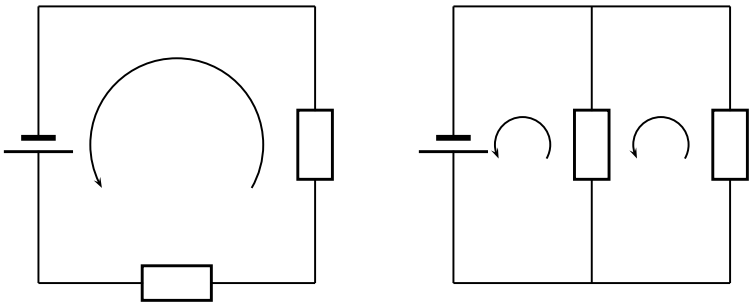
(1.) 01hm (2.) 01hn (3.) 01hp

19.3 Resistance

ESBIJ

In Grade 10, you learnt about resistors and were introduced to circuits where resistors were connected in series and circuits where resistors were connected in parallel. In a series circuit there is one path for the current to flow through. In a parallel circuit there are multiple paths for the current to flow through.



series circuit
one current path

parallel circuit
multiple current paths

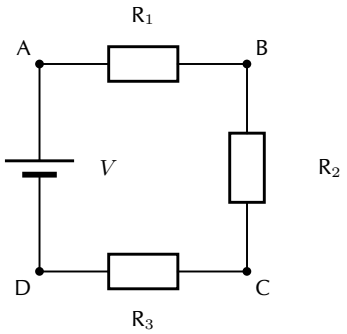
Equivalent resistance

ESBIK

When there is more than one resistor in a circuit, we are usually able to calculate the total combined resistance of all the resistors. The resistance of the single resistor is known as *equivalent resistance*.

Equivalent Series Resistance

Consider a circuit consisting of three resistors and a single cell connected in series.



The first principle to understand about series circuits is that the amount of current is the same through any component in the circuit. This is because there is only one path for electrons to flow in a series circuit. From the way that the battery is connected, we can tell which direction the current will flow. We know that current flows from positive to negative, by convention. Current in this circuit will flow in a clockwise direction, from point A to B to C to D and back to A.

So, how do we use this knowledge to calculate the total resistance in the circuit?

We know that in a series circuit the current has to be the same in all components. So we can write:

$$I = I_1 = I_2 = I_3$$

We also know that total voltage of the circuit has to be equal to the sum of the voltages over all three resistors. So we can write:

$$V = V_1 + V_2 + V_3$$

Finally, we know that Ohm's Law has to apply for each resistor individually, which gives us:

$$\begin{aligned} V_1 &= I_1 \cdot R_1 \\ V_2 &= I_2 \cdot R_2 \\ V_3 &= I_3 \cdot R_3 \end{aligned}$$

Therefore:

$$V = I_1 \cdot R_1 + I_2 \cdot R_2 + I_3 \cdot R_3$$

However, because

$$I = I_1 = I_2 = I_3$$

, we can further simplify this to:

$$\begin{aligned} V &= I \cdot R_1 + I \cdot R_2 + I \cdot R_3 \\ &= I(R_1 + R_2 + R_3) \end{aligned}$$

Further, we can write an Ohm's Law relation for the entire circuit:

$$V = I \cdot R$$

Therefore:

$$\begin{aligned} V &= I(R_1 + R_2 + R_3) \\ I \cdot R &= I(R_1 + R_2 + R_3) \\ \therefore \quad R &= R_1 + R_2 + R_3 \end{aligned}$$

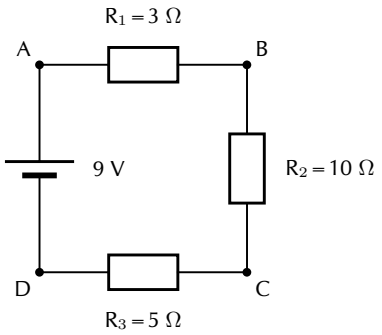
DEFINITION: Equivalent resistance in a series circuit, R_s

For n resistors in series the equivalent resistance is:

$$R_s = R_1 + R_2 + R_3 + \cdots + R_n$$

See simulation: VPmgv at www.everythingscience.co.za)

Let us apply this to the following circuit.



The resistors are in series, therefore:

$$\begin{aligned} R_s &= R_1 + R_2 + R_3 \\ &= 3\,\Omega + 10\,\Omega + 5\,\Omega \\ &= 18\,\Omega \end{aligned}$$

See video: VPmiy at www.everythingscience.co.za

Example 2: *Equivalent series resistance I*

QUESTION

Two 10 kΩ resistors are connected in series. Calculate the equivalent resistance.

SOLUTION

Step 1 : ***Determine how to approach the problem***
Since the resistors are in series we can use:

$$R_s = R_1 + R_2$$

Step 2 : ***Solve the problem***

$$\begin{aligned} R_s &= R_1 + R_2 \\ &= 10\,\text{k}\,\Omega + 10\,\text{k}\,\Omega \\ &= 20\,\text{k}\,\Omega \end{aligned}$$

Step 3 : ***Write the final answer***
The equivalent resistance of two 10 kΩ resistors connected in series is 20 kΩ.

Example 3: *Equivalent series resistance II*

QUESTION

Two resistors are connected in series. The equivalent resistance is 100 Ω. If one resistor is 10 Ω, calculate the value of the second resistor.

SOLUTION

Step 1 : ***Determine how to approach the problem***
Since the resistors are in series we can use:

$$R_s = R_1 + R_2$$

We are given the value of R_s and R_1.

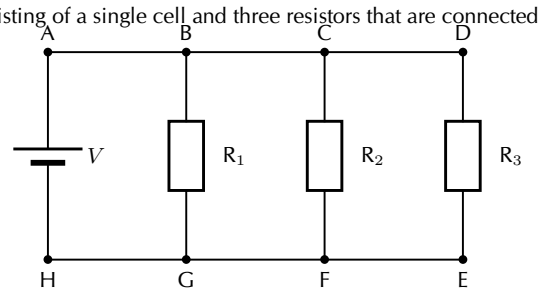
Step 2 : ***Solve the problem***

$$\begin{aligned} R_s &= R_1 + R_2 \\ \therefore \quad R_2 &= R_s - R_1 \\ &= 100\,\Omega - 10\,\Omega \\ &= 90\,\Omega \end{aligned}$$

Step 3 : ***Write the final answer***
The second resistor has a resistance of 90 Ω.

Equivalent parallel resistance

Consider a circuit consisting of a single cell and three resistors that are connected in parallel.



The first principle to understand about parallel circuits is that the voltage is equal across all components in the circuit. This is because there are only two sets of electrically common points in a parallel circuit, and voltage measured between sets of common points must always be the same at any given time. So, for the circuit shown, the following is true:

$$V = V_1 = V_2 = V_3$$

The second principle for a parallel circuit is that all the currents through each resistor must add up to the total current in the circuit.

$$I = I_1 + I_2 + I_3$$

Also, from applying Ohm's Law to the entire circuit, we can write:

$$V = \frac{I}{R_p}$$

where R_p is the equivalent resistance in this parallel arrangement.
We are now ready to apply Ohm's Law to each resistor, to get:

$$\begin{aligned} V_1 &= R_1 \cdot I_1 \\ V_2 &= R_2 \cdot I_2 \\ V_3 &= R_3 \cdot I_3 \end{aligned}$$

This can be also written as:

$$\begin{aligned} I_1 &= \frac{V_1}{R_1} \\ I_2 &= \frac{V_2}{R_2} \\ I_3 &= \frac{V_3}{R_3} \end{aligned}$$

Now we have:

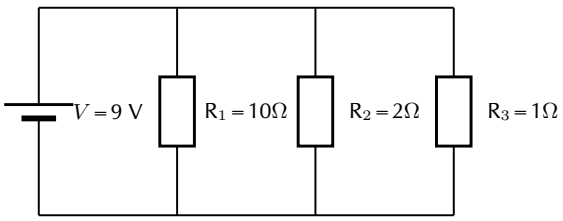
$$\begin{aligned} I &= I_1 + I_2 + I_3 \\ \frac{V}{R_p} &= \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3} \\ &= \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3} \\ \text{because} \quad & V = V_1 = V_2 = V_3 \\ &= V\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right) \\ \therefore \quad \frac{1}{R_p} &= \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right) \end{aligned}$$

DEFINITION: Equivalent resistance in a parallel circuit, R_p

For n resistors in parallel, the equivalent resistance is:

$$\frac{1}{R_p} = \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \cdots + \frac{1}{R_n}\right)$$

Let us apply this formula to the following circuit.



What is the total resistance in the circuit?

$$\begin{aligned}
\frac{1}{R_p} &= \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right) \\
&= \left(\frac{1}{10\,\Omega} + \frac{1}{2\,\Omega} + \frac{1}{1\,\Omega}\right) \\
&= \left(\frac{1+5+10}{10}\right) \\
&= \left(\frac{16}{10}\right) \\
\therefore \quad R_p &= 0{,}625\,\Omega
\end{aligned}$$

See video: VPmje at www.everythingscience.co.za

See video: VPmkf at www.everythingscience.co.za

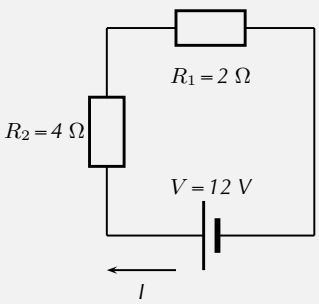
Use of Ohm's Law in series and parallel Circuits

ESBIL

Example 4: *Ohm's Law*

QUESTION

Calculate the current (I) in this circuit if the resistors are both ohmic in nature.



SOLUTION

Step 1 : ***Determine what is required***
We are required to calculate the current flowing in the circuit.

Step 2 : ***Determine how to approach the problem***
Since the resistors are Ohmic in nature, we can use Ohm's Law. There are however two resistors in the circuit and we need to find the total resistance.

Step 3 : ***Find total resistance in circuit***
Since the resistors are connected in series, the total resistance R is:

$$R = R_1 + R_2$$

Therefore,

$$R = 2 + 4 = 6\ \Omega$$

Step 4 : ***Apply Ohm's Law***

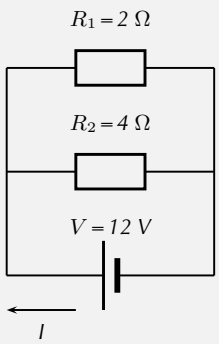
$$\begin{aligned} V &= R \cdot I \\ \therefore\ I &= \frac{V}{R} \\ &= \frac{12}{6} \\ &= 2\ \text{A} \end{aligned}$$

Step 5 : ***Write the final answer***
A 2 A current is flowing in the circuit.

Example 5: *Ohm's Law I*

QUESTION

Calculate the current (I) in this circuit if the resistors are both ohmic in nature.



SOLUTION

Step 1 : ***Determine what is required***
We are required to calculate the current flowing in the circuit.

Step 2 : ***Determine how to approach the problem***
Since the resistors are Ohmic in nature, we can use Ohm's Law. There are however two resistors in the circuit and we need to find the total resistance.

Step 3 : ***Find total resistance in circuit***
Since the resistors are connected in parallel, the total resistance R is:

$$\frac{1}{R} = \frac{1}{R_1} + \frac{1}{R_2}$$

Therefore,

$$\begin{aligned}
\frac{1}{R} &= \frac{1}{R_1} + \frac{1}{R_2} \\
&= \frac{1}{2} + \frac{1}{4} \\
&= \frac{2+1}{4} \\
&= \frac{3}{4} \\
Therefore, R &= 1{,}33\ \Omega
\end{aligned}$$

Step 4 : ***Apply Ohm's Law***

$$\begin{aligned}
V &= R \cdot I \\
\therefore \quad I &= \frac{V}{R} \\
&= \frac{12}{\frac{4}{3}} \\
&= 9\ \text{A}
\end{aligned}$$

Step 5 : ***Write the final answer***
A 9 A current is flowing in the circuit.

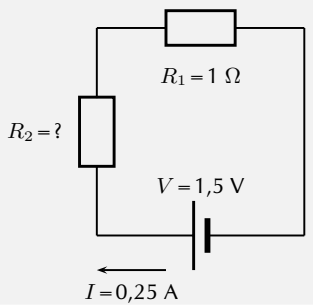
Example 6: *Ohm's Law II*

QUESTION

Two ohmic resistors (R_1 and R_2) are connected in series with a cell. Find the resistance of R_2, given that the current flowing through R_1 and R_2 is 0,25 A and that the voltage across the cell is 1,5 V. $R_1 = 1\ \Omega$.

SOLUTION

Step 1 : ***Draw the circuit and fill in all known values.***



Step 2 : ***Determine how to approach the problem.***
We can use Ohm's Law to find the total resistance R in the circuit, and then calculate the unknown resistance using:

$$R = R_1 + R_2$$

because it is in a series circuit.

Step 3 : ***Find the total resistance***

$$\begin{aligned} V &= R \cdot I \\ \therefore \quad R &= \frac{V}{I} \\ &= \frac{1{,}5}{0{,}25} \\ &= 6\,\Omega \end{aligned}$$

Step 4 : ***Find the unknown resistance***
We know that:

$$R = 6\,\Omega$$

and that

$$R_1 = 1\,\Omega$$

Since

$$R = R_1 + R_2$$

$$R_2 = R - R_1$$

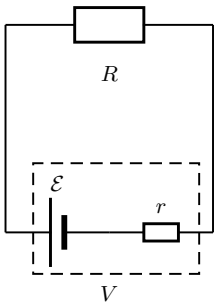
Therefore,

$$R_2 = 5\,\Omega$$

Batteries and internal resistance

ESBIM

Real batteries are made from materials which have resistance. This means that real batteries are not just sources of potential difference (voltage), but they also possess internal resistance. If the total voltage source is referred to as the emf, $\mathcal{E}$, then a real battery can be represented as an emf connected in series with a resistor r. The internal resistance of the battery is represented by the symbol r.



DEFINITION: Load

The external resistance in the circuit is referred to as the load.

Suppose that the battery with emf $\mathcal{E}$ and internal resistance r supplies a current I through an external load resistor R. Then the voltage drop across the load resistor is that supplied by the battery:

$$V = I \cdot R$$

Similarly, from Ohm's Law, the voltage drop across the internal resistance is:

$$V_r = I \cdot r$$

The voltage V of the battery is related to its emf $\mathcal{E}$ and internal resistance r by:

$$\begin{aligned} \mathcal{E} &= V + Ir; or \\ V &= \mathcal{E} - Ir \end{aligned}$$

The emf of a battery is essentially constant because it only depends on the chemical reaction (that converts chemical energy into electrical energy) going on inside the battery. Therefore, we can see that the voltage across the terminals of the battery is dependent on the current drawn by the load. The higher the current, the lower the voltage across the terminals, because the emf is constant. By the same reasoning, the voltage only equals the emf when the current is very small.

The maximum current that can be drawn from a battery is limited by a critical value I_c. At a current of I_c, V = 0 V. Then, the equation becomes:

$$\begin{aligned} 0 &= \mathcal{E} - I_c r \\ I_c r &= \mathcal{E} \\ I_c &= \frac{\mathcal{E}}{r} \end{aligned}$$

The maximum current that can be drawn from a battery is less than $\frac{\mathcal{E}}{r}$.

Example 7: *Internal resistance*

QUESTION

What is the internal resistance of a battery if its emf is 12 V and the voltage drop across its terminals is 10 V when a current of 4 A flows in the circuit when it is connected across a load?

SOLUTION

Step 1 : ***Determine how to approach the problem***

It is an internal resistance problem. So we use the equation:

$$\mathcal{E} = V + Ir$$

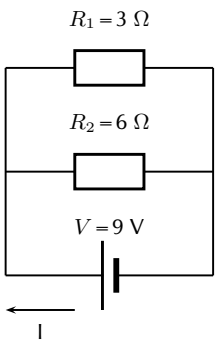
Step 2 : ***Solve the problem***

$$\begin{aligned} \mathcal{E} &= V + Ir \\ 12 &= 10 + 4(r) \\ &= 0.5 \end{aligned}$$

Step 3 : ***Write the final answer***
The internal resistance of the resistor is 0.5 Ω.

Exercise 19 - 2

1. Calculate the equivalent resistance of:
   (a) three 2 Ω resistors in series;
   (b) two 4 Ω resistors in parallel;
   (c) a 4 Ω resistor in series with a 8 Ω resistor;
   (d) a 6 Ω resistor in series with two resistors (4 Ω and 2 Ω) in parallel.
2. Calculate the total current in this circuit if both resistors are ohmic.



3. Two ohmic resistors are connected in series. The resistance of the one resistor is 4 Ω . What is the resistance of the other resistor if a current of 0,5 A flows through the resistors when they are connected to a voltage supply of 6 V.
4. Describe what is meant by the *internal resistance* of a real battery.
5. Explain why there is a difference between the emf and terminal voltage of a battery if the load (external resistance in the circuit) is comparable in size to the battery's internal resistance
6. What is the internal resistance of a battery if its emf is 6 V and the voltage drop across its terminals is 5,8 V when a current of 0,5 A flows in the circuit when it is connected across a load?

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(1.) 00us (2.) 00ut (3.) 00uu (4.) 00uv (5.) 00uw (6.) 00ux

19.4 Series and parallel networks of resistors

ESBIN

Now that you know how to handle simple series and parallel circuits, you are ready to tackle problems like this:

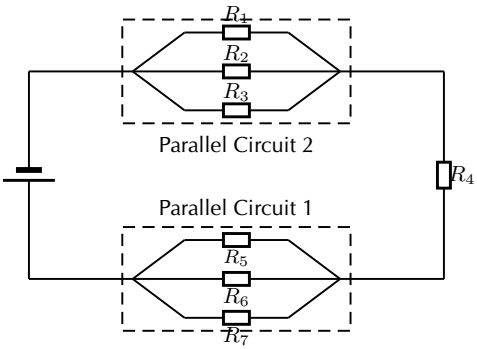
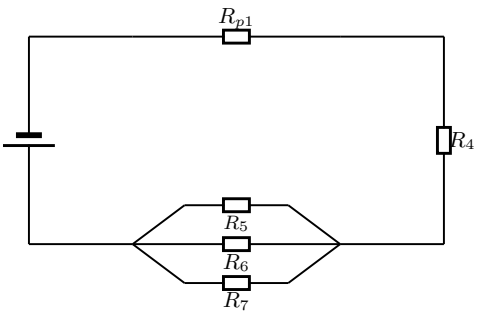


Figure 19.1: An example of a series-parallel network. The dashed boxes indicate parallel sections of the circuit.

It is relatively easy to work out these kind of circuits because you use everything you have already learnt about series and parallel circuits. The only difference is that you do it in stages. In Figure 19.1, the circuit consists of 2 parallel portions that are then in series with 1 resistor. So, in order to work out the equivalent resistance, you start by calculating the total resistance of the parallel portions and then add up all the resistances in series. If all the resistors in Figure 19.1 had resistances of 10 Ω, we can calculate the equivalent resistance of the entire circuit.

We start by calculating the total resistance of *Parallel Circuit 1*.

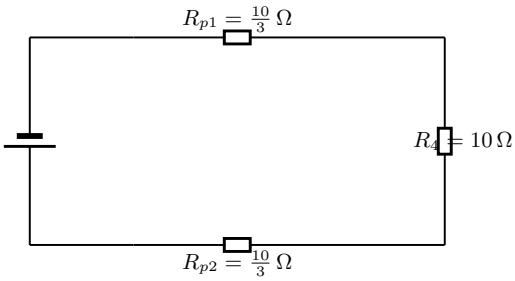


The value of R_{p1} is:

$$\begin{aligned}
\frac{1}{R_{p1}} &= \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \\
R_{p1} &= \left(\frac{1}{10} + \frac{1}{10} + \frac{1}{10}\right)^{-1} \\
&= \left(\frac{1+1+1}{10}\right)^{-1} \\
&= \left(\frac{3}{10}\right)^{-1} \\
&= 3{,}33\,\Omega
\end{aligned}$$

We can similarly calculate the total resistance of *Parallel Circuit 2*:

$$\begin{aligned}
\frac{1}{R_{p2}} &= \frac{1}{R_5} + \frac{1}{R_6} + \frac{1}{R_7} \\
R_{p2} &= \left(\frac{1}{10} + \frac{1}{10} + \frac{1}{10}\right)^{-1} \\
&= \left(\frac{1+1+1}{10}\right)^{-1} \\
&= \left(\frac{3}{10}\right)^{-1} \\
&= 3{,}33\,\Omega
\end{aligned}$$



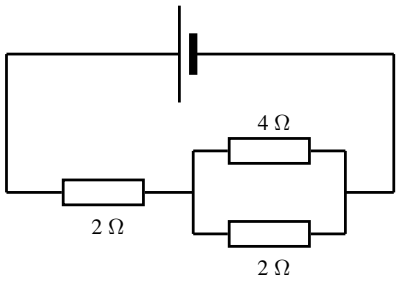
This has now being simplified to a simple series circuit and the equivalent resistance is:

$$\begin{aligned}
R &= R_{p1} + R_4 + R_{p2} \\
&= \frac{10}{3} + 10 + \frac{10}{3} \\
&= \frac{100+30+100}{30} \\
&= \frac{230}{30} \\
&= 7{,}66\,\Omega
\end{aligned}$$

The equivalent resistance of the circuit in Figure 19.1 is 7,66 Ω.

Exercise 19 - 3

Determine the equivalent resistance of the following circuits:



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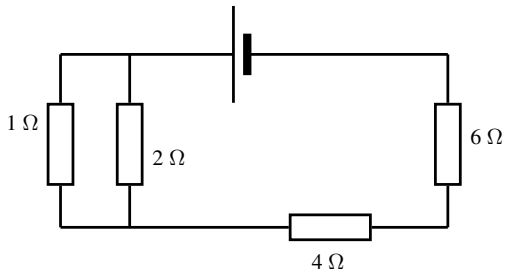
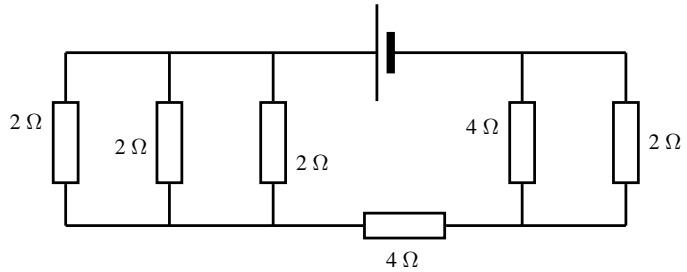
2. 

3. 

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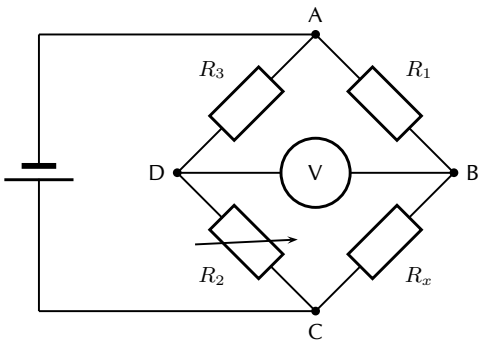
19.5 Wheatstone bridge

ESBIO

Another method of finding an unknown resistance is to use a *Wheatstone bridge*. A Wheatstone bridge is a measuring instrument that is used to measure an unknown electrical resistance by balancing two legs of a bridge circuit, one leg of which includes the unknown component. Its operation is similar to the original potentiometer except that in potentiometer circuits the meter used is a sensitive galvanometer.

FACT

The Wheatstone bridge was invented by Samuel Hunter Christie in 1833 and improved and popularised by Sir Charles Wheatstone in 1843.



Circuit for Wheatstone bridge

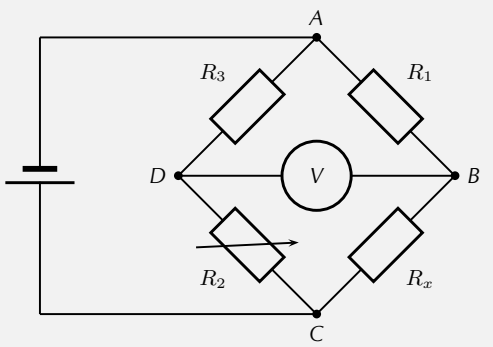
In the circuit of the Wheatstone bridge, R_x is the unknown resistance. R_1, R_2 and R_3 are resistors of known resistance and the resistance of R_2 is adjustable. If the ratio of R_2:R_1 is equal to the ratio of R_x:R_3, then the voltage between the two midpoints will be zero and no current will flow between

the midpoints. In order to determine the unknown resistance, R_2 is varied until this condition is reached. That is when the voltmeter reads 0 V.

Example 8: *Wheatstone bridge*

QUESTION

What is the resistance of the unknown resistor R_x in the diagram below if $R_1 = 4\Omega$ $R_2 = 8\Omega$ and $R_3 = 6\Omega$.



Circuit for Wheatstone bridge

SOLUTION

Step 1 : ***Determine how to approach the problem***
The arrangement is a Wheatstone bridge. So we use the equation:

$$R_x : R_3 = R_2 : R_1$$

Step 2 : ***Solve the problem***

$$\begin{aligned} R_x : R_3 &= R_2 : R_1 \\ R_x : 6 &= 8 : 4 \\ R_x &= 12\ \Omega \end{aligned}$$

Step 3 : ***Write the final answer***
The resistance of the unknown resistor is 12 Ω.

Extension:	*Power in electric circuits*

In addition to voltage and current, there is another measure of free electron activity in a circuit: *power*. Power is a measure of how rapidly a standard amount of *work* is done. In electric circuits, power is a function of both voltage and current:

DEFINITION: Electrical Power

Electrical power is calculated as:

$$P = I \cdot V$$

Power (P) is exactly equal to current (I) multiplied by voltage (V) and there is no extra constant of proportionality. The unit of measurement for power is the *Watt* (abbreviated W).

Activity: *Equivalence*

Use Ohm's Law to show that:

$$P = VI$$

is identical to

$$P = I^2 R$$

and

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

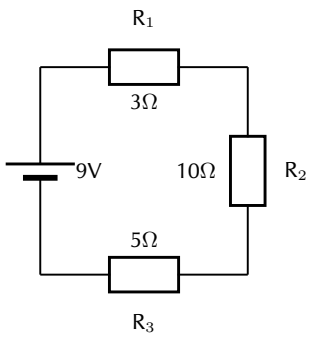
Chapter 19 — Summary

See the summary presentation (▶ Presentation: VPmmk at www.everythingscience.co.za)

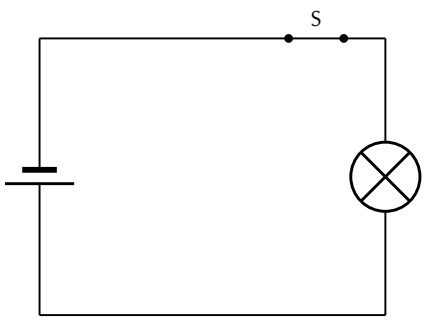
1. Ohm's Law states that the amount of current through a conductor, at constant temperature, is proportional to the voltage across the resistor. Mathematically we write $V = I \cdot R$
2. Conductors that obey Ohm's Law are called ohmic conductors; those that do not are called non-ohmic conductors.
3. We use Ohm's Law to calculate the resistance of a resistor. $R = \frac{V}{I}$
4. The equivalent resistance of resistors in series (R_s) can be calculated as follows: $R_s = R_1 + R_2 + R_3 + ... + R_n$
5. The equivalent resistance of resistors in parallel (R_p) can be calculated as follows: $\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + ... + \frac{1}{R_n}$
6. Real batteries have an internal resistance.
7. Wheatstone bridges can be used to accurately determine the resistance of an unknown resistor.

Chapter 19 End of Chapter Exercises

1. Calculate the current in the following circuit and then use the current to calculate the voltage drops across each resistor.



2. Explain why a voltmeter is placed in parallel with a resistor.
3. Explain why an ammeter is placed in series with a resistor.
4. [IEB 2001/11 HG1] - **Emf**
   (a) Explain the meaning of each of these two statements:
      i. "The current through the battery is 50 mA."
      ii. "The emf of the battery is 6 V."
   (b) A battery tester measures the current supplied when the battery is connected to a resistor of 100 Ω. If the current is less than 50 mA, the battery is "flat" (it needs to be replaced). Calculate the maximum internal resistance of a 6 V battery that will pass the test.
5. [IEB 2005/11 HG] The electric circuit of a torch consists of a cell, a switch and a small light bulb, as shown in the diagram below.



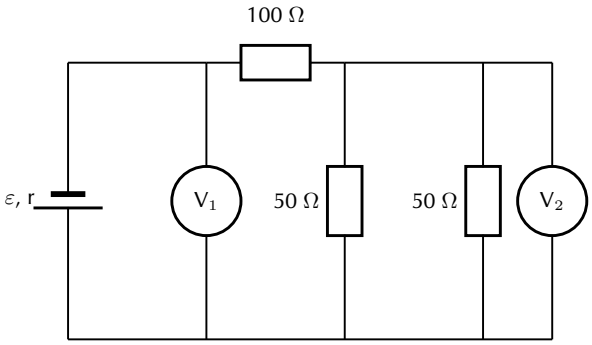
The electric torch is designed to use a D-type cell, but the only cell that is available for use is an AA-type cell. The specifications of these two types of cells are shown in the table below:

Cell	emf	Appliance for which it is designed	Current drawn from cell when connected to the appliance for which it is designed
D	1,5 V	torch	300 mA
AA	1,5 V	TV remote control	30 mA

What is likely to happen and why does it happen when the AA-type cell replaces the D-type cell in the electric torch circuit?

	What happens	Why it happens
(a)	the bulb is dimmer	the AA-type cell has greater internal resistance
(b)	the bulb is dimmer	the AA-type cell has less internal resistance
(c)	the brightness of the bulb is the same	the AA-type cell has the same internal resistance
(d)	the bulb is brighter	the AA-type cell has less internal resistance

6. [IEB 2005/11 HG1] A battery of emf ε and internal resistance r = 25 Ω is connected to this arrangement of resistors.



The resistances of voltmeters V_1 and V_2 are so high that they do not affect the current in the circuit.

(a) Explain what is meant by "the emf of a battery".
The power dissipated in the 100 Ω resistor is 0,81 W.
(b) Calculate the current in the 100 Ω resistor.
(c) Calculate the reading on voltmeter V_2.
(d) Calculate the reading on voltmeter V_1.
(e) Calculate the emf of the battery.

7. [SC 2003/11] A kettle is marked 240 V; 1 500 W.
(a) Calculate the resistance of the kettle when operating according to the above specifications.
(b) If the kettle takes 3 minutes to boil some water, calculate the amount of electrical energy transferred to the kettle.

8. [IEB 2001/11 HG1] - **Electric Eels**
Electric eels have a series of cells from head to tail. When the cells are activated by a nerve impulse, a potential difference is created from head to tail. A healthy electric eel can produce a potential difference of 600 V.
(a) What is meant by "a potential difference of 600 V"?
(b) How much energy is transferred when an electron is moved through a potential difference of 600 V?

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(1.) 00uy (2.) 00uz (3.) 00v0 (4.) 00v1 (5.) 00v2 (6.) 00v3
(7.) 00v4 (8.) 00v5

Electronic Properties of Matter

20

20.1 Introduction

ESBIP

We can study many different features of solids. Just a few of the things we could study are how hard or soft they are, what their magnetic properties are or how well they conduct heat. The thing that we are interested in, in this chapter are their electronic properties. Simply, how well do they conduct electricity and how do they do it.

We are only going to discuss materials that form a 3-dimensional lattice. This means that the atoms that make up the material have a regular pattern (carbon, silicon, etc.). We won't discuss materials where the atoms are jumbled together in a irregular way (plastic, glass, rubber etc.).

See introductory video: VPmms at www.everythingscience.co.za

20.2 Conduction

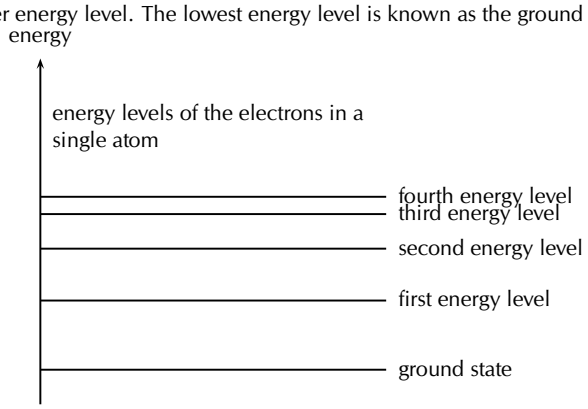
ESBIQ

We know that there are materials that do conduct electricity, called conductors, like the copper wires in the circuits you build. There are also materials that do not conduct electricity, called insulators, like the plastic covering on the copper wires.

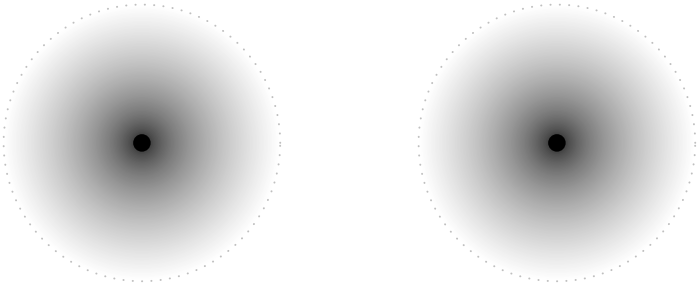
Conductors come in two major categories: metals (e.g. copper) and semi-conductors (e.g. silicon). Metals conduct very well and semi-conductors don't. One very interesting difference is that metals conduct less as they become hotter but semi-conductors conduct more.

What is different about these substances that makes them conduct differently? That is what we are about to find out.

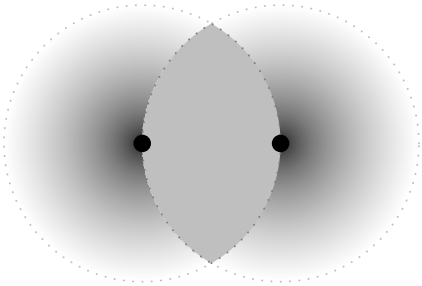
We have learnt that electrons in an atom have discrete energy levels. When an electron is given the right amount of energy, it can jump to a higher energy level, while if it loses the right amount of energy it can drop to a lower energy level. The lowest energy level is known as the ground state.



When two atoms are far apart from each other they don't influence each other. Look at the picture below. There are two atoms depicted by the black dots. When they are far apart their electron clouds (the gray clouds) are distinct. The dotted line depicts the distance of the outermost electron energy level that is occupied.

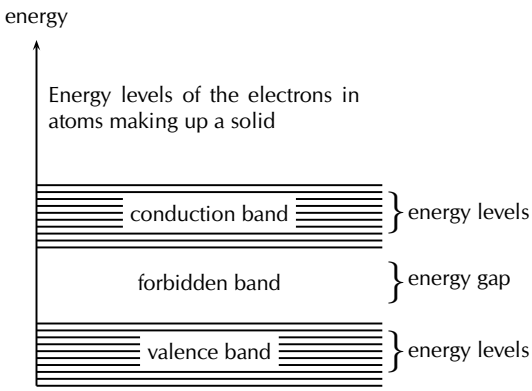


In some lattice structures the atoms would be closer together. If they are close enough their electron clouds, and therefore electron energy levels start to overlap. Look at the picture below. In this picture the two atoms are closer together. The electron clouds now overlap. The overlapping area is coloured in solid gray to make it easier to see.



When this happens we might find two electrons with the same energy and spin in the same space. We know that this is not allowed from the Pauli exclusion principle. Something must change to allow the overlapping to happen. The change is that the energies of the energy levels change a tiny bit so that the electrons are not in exactly the same spin and energy state at the same time.

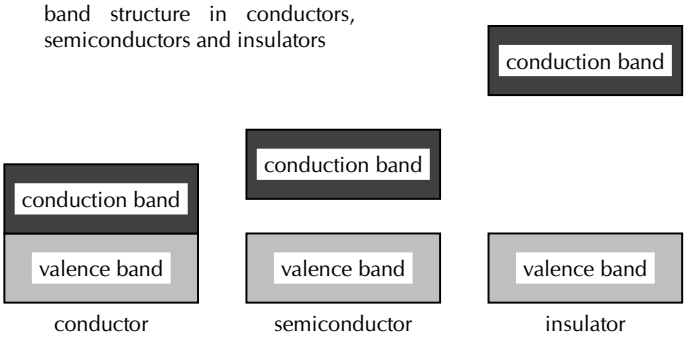
So if we have 2 atoms then in the overlapping area we will have twice the number of electrons and energy levels but the energy levels from the different atoms will be very very close in energy. If we had 3 atoms then there would be 3 energy levels very close in energy and so on. In a solid there may be very many energy levels that are very close in energy. These groups of energy levels are called bands. The spacing between these bands determines whether the solid is a conductor or an insulator.



In a gas, the atoms are spaced far apart and they do not influence each other. However, the atoms in a solid greatly influence each other. The forces that bind these atoms together in a solid affect how the electrons of the atoms behave, by causing the individual energy levels of an atom to break up and form energy bands. The resulting energy levels are more closely spaced than those in the individual atoms. The energy bands still contain discrete energy levels, but there are now many more energy levels than in the single atom.

In crystalline solids, atoms interact with their neighbours, and the energy levels of the electrons in isolated atoms turn into bands. Whether a material conducts or not is determined by its band structure.

band structure in conductors, semiconductors and insulators



Electrons follow the Pauli exclusion principle, meaning that two electrons cannot occupy the same state. Thus electrons in a solid fill up the energy bands up to a certain level (this is called the Fermi energy). Bands which are completely full of electrons cannot conduct electricity, because there is no state of nearby energy to which the electrons can jump. Materials in which all bands are full are insulators.

Metals

ESBIR

Metals are good conductors because they have unfilled spaces in the valence energy band. In the absence of an electric field, there are electrons travelling in all directions. When an electric field is applied the mobile electrons flow. Electrons in this band can be accelerated by the electric field because there are plenty of nearby unfilled spaces in the band.

Insulator

ESBIS

The energy diagram for the insulator shows the insulator with a very wide energy gap. The wider this gap, the greater the amount of energy required to move the electron from the valence band to the conduction band. Therefore, an insulator requires a large amount of energy to obtain a small amount of current. The insulator “insulates” because of the wide forbidden band or energy gap.

Breakdown

A solid with filled bands is an insulator. If we raise the temperature the electrons gain thermal energy. If there is enough energy added then electrons can be thermally excited from the valence band to the conduction band. The fraction of electrons excited in this way depends on:

- the temperature and
- the band gap, the energy difference between the two bands.

Exciting these electrons into the conduction band leaves behind positively charged holes in the valence band, which can also conduct electricity.

Semi-conductors

ESBIT

A semi-conductor is very similar to an insulator. The main difference between semiconductors and insulators is the size of the band gap between the conduction and valence bands. The band gap in insulators is larger than the band gap in semiconductors.

In semi-conductors at room temperature, just as in insulators, very few electrons gain enough thermal energy to leap the band gap, which is necessary for conduction. For this reason, pure semi-conductors and insulators, in the absence of applied fields, have roughly similar electrical properties. The smaller band gaps of semi-conductors, however, allow for many other means besides temperature to control their electrical properties. The most important one being that for a certain amount of applied voltage, more current will flow in the semiconductor than in the insulator.

Exercise 20 - 1

1. Explain how energy levels of electrons in an atom combine with those of other atoms in the formation of crystals.
2. Explain how the resulting energy levels are more closely spaced than those in the individual atoms, forming energy bands.
3. Explain the existence of energy bands in metal crystals as the result of superposition of energy levels.
4. Explain and contrast the conductivity of conductors, semi-conductors and insulators using energy band theory.
5. What is the main difference in the energy arrangement between an isolated atom and the atom in a solid?
6. What determines whether a solid is an insulator, a semiconductor, or a conductor?

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(1.) 00w1 (2.) 00w2 (3.) 00w3 (4.) 00w4 (5.) 00w5 (6.) 00w6

20.3 Intrinsic Properties and Doping

ESBIU

We have seen that the size of the energy gap between the valence band and the conduction band determines whether a solid is a conductor or an insulator. However, we have seen that there is a material known as a semi-conductor. A semi-conductor is a solid whose band gap is smaller than that of an insulator and whose electrical properties can be modified by a process known as *doping*.

> *DEFINITION: Doping*
>
> Doping is the deliberate addition of impurities to a pure semiconductor material to change its electrical properties.

FACT

Si has a band gap of 1.744×10^{-19} J while Ge has a band gap of 1.152×10^{-19} J.

Semiconductors are often the Group IV elements in the periodic table. The most common semiconductor elements are silicon (Si) and germanium (Ge). The most important property of Group IV elements is that they have 4 valence electrons.

So, if we look at the arrangement of for example Si atoms in a crystal, they would look like that shown in Figure 20.1.

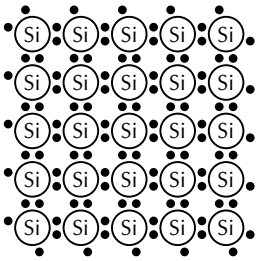


Figure 20.1: Arrangement of atoms in a Si crystal.

The main aim of doping is to make sure there are either too many (surplus) or too few electrons (deficiency). Depending on what situation you want to create you use different elements for the doping.

Surplus

ESBIV

A surplus of electrons is created by adding an element that has more valence electrons than Si to the Si crystal. This is known as *n-type* doping and elements used for n-type doping usually come from Group V in the periodic table. Elements from Group V have 5 valence electrons, one more than the Group IV elements.

A common n-type dopant (substance used for doping) is arsenic (As). The combination of a semiconductor and an n-type dopant is known as an n-type semiconductor. A Si crystal doped with As is shown in Figure 20.2. When As is added to a Si crystal, 4 of the 5 valence electrons in As bond with the 4 Si valence electrons. The fifth As valence electron is free to move around.

It takes only a few As atoms to create enough free electrons to allow an electric current to flow through the silicon. Since n-type dopants 'donate' their free atoms to the semiconductor, they are known as *donor atoms*.

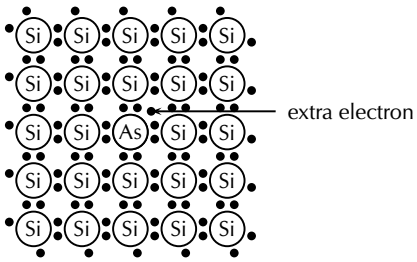


Figure 20.2: Si crystal doped with As. For each As atom present in the Si crystal, there is one extra electron. This combination of Si and As is known as an n-type semiconductor, because of its overall surplus of electrons.

Deficiency

ESBIW

A deficiency of electrons is created by adding an element that has less valence electrons than Si to the Si crystal. This is known as *p-type* doping and elements used for p-type doping usually come from Group III in the periodic table. Elements from Group III have 3 valence electrons, one less than the semiconductor elements that come from Group IV. A common p-type dopant is boron (B). The combination of a semiconductor and a p-type dopant is known as an p-type semiconductor. A Si crystal doped with B is shown in Figure 20.3. When B is mixed into the silicon crystal, there is a Si valence electron that is left unbonded.

The lack of an electron is known as a *hole* and has the effect of a positive charge. Holes can conduct current. A hole happily accepts an electron from a neighbour, moving the hole over a space. Since p-type dopants 'accept' electrons, they are known as *acceptor atoms*.

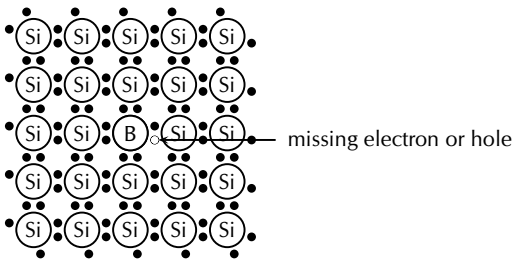
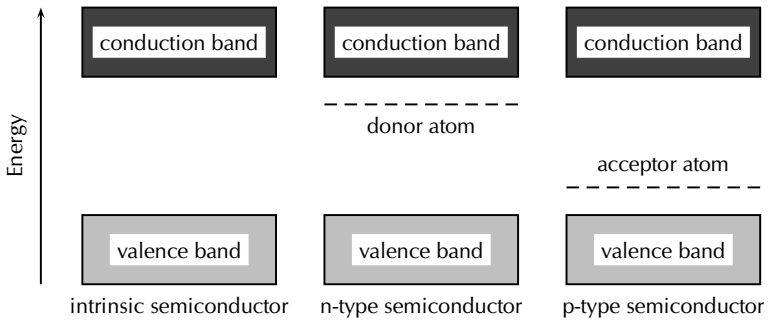


Figure 20.3: Si crystal doped with B. For each B atom present in the Si crystal, there is one less electron. This combination of Si and B is known as a p-type semiconductor, because of its overall deficiency of electrons.

Donor (n-type) impurities have extra valence electrons with energies very close to the conduction band which can be easily thermally excited to the conduction band. Acceptor (p-type) impurities capture electrons from the valence band, allowing the easy formation of holes.



The energy level of the donor atom is close to the conduction band and it is relatively easy for electrons to enter the conduction band. The energy level of the acceptor atom is close to the valence band and it is relatively easy for electrons to leave the valence band and enter the vacancies.

Exercise 20 - 2

1. Explain the process of doping using detailed diagrams for p-type and n-type semiconductors.
2. Draw a diagram showing a Ge crystal doped with As. What type of semiconductor is this?
3. Draw a diagram showing a Ge crystal doped with B. What type of semiconductor is this?
4. Explain how doping improves the conductivity of semi-conductors.
5. Would the following elements make good p-type dopants or good n-type dopants?
   (a) B
   (b) P
   (c) Ga
   (d) As
   (e) In
   (f) Bi

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(1.) 00w7 (2.) 00w8 (3.) 00w9 (4.) 00wa (5.) 00wb

20.4 The p-n junction

ESBIX

Differences between p- and n-type semiconductors

ESBIY

We have seen that the addition of specific elements to semiconductor materials turns them into p-type semiconductors or n-type semiconductors. The differences between n- and p-type semiconductors are summarised in Table **??**.

The p-n Junction

ESBIZ

When p-type and n-type semiconductors are placed in contact with each other, a p-n junction is formed. Near the junction, electrons and holes combine to create a depletion region.

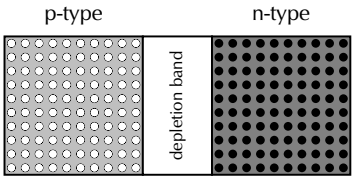


Figure 20.4: The p-n junction forms between p- and n-type semiconductors. The free electrons from the n-type material combine with the holes in the p-type material near the junction. There is a small potential difference across the junction. The area near the junction is called the depletion region because there are few holes and few free electrons in this region.

Electric current flows more easily across a p-n junction in one direction than in the other. If the positive pole of a battery is connected to the p-side of the junction, and the negative pole to the n-side, charge flows across the junction. If the battery is connected in the opposite direction, very little charge can flow.

This might not sound very useful at first but the p-n junction forms the basis for computer chips, solar cells, and other electronic devices.

Unbiased

ESBJA

In a p-n junction, without an external applied voltage (no bias), an equilibrium condition is reached in which a potential difference is formed across the junction.

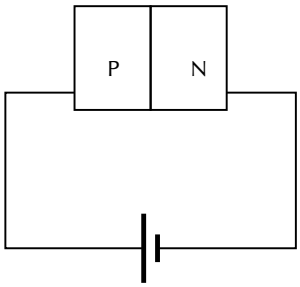
P-type is where you have more ”holes”; n-type is where you have more electrons in the material. Initially, when you put them together to form a junction, holes near the junction tends to ”move” across to the n-region, while the electrons in the n-region drift across to the p-region to ”fill” some holes. This current will quickly stop as the potential barrier is built up by the migrated charges. So in steady state no current flows.

Then now when you put a potential different across the terminals you have two cases: forward biased and reverse biased.

Forward biased

ESBJB

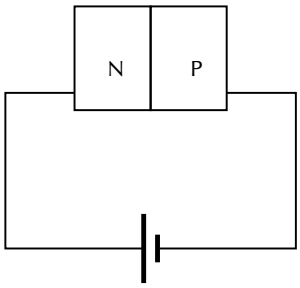
Forward-bias occurs when the p-type semiconductor material is connected to the positive terminal of a battery and the n-type semiconductor material is connected to the negative terminal.



The electric field from the external potential different can easily overcome the small internal field (in the so-called depletion region, created by the initial drifting of charges): usually anything bigger than 0.6V would be enough. The external field then attracts more e- to flow from n-region to p-region and more holes from p-region to n-region and you have a forward biased situation. The diode is forward biased and so current will flow.

Reverse biased

ESBJC



In this case the external field pushes e- back to the n-region while more holes into the p-region, as a result you get no current flow. Only the small number of thermally released minority carriers (holes in the n-type region and e- in the p-type region) will be able to cross the junction and form a very small current, but for all practical purposes, this can be ignored.

Of course if the reverse biased potential is large enough you get what is called avalanche break down and current flow in the opposite direction. In many cases, except for Zener diodes, you most likely will destroy the diode.

Real-World Applications of Semiconductors

ESBJD

Semiconductors form the basis of modern electronics. Every electrical appliance usually has some semiconductor-based technology inside it. The fundamental uses of semiconductors are in microchips (also known as integrated circuits) and microprocessors.

Integrated circuits are miniaturised circuits. The use of integrated circuits makes it possible for electronic devices (like a cellular telephone or a hi-fi) to get smaller.

Microprocessors are a special type of integrated circuit.

Activity: *Semiconductors*

Assess the impact on society of the invention of transistors, with particular reference to their use in microchips (integrated circuits) and microprocessors.

Chapter 20 — Summary

See the summary presentation (▶ Presentation: VPrpp at www.everythingscience.co.za)

- There are two types of conductors, metals and semi-conductors.
- Overlapping electron orbitals in a crystal lattice form a "band".
- The gap between valence and conduction bands determines whether a material is a good conductor, semi-conductor or insulator.
- Doping is the deliberate addition of impurities to a substance to alter the electrical properties.
- Adding a dopant that has more valence electrons is n-type doping (a donor impurity).
- Adding a dopant that has less valence electrons is p-type doping (an acceptor impurity).
- Combining p- and n-type semi-conductors creates a junction through which current flows more easily in one direction than the other.

Chapter 20 End of Chapter Exercises

1. Compare p- and n-type semi-conductors.
2. Explain how a p-n junction works using a diagram.
3. Give everyday examples of the application.
4. What is a conductor?
5. What is an insulator?
6. What is a semiconductor?

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