13. ATOMS AND CHEMISTRY

13.1 ATOMIC STRUCTURE: PROTONS, NEUTRONS AND ELECTRONS

First we must summarise what you learnt in Chapter 9 about elements and atoms. Elements are the simple basic substances from which all matter is made. There are 90 naturally occurring elements including metals such as aluminium, iron and zinc and non-metals such as carbon, silicon and oxygen. If possible, you should review Modules 9.4/5 and Appendix B now.

Atoms are the smallest particles of elements. There are 90 different kinds of atoms corresponding to the 90 different elements. Atoms are incredibly small. More than $10^9$ can fit on a full stop! Chemists study how atoms behave and how they interact. Just as the 26 letters of the alphabet can be combined to form thousands of different words, so the 90 different kinds of atoms can come together to form millions of different compounds. All the processes of nature (including the processes of life), and all the processes of technology, depend on the interactions of atoms.

At first, scientists thought that atoms were like tiny, hard balls. Now we know that they are made of even tinier sub-atomic particles. At the centre of every atom is a very tiny, very heavy, part called the nucleus. Almost all the mass of an atom is in the nucleus. The nucleus is made of protons, which are very heavy particles with a positive electric charge, and neutrons, which have virtually the same mass as protons but no electric charge. Outside the nucleus there are very tiny, very light particles called electrons. Each electron has a negative electric charge. There is one electron to balance every proton in the nucleus. This means that the atom as a whole has no electric charge. We can think of electrons as orbiting around the nucleus at considerable distances, like the planets around the sun. This is a simplified picture but it will do for now. The diagram shows a simple model of an atom of the element lithium. In the nucleus there are three protons and four neutrons. Orbiting the nucleus there are three electrons; one to balance each proton.

Each different element has a different number of protons in the nucleus. The lightest element is hydrogen. Atoms of hydrogen have just one proton in the nucleus with one electron in orbit around it. The heaviest element is uranium. An atom of uranium has 92 protons and about 146 neutrons (the number can vary a little). A uranium atom also has 92 electrons in orbit.

In this chapter we will look first at the nucleus and how it influences some of the properties of the elements including their relative masses, radio-activity and the different nuclear reactions that occur in nuclear power stations, atom bombs, and stars. Then we will look briefly at the way electrons, on the outside of atoms, control the basic chemistry of the elements. After that, we will learn how chemists write balanced chemical equations and how they use them to calculate quantities for the ‘recipes’ used in the chemical industry. Finally, we will describe some aspects of chemistry that are important in everyday life including the simple chemistry of acids and bases; carbon, fossil fuels and plastics; and metals, ceramics, glass and cement.

1. In any atom, what is (i) the nucleus, (ii) a proton, (iii) a neutron, (iv) an electron? (v) Try to find out the mass of a proton or neutron compared to that of an electron.

2. In an atom of lithium: (i) What is mainly responsible for the mass of the atom? (ii) What is mainly responsible for the way it interacts with other atoms?
13.2 THE NUCLEUS 1 - ATOMIC NUMBER, ATOMIC MASS AND ISOTOPES

Atomic number. The atomic number (Z) of an element is the number of protons in the nucleus of one atom of that element. This is also the number of electrons orbiting the nucleus. Every element has its own atomic number. Hydrogen is the lightest element and has an atomic number of one. Hydrogen atoms have one proton in the nucleus and one electron in orbit. The second lightest element is the inert gas helium which has an atomic number of two (two protons and two electrons). For the element carbon, which is the basis of all living things, Z = 6 (six protons and six electrons) and for the heaviest naturally occurring element uranium, Z = 92.

Atomic mass. The atomic mass (A) of an element used to be defined as the mass of one atom of that element compared to the mass of one atom of hydrogen. On that standard, the atomic mass of hydrogen was exactly one, and the atoms of all other elements were compared to that. Now the standard has been adjusted slightly so that an atom of carbon with 6 protons, 6 neutrons and 6 electrons, has an atomic mass of exactly 12. For most purposes this makes very little difference (see the text box on the right) so we will use the old standard in this book. Look at the simple models of the atoms shown above. Remember that protons and neutrons are equally heavy, and that the mass of the electrons is so tiny that we can ignore it. You can see that hydrogen has an atomic mass (A) of 1 (the nucleus contains one proton only), helium has an atomic mass of 4 (2 protons and 2 neutrons), lithium has an atomic mass of 7 (3 protons and 4 neutrons), and carbon has an atomic mass of 12 (6 protons and 6 neutrons). Now study Appendix B and check out the atomic numbers and atomic masses of your favourite elements.

Isotopes. Isotopes are atoms of the same element that have different atomic masses; they have the same number of protons, but different numbers of neutrons. Look at the element chlorine in Appendix B. Its atomic number Z is 17 so all atoms of chlorine have 17 protons. About 75% of chlorine atoms have 18 neutrons (so the atomic mass A of these atoms is 35), while the rest have 20 neutrons (so A = 37). We say that chlorine has two isotopes, one with an atomic mass of 35, and the other with an atomic mass of 37. The atomic mass given in Appendix B is 35.5 which is the average mass of chlorine atoms as compared to a standard hydrogen atom.

Many elements have two or more isotopes, but one is usually much more common than the rest. The diagram on the left shows the three isotopes of hydrogen. 99.99% of all hydrogen atoms are the first isotope with one proton only in the nucleus (A = 1); 0.01% are the second isotope which has a neutron as well as a proton (A = 2); only a very few are the third isotope with two neutrons (A = 3).

Other terms and standards. Atomic mass, relative atomic mass and atomic weight are alternative terms that have been used in various circumstances and times. On the hydrogen standard, the atomic mass of hydrogen was exactly 1. On the present carbon standard, the atomic mass of hydrogen is 1.008 so the difference is very small.
Radioactivity was discovered accidently by Frenchman Henri Becquerel in 1896. He found that a photographic film left in a drawer had become exposed, even though it was wrapped in black paper to keep out light. In the same drawer was a piece of a mineral called pitchblende. He realised that this was giving out invisible rays that could pass through the paper. Marie Curie spent much of her life studying these rays and she named the effect radioactivity. She was awarded the Nobel prize for her research.

Radioactivity is a property of certain isotopes, especially isotopes of heavy metals such as uranium (which is found in pitchblende). The nuclei of these isotopes are unstable and decay, giving out three kinds of invisible rays called α-rays (alpha rays), β-rays (beta rays), and γ-rays (gamma rays):

- **Alpha-rays** are streams of fast-moving, positively-charged α-particles. An α-particle consists of two protons and two neutrons bound together, like the nucleus of a helium atom. Alpha-rays damage whatever they pass through, but are not very penetrating. They are stopped by a few cm of air, a thin sheet of paper or a few human skin cells.

- **Beta-rays** are streams of fast-moving, negatively-charged β-particles; β-particles are just electrons. Beta-rays come from the nucleus when a neutron breaks down to form a proton, (which remains in the nucleus) and an electron (which is thrown out). They are less destructive than α-rays, but more penetrating. Beta-rays are stopped by a few metres of air, or a few millimetres of a light metal such as aluminium, or a very thin sheet of a heavy metal such as lead.

- **Gamma-rays** are very energetic, electro-magnetic waves; like light rays or X-rays but with even greater energy. They damage whatever they pass through and they are very penetrating and dangerous. Thick lead shielding is required to give protection from γ-rays.

**Ionising radiation** includes α, β and γ-rays, and also the X-rays used in health care and cosmic rays from the sun. As they pass through matter, these rays knock electrons off atoms forming electrically charged atoms (or groups of atoms) called ions. Occasionally, ionising rays hit a nucleus and cause it to break up forming new isotopes (some of which may be radioactive and give out more ionising radiation). Ionising radiation is harmful to all living organisms and particularly to animals including humans. Living cells are damaged or destroyed by the energy of the rays and the ions they create. Burns may occur in severe cases, and delayed effects include certain kinds of cancer. Damage to reproductive cells may lead to the birth of deformed children or grandchildren. Because of this, sources of ionising radiation must be kept in lead containers and used behind lead screens. People who work with radioactivity follow special safety procedures, and they have to wear protective clothing and monitoring devices.

**Background radiation** is the very small amount of ionising radiation that we are all exposed to all the time. Most background radiation comes from natural sources including: a radioactive isotope of the rare inert gas radon in the air (see Module 6.7), radioactive isotopes in the soil and rocks, and cosmic rays. Fortunately for life on Earth, almost all cosmic rays are absorbed by the atmosphere.
Radioactive decay. When a radioactive isotope emits radiation, the nucleus decays becoming an isotope of a new element. The nuclear equation below is an example of α radioactive decay.

\[
\begin{align*}
238\text{U} & \rightarrow 234\text{Th} + 4\alpha + \gamma-\text{rays} \\
(Z=92, A=238) & \rightarrow (Z=90, A=234) & (Z=2, A=4)
\end{align*}
\]

The symbol \(238\text{U}\) stands for an isotope of uranium with an atomic mass of 238. All atoms of uranium have 92 protons in the nucleus, and this isotope also has 146 neutrons to make up the total mass of 238. The equation shows the nucleus decaying, throwing out an α-particle and gamma rays. The α-particle takes two protons and two neutrons from the uranium, leaving a nucleus with 90 protons and 144 neutrons; this is an isotope of the element thorium.

The thorium isotope \(234\text{Th}\) is also radioactive. It gives out a β-particle (electron) and gamma rays. Study the equation below and see if you can work out what happens to the nucleus.

\[
\begin{align*}
234\text{Th} & \rightarrow 234\text{Pa} + 0\beta + \gamma-\text{rays} \\
(Z=90, A=234) & \rightarrow (Z=91, A=234) & (Z=-1, A=0)
\end{align*}
\]

The β-particle (electron) is thrown out when a neutron, in the nucleus of the thorium, changes into a proton and an electron. The lost electron does not change the atomic mass, but the extra proton in the nucleus makes it an isotope of protactinium \((Z=91)\). This too is radioactive, and decay continues through many steps, eventually forming a stable isotope of lead \(206\text{Pb}\) \((Z=82)\).

Half-life. Every radioactive isotope decays at its own, fixed rate as measured by the half-life of the isotope. The half-life is the time taken for half of the atoms to decay. \(238\text{U}\) decays very slowly with a half-life of 4.5 billion years, but the half-life of \(234\text{Th}\) is only 24 days. This means that half of any piece of \(234\text{Th}\) will decay in 24 days, then half of the rest will decay in another 24 days and so on. The half-life of an isotope does not vary with the temperature or any other external factor. Some very unstable isotopes have a half-life of only a few seconds or even less.

Radio-isotopes and their uses. Radio-isotopes are mainly used in three different ways.

Dating rocks and historical objects. Many rocks contain small amounts of radioactive isotopes. If the half-lives of these isotopes are known, the age of the rock can be worked out by measuring what proportion of the atoms has decayed. Historical objects made of wood can be dated using the natural radio-isotope \(14\text{C}\). This isotope of carbon is formed when cosmic rays interact with nitrogen atoms in the atmosphere. Because of this, there is a small but fixed proportion of \(14\text{C}\) atoms in the carbon dioxide in the air. While a tree is living, it takes in this proportion of \(14\text{C}\) atoms by photosynthesis. This stops when the tree dies, and the \(14\text{C}\) it contains decays with a half-life of about 5730 years. By carefully measuring the proportion of \(14\text{C}\) atoms remaining in a piece of old wood, we can calculate how long ago the tree died. Radio-carbon dating can be used to date any once-living material; because of food chains, this also includes the remains of animals.

Radioactive tracers. Radio-isotopes are used in industry, agriculture and medicine to follow the movement of materials. For example, the flow of water through a pipe, and the presence of leaks, can be checked by dissolving salt containing radioactive sodium \(24\text{Na}\) in the water. \(24\text{Na}\) gives off γ-rays so it’s movement through the pipe, or out through a leak, can be monitored with a Geiger counter. Salt containing tiny amounts of \(24\text{Na}\) has also been used by doctors to follow the flow of blood in a patient’s body. Many other radio-isotopes are used as tracers in similar ways.

Radioactive sources. Radio-isotopes are used in industry, agriculture and medicine as sources of radioactive rays where these are needed. For example \(60\text{Co}\), a radio-isotope of cobalt, produces strong γ-rays that are used to check welds in metal pipes. A small piece of \(60\text{Co}\) is placed inside the pipe and a gamma-ray photo (like an X-ray photo) is taken through the weld. This will show any cracks or bubbles in the weld. In medicine, \(60\text{Co}\) and other radioactive sources are used to deliver γ-rays for sterilising instruments (killing bacteria), and for destroying cancers in the body.

- 1. What are (i) α, β and γ-rays, (ii) ions, (iii) a Geiger counter, (iv) background radiation, (v) radioactive decay, (vi) radioactive tracers?
- 2. Explain why ionising radiation is very dangerous. List three ways that people can be protected from it.
- 3. The half-life of \(239\text{Pa}\) is about 1 day. How much of it will have decayed after three days?
- 4. The remains of an animal are found in the ice of a glacier. How could scientists discover how long ago it died? Explain how food chains are involved.
13.4 THE NUCLEUS 3 – NUCLEAR FISSION AND NUCLEAR FUSION

Fission means breaking apart and fusion means joining together.

**Nuclear fission** refers to the breaking apart of the nucleus of an atom. The best known example of nuclear fission occurs when the nucleus of the uranium isotope $^{235}\text{U}$ captures an extra neutron. This makes the nucleus unstable and it breaks into two roughly equal parts called fission fragments; these are isotopes of two much lighter elements. The fission process also produces a few neutrons and a lot of energy in the form of $\gamma$-rays and heat. The equation below summarises one example of this fission process.

$$^1\text{n} + ^{235}\text{U} \rightarrow ^{143}\text{Ba} + ^{90}\text{Kr} + ^1\text{n} + ^1\text{n} + ^1\text{n} + \text{energy}$$

The equation shows a neutron combining with a $^{235}\text{U}$ nucleus. The nucleus breaks down to form isotopes of the elements barium and krypton, together with three neutrons and a huge amount of energy. Less than 1% of natural uranium is $^{235}\text{U}$; however, this can be increased by modern technology to yield *enriched uranium*. If the percentage of $^{235}\text{U}$ is sufficient, then the neutrons produced by the fission of one nucleus, will be captured by another nucleus, which will break down releasing more neutrons, which will be captured by more nuclei and so on. This is called a *chain reaction*. If this chain reaction is not controlled, it will release vast quantities of heat and $\gamma$-rays in a devastating explosion. This uncontrolled chain reaction fuelled the *atomic bombs* that were dropped on Hiroshima and Nagasaki to end World War 2. In *Nuclear power stations*, heat from the same chain reaction is used to make steam to generate electricity. The chain reaction is controlled by using uranium that has not been enriched so much, and by using *control rods* of materials that absorb neutrons. In nuclear power stations, workers must be protected from $\gamma$-rays by thick shields of lead and concrete.

**Nuclear fusion** is the process of joining together two nuclei to create a new nucleus. The new nucleus will be an isotope of a new, heavier element. Nuclear fusion produces even more energy than nuclear fission.

Nuclear fusion is the process that fuels the stars, including the sun (see Module 11.2). A series of nuclear fusion reactions result in the nuclei of four hydrogen atoms coming together to form the nucleus of a helium atom. As stars get older, they start producing heavier elements by nuclear fusion. All the 90 different elements that we find on Earth were made by nuclear fusion in ancient stars.

Energy from nuclear fusion reactions in the sun reach us as heat, light and $\gamma$-rays. Gamma-rays from stars are often called *cosmic rays*. Nuclear fusion has been used in *hydrogen bombs*, however it has not yet been controlled for peaceful uses such as generating electricity.

- 1. What are the similarities and differences as between nuclear fission and nuclear fusion?
- 2. What is a *chain reaction*? Why does $^{235}\text{U}$ explode in an atomic bomb, but not in a nuclear power station?
13.5 THE ROLE OF ELECTRONS: IONIC AND COVALENT COMPOUNDS

Electrons control chemical reactions. Metal atoms tend to lose electrons, and non-metal atoms tend to grab more electrons. Before you continue, review Modules 9.4 to 9.7.

Metals conduct electricity. In a solid metal, the particles are arranged in a regular pattern called a lattice. Each atom tends to lose control of one or more negatively charged electrons. This means that the atoms tend to become positively charged ions. The lattice of positive ions is held together by the ‘cloud’ of negative electrons drifting between them. These electrons are not very firmly attached to the atoms. If an electric voltage is applied to the metal, and if there is a complete electrical circuit (see Module 4.2), then electrons will flow through the metal away from the – terminal and towards the +. In fact, an electric current is simply a flow of electrons! The diagram shows the lattice of the metal iron.

Alloys. Metals do not form simple compounds with other metals. If two or more metals are heated strongly together, one will melt and dissolve the other. When the mixture cools, it solidifies to form a solid solution called an alloy. In the lattice of an alloy, some of the particles are ions of one metal, and some are ions of another metal. We can make alloys with a wide range of different properties by using different metals and different proportions of each. Useful alloys include brass (Cu and Zn), bronze (Cu and Sn), pewter (Sn and Pb) and steel (Fe with other metals and a little carbon).

Ionic compounds. When metal elements form compounds with non-metal elements, the non-metal atoms take electrons from the metal atoms. The metal atoms become positively charged ions, and the non-metal atoms become negatively charged ions. Compounds like this are called ionic compounds. The ions form a lattice in which each positive ion is surrounded by negative ions and each negative ion is surrounded by positive ions. A well known example is sodium chloride (common salt) which is illustrated on the right. Sodium chloride has a cubic lattice and that is why salt crystals are tiny cubes. Unlike alloys and other mixtures, every ionic compound has a fixed composition and can be represented by a definite formula. The formula of salt is NaCl; this means that there is one chlorine ion for every sodium ion. Ionic compounds do not have molecules, but we can say that NaCl represents one formula unit of salt.

Covalent compounds. Non-metal atoms form compounds by gaining control of extra electrons. They do this either by taking electrons from metal atoms to form ionic compounds, or by sharing electrons with another non-metal atom to form a covalent bond. Covalent compounds are made of molecules which are small groups of atoms held together by covalent bonds. Every covalent compound has a fixed composition and can be represented by a definite formula. Chemists often show covalent bonds by lines joining the symbols for atoms. Here are examples of some common covalent molecules.

<table>
<thead>
<tr>
<th>Name</th>
<th>hydrogen</th>
<th>hydrogen chloride</th>
<th>water</th>
<th>carbon dioxide</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formula</td>
<td>H₂</td>
<td>HCl</td>
<td>H₂O</td>
<td>CO₂</td>
</tr>
<tr>
<td>Structure</td>
<td>H – H</td>
<td>H – Cl</td>
<td>H(\overset{\text{O}}{\text{O}})H</td>
<td>O=C=O</td>
</tr>
</tbody>
</table>

Crystals of the non-metal sulphur growing on the side of a volcano

- 1. What are (i) a lattice, (ii) an alloy, (iii) an ionic compound, (iv) a molecule, and (v) a covalent bond?
- 2. What is an electric current and which way does it flow?
- 3. Metal atoms have one way of forming compounds, but non-metal atoms have two. Describe what these ways are.
13.6 THE NAMES, FORMULAE AND COMPOSITION OF SIMPLE COMPOUNDS

You will find it helpful to review Modules 9.6 and 9.7 before you continue.

Names. For simple inorganic compounds containing only two elements, if one of the elements is a metal or hydrogen, that is named first; the other element is named second with the ending –ide. Examples are sodium chloride, hydrogen sulphide and iron oxide.

For compounds of two elements that do not contain a metal or hydrogen, there is no simple rule for which element comes first, but oxygen usually comes last. Sometimes we use the prefixes mono- (one), di- (two), tri- (three), tetra- (4), penta- (5) and hexa- (6) to show the number of atoms in a formula, as in carbon dioxide (CO$_2$) and sulphur trioxide (SO$_3$).

Finally, we will consider compounds that contain radicals. Radicals are usually small groups of atoms linked together by covalent bonds. Examples of common radicals are illustrated on the right. If a radical contains oxygen, this is often shown by a name ending in –ate; for example the radical ‘nitrate’ contains nitrogen and oxygen. Radicals do not exist alone; they can only be part of a compound. When combined with metals, the radicals illustrated gain additional electrons from the metals and become negative ions. However, these radicals can also combine with hydrogen by sharing electrons in a covalent bond; for example in hydrogen hydroxide (HOH), which is water of course, and hydrogen sulphate (H$_2$SO$_4$) which is sulphuric acid.

Formulæ. The valency (or combining power) of an atom or radical is the number of electrons it loses, or gains, or shares, when it forms compounds. The valencies of some of the elements and radicals mentioned in this book are listed in the table (left). Most elements and all radicals have fixed valencies, but some elements have more than one valency.

If two elements, or an element and a radical, have the same valency they combine one-to-one and writing the formula is simple; for example sodium chloride is NaCl, potassium hydroxide is KOH, calcium oxide is CaO, and copper sulphate is CuSO$_4$. Now consider magnesium chloride; magnesium has a valency of two – a magnesium atom has two electrons to lose; chlorine has a valency of one – a chlorine atom has room to add only one electron, so two atoms of chlorine are needed to satisfy one atom of magnesium. This gives us the formula MgCl$_2$ (where the subscript 2 after the Cl indicates two atoms of chlorine). In the same way, you should be able to work out that sodium oxide is Na$_2$O and calcium hydroxide is Ca(OH)$_2$. Notice that when we need to show more that one radical, we enclose the radical in brackets and write the subscript outside the last bracket. Try to work out for yourself what are the formulæ of copper nitrate and aluminium chloride. These and other examples are included in the questions at the end of this module. (Note that just because you can make up a name for a substance, does not mean that the substance actually exists; for example there are no such substances as carbon sulphate or copper hydride).

Composition. In industry, technicians often need to know the percentage composition of a compound. We can easily work this out from the chemical formula of the compound and a table of atomic masses. For example, what is the percentage of carbon in carbon dioxide? The calculation is summarised in the box on the right. The formula CO$_2$ tells us that a molecule of this gas contains one atom of carbon and two atoms of oxygen. Appendix B tells us the atomic mass of carbon is 12 and that of oxygen is 16. Adding up the masses of all three atoms we get the formula mass which is 44. 12 parts of the 44 are carbon, so the percentage of carbon is $(12/44) \times 100 = 27.3\%$. The same method can be used to find the percentage composition of any compound from its formula.

- 1. Use the information above to write the formulæ of the following: hydrogen chloride, magnesium oxide, potassium nitrate, aluminium chloride, sodium carbonate, copper nitrate, sulphur dioxide, sulphur hexafluoride, aluminium oxide.
- 2. Work out the percentages of calcium, carbon and oxygen in marble (calcium carbonate).
13.7 CHEMICAL EQUATIONS

In Module 9.8 you learnt that chemical changes can be represented by an equation in the form:

**REACTANTS** → **PRODUCTS**

For example, we can summarise the laboratory preparation of carbon dioxide (Module 6.5) as shown below. We have written the equation first in words, and then in symbols.

\[ \text{hydrochloric acid} + \text{calcium carbonate} \rightarrow \text{calcium chloride} + \text{water} + \text{carbon dioxide} \]

\[ \text{HCl} + \text{CaCO}_3 \rightarrow \text{CaCl}_2 + \text{H}_2\text{O} + \text{CO}_2 \]

In any chemical reaction, the atoms of the elements in the reactants are rearranged to form the products. In the reaction above, the hydrogen atom is attached to a chlorine atom to start with, but ends up attached to an oxygen atom; the chlorine atom is attached to a hydrogen atom to start with, and ends up as a chlorine ion that is associated with a calcium ion in calcium chloride. Chemists prefer to use symbolic equations because these give the best picture of how the atoms are rearranged. In a symbolic equation, every atom has to be counted; no atoms can vanish and no atoms can appear out of nowhere. Look carefully at the equation in red. It is in red because it is wrong. Can you see what is wrong with it? If you look at the products on the right of the equation, you will see that there are two atoms of chlorine and two atoms of hydrogen - but in the reactants on the left we have only one atom of each! When the atoms of every element on the left and right of the arrow do not add up, the equation is unbalanced. Here is the balanced equation.

\[ 2\text{HCl} + \text{CaCO}_3 \rightarrow \text{CaCl}_2 + \text{H}_2\text{O} + \text{CO}_2 \]

As you can see, all we have done is put ‘2’ in front of HCl. This indicates that we have two complete molecules of hydrogen chloride (hydrochloric acid). Now there are two atoms of hydrogen and two atoms of chlorine on both sides of the equation. Balancing the equation in this way reminds us that hydrogen and calcium have different valencies. Because of this, we need to provide two molecules of hydrogen chloride to react with one formula unit of calcium carbonate. Here is another example from Module 6.10 – a simple equation for the rusting of iron.

\[ \text{iron} + \text{oxygen} \rightarrow \text{rust} \]

\[ \text{Fe} + \text{O}_2 \rightarrow \text{Fe}_2\text{O}_3 \]

\[ 4\text{Fe} + 3\text{O}_2 \rightarrow 2\text{Fe}_2\text{O}_3 \]

In rust, iron has a valency of 3 and oxygen has a valency of 2, so the formula of rust is Fe$_2$O$_3$. Note that the formula for oxygen is O$_2$. Like most of the common gases, oxygen exists as molecules containing two atoms (see Module 9.4). As before, the equation in red is unbalanced, and the equation with the blue numbers is correct. The balanced equation tells us that 4 atoms of Fe react with 3 molecules of O$_2$ to make 2 formula units of Fe$_2$O$_3$. There are 4 atoms of Fe and 6 atoms of O on the left of the equation and the same on the right. When balancing equations, remember that formulae are fixed; you can change only the numbers in front of the formulae.

**Calculating masses from equations.** If we have a balanced equation and a table of atomic masses (Appendix B), we can calculate exactly what mass of any reactant we need to make a particular mass of a product. For example, if we want to make 50 g of carbon dioxide using the laboratory preparation, how much calcium carbonate and hydrochloric acid do we need? We start by writing the balanced equation as shown in the table on the right. Under the equation, we add up the masses of each atom to obtain formula masses.

<table>
<thead>
<tr>
<th>Equation:</th>
<th>2HCl + CaCO$_3$ → CaCl$_2$ + H$_2$O + CO$_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atomic masses:</td>
<td>2x(1+35.5) + 40 + 12 + (3x16) + 12 + 2x(16)</td>
</tr>
<tr>
<td>Formula masses:</td>
<td>73 + 100 + 44</td>
</tr>
<tr>
<td>Mass needed:</td>
<td>(73/44)x50 + (100/44)x50</td>
</tr>
<tr>
<td>Answer:</td>
<td>84 g + 113.6 g</td>
</tr>
</tbody>
</table>

This tells us that 100 mass units of CaCO$_3$ make 44 mass units of CO$_2$. The units can be grams, kilograms, tonnes or any unit of mass. So to make 50g of CO$_2$, we need (100/44) x 50g of CaCO$_3$ and that works out to 113.6g. Similarly we can calculate that we need 84g of HCl.

- 1. Check if each of the following equations is balanced or not, and correct any equations that are not balanced.
  (i) KNO$_3$ → KNO$_2$ + O$_2$  (ii) CH$_4$ + O$_2$ → H$_2$O + CO$_2$  (iii) Ca(OH)$_2$ + CO$_2$ → CaCO$_3$ + H$_2$O
- 2. Use the equation for the rusting of iron, and the atomic masses in Appendix B, to calculate the mass of rust formed when 1 kg of iron is completely changed to rust.
13.8 INDICATORS AND THE pH SCALE

**Indicators** are substances that change colour with an acid or a base. Acids and bases are opposites. Household solutions that are acids include vinegar (acetic acid) and lemon juice (citric acid); solutions that are bases include baking soda (sodium bicarbonate), soap, and ammonia. An indicator that is used in many laboratories is litmus; litmus goes red with acids and blue with bases. Litmus paper is paper that has been stained with litmus solution. We can test any liquid by placing a drop of it onto a piece of litmus paper. If the liquid makes blue litmus paper go red, it is an acid; if the liquid makes red litmus paper go blue it is a base. Notice that bases affect litmus, and any indicator, in the opposite way to acids. You can try to make your own indicator by extracting colours from flowers or other plant materials.

**Making indicators**: Collect bowls of petals from different flowers. (You could also try other coloured plant material such as the bark from a tree, or a root). Add a little boiling water and mash up well with a clean spoon. Pour the coloured liquid into two glasses. To one glass add an acid (such as vinegar or lemon juice), to the other glass add a base (such as household ammonia or a solution of sodium bicarbonate).

The illustrations show the results with petals from three different flowers. The blue petals gave a blue solution that went red with acids and green with bases. The purple petals gave a purple solution that went red with acids and blue with bases. The orange petals (surprisingly) gave a red solution that remained red with acids and went a dark greenish colour with bases.

**Universal indicators** are special mixtures of several indicators. The colour of a universal indicator shows how strongly acidic or basic a solution is. The strengths of acids and bases are measured on the pH scale which goes from 0 to 14 (see table below). A pH of 0 corresponds to the strongest acids, and 14 corresponds to the strongest bases. Pure water comes in the middle with a pH of 7. The sulphuric acid in car batteries has a pH of 0, and the hydrochloric acid in the human stomach (more than 10 times weaker) has a pH of 1 or 2. Vinegar is a fairly weak acid with a pH of about 3. A solution of soap is a weak base with a pH of 9 or 10, and ammonia solution is a bit stronger at about 11. Sodium hydroxide (caustic soda) solution is strongly basic with a pH of 14.

![](image1)

The pictures show two different universal indicator papers. Each paper comes with its own colour chart. When a drop of a solution is placed on the indicator paper, the colour will show you the pH.

- 1. What are (i) an indicator, (ii) a base, (iii) universal indicator paper?
- 2. What do these pH values tell you about a solution? (i) 13, (ii) 6, (iii) 7, (iv) 2, (v) 8.
13.9 ACIDS AND BASES

Acids and bases are groups of substances that have certain characteristics in common. Some characteristics of each are summarised below.

<table>
<thead>
<tr>
<th>SAFETY NOTE: Strong acids and bases are dangerous. They should not be handled (or tasted!) except under qualified supervision.</th>
<th>Solutions of acids:</th>
<th>Solutions of bases:</th>
</tr>
</thead>
<tbody>
<tr>
<td>• have a sour taste;</td>
<td>• have a ‘soapy’ feel;</td>
<td></td>
</tr>
<tr>
<td>• are corrosive (they destroy most metals and many other solids including skin, flesh, clothing and paper);</td>
<td>• are caustic (they destroy organic solids including skin, flesh, clothing and paper; also a few metals);</td>
<td></td>
</tr>
<tr>
<td>• change the colour of indicators (in the opposite way to bases).</td>
<td>• change the colour of indicators (in the opposite way to acids).</td>
<td></td>
</tr>
</tbody>
</table>

Strong acids used in industry include sulphuric acid, H₂SO₄ (used to make of other chemicals, particularly fertilisers, and in car batteries), nitric acid, HNO₃ (used to make agricultural chemicals and explosives), and hydrochloric acid, HCl (used to clean steel sheets and make chemicals, particularly plastics, and in some drain cleaners). These acids are all dangerous and have to be handled with great care. A dilute solution of hydrochloric acid is found in the human stomach where it starts the breakdown and digestion of food. Weaker acids found at home include acetic acid (in vinegar) and citric acid (in lemon juice).

Strong bases used in industry include sodium hydroxide or caustic soda, NaOH (used to make paper, textiles and soap, and used in some drain cleaners) and calcium oxide or quick lime, CaO (used in to make other chemicals including cement and steel). These bases are dangerous and have to be handled with great care. Weaker bases include ammonia solution (used in household cleaners), and calcium hydroxide which is better known as slaked lime, lime wash or lime water (used in the building industry and to condition soils).

The role of water. Water plays an important part in the behaviour of acids and bases. H₂O is a covalent molecule, but about one molecule in every ten million breaks into ions.

\[
\text{H}_2\text{O} \rightarrow \text{H}^+ + \text{OH}^- 
\]

The concentration of hydrogen ions (H⁺) and hydroxide ions (OH⁻) in pure water is 10⁻⁷ moles per litre. The pH of a solution is related to the concentration of H⁺ ions it contains; that is why the pH of water is 7. To understand more about pH and ‘moles’, you will have to study chemistry at a higher level. The important thing for now is that all acids contain hydrogen, and that the hydrogen becomes H⁺ ions when the acid dissolves in water. Even dilute solutions of strong acids like sulphuric, nitric and hydrochloric, produce high concentrations of H⁺ ions. These correspond to low pH numbers like 0, 1 or 2. Weak acids produce much lower concentrations of H⁺ ions corresponding to pH numbers from about 3 to 6.

Strong bases like sodium hydroxide are ionic compounds that contain OH⁻ ions. When they dissolve in water, the OH⁻ ions react with the H⁺ ions in the water so that even fewer H⁺ ions remain. The equation for this reaction is the reverse of the last one!

\[
\text{H}^+ + \text{OH}^- \rightarrow \text{H}_2\text{O}
\]

The OH⁻ ions in strong bases force the H⁺ ion concentration down as low as 10⁻¹⁴ moles per litre. This corresponds to a pH of 14. Weak bases also increase the concentration of OH⁻ ions in a solution and reduce the concentration of H⁺ ions, but less than strong bases. They raise the pH to between 8 and 11. Sea water, for example, has about ten times more OH⁻ ions and ten times less H⁺ ions than pure water. It is weakly basic and has a pH of about 8.

1. List 4 characteristics of acids, and 4 of bases.
2. When a base dissolves in water, explain how it changes the pH.
3. Use the information in the text above to try to work out these problems. (i) A dilute solution of nitric acid contains 10⁻¹ moles per litre of H⁺ ions; what is its pH? (ii) What is the concentration of H⁺ ions in sea water?
13.10 NEUTRALISATION AND SALT FORMATION

Test tube A contains a dilute solution of hydrochloric acid and a few drops of litmus solution. When a solution of a base like sodium hydroxide is added a little at a time, and mixed well, at first there seems to be no change. But when enough of the base has been added, suddenly the mixture goes purple or blue (test tube B). The mixture is no longer acidic and we say that the base has neutralised the acid. Here is the equation for the neutralisation of hydrochloric acid by sodium hydroxide.

\[
\text{HCl} + \text{NaOH} \rightarrow \text{NaCl} + \text{H}_2\text{O}
\]

The hydrogen ions from the acid combine with the hydroxide ions from the base to make water, leaving just a solution of sodium chloride (common salt). All acids and bases react in this way and we can summarise the reaction in a general equation:

\[\text{ACID} + \text{BASE} \rightarrow \text{SALT} + \text{WATER}\]

Here are two more examples of neutralisation. In the first example, nitric acid is neutralised by the base potassium hydroxide forming a salt called potassium nitrate and water. In the second example, sulphuric acid is neutralised by the base copper oxide forming a salt called copper sulphate and water.

\[
\text{HNO}_3 + \text{KOH} \rightarrow \text{KNO}_3 + \text{H}_2\text{O} \quad \text{::} \quad \text{H}_2\text{SO}_4 + \text{CuO} \rightarrow \text{CuSO}_4 + \text{H}_2\text{O}
\]

Neutralisation can be very useful. In agriculture, some crops do not grow well on soils that are too acidic. The pH of the soil can be tested with universal indicator and if the pH is too low (too acidic), the base calcium hydroxide (slaked lime) is added to neutralise the acid and improve the soil. Sometimes indigestion occurs because we have too much acid in our stomachs. Acid indigestion can be cured by swallowing a base such as magnesium hydroxide (milk of magnesia).

A salt can be defined as the substance made, apart from water, when an acid is neutralised by a base. In the box below are instructions for making the salts sodium chloride and copper sulphate. The first method can be used with soluble bases, and the second method with insoluble bases.

To make sodium chloride, pour about 20 ml of dilute NaOH into a beaker. Add dilute HCl a little at a time, stirring well. Test a drop of the solution with red litmus paper. Go on adding HCl until the litmus paper no longer turns blue. Evaporate the solution to obtain NaCl.

To make copper sulphate, pour about 20 ml of dilute H$_2$SO$_4$ into a beaker and warm it up. Add solid CuO (black) a little at a time stirring well. As the CuO reacts, the solution will go blue. Go on adding CuO until some remains in the beaker and will not dissolve, even after a long time. Decant or filter the solution into another beaker. Allow it to evaporate slowly to obtain CuSO$_4$.

Acids are also neutralised by carbonates; carbon dioxide is given off and the general equation is:

\[\text{ACID} + \text{CARBONATE} \rightarrow \text{SALT} + \text{WATER} + \text{CARBON DIOXIDE}\]

An example of this reaction is the laboratory preparation of carbon dioxide from hydrochloric acid and calcium carbonate (you can find the equation in Module 13.7). Another example is sodium carbonate reacting with sulphuric acid to make sodium sulphate, water and carbon dioxide.

\[
\text{Na}_2\text{CO}_3 + \text{H}_2\text{SO}_4 \rightarrow \text{Na}_2\text{SO}_4 + \text{H}_2\text{O} + \text{CO}_2
\]

- 1. For each formula, name the substance and state if it is an acid, a base or a salt: (i) HNO$_3$, (ii) Na$_2$SO$_4$, (iii) Ca(OH)$_2$, (iv) MgO, (v) CaCl$_2$, (vi) PbCO$_3$, (vii) Al$_2$O$_3$.
- 2. Write the equations for the reactions of (i) calcium carbonate with nitric acid, (ii) MgO with HCl.
- 3. Describe how to make lead nitrate from lead oxide.
13.11 CARBON – THE ELEMENT OF LIFE

Most living organisms contain 70% or more of water (see Module 3.11). The rest is mainly compounds of carbon, all acquired initially as carbon dioxide by plants during photosynthesis. Carbon has a valency of four and it can form large complex covalent molecules. These molecules contain carbon atoms linked together in rings and chains, together with oxygen, hydrogen and a few other elements. The study of carbon compounds is called organic chemistry (Module 9.7). Living things contain three main groups of organic compounds: carbohydrates, lipids, proteins.

**Carbohydrates** contain carbon, hydrogen and oxygen only, and their molecules contain twice as many hydrogen atoms as oxygen atoms. Important carbohydrates include starch, sugars and cellulose. All green plants produce starch by photosynthesis. Starch is the energy store of the plant and has the formula \((\text{C}_6\text{H}_10\text{O}_5)_n\). The molecule consists of a large number \(n\) of identical units linked together in various ways. Starch is easily broken down in plants, and in the digestive systems of animals, into simple sugars including sucrose (cane sugar - \(\text{C}_{12}\text{H}_{22}\text{O}_{11}\)) and glucose (blood sugar - \(\text{C}_6\text{H}_{12}\text{O}_6\)). Enzymes in the digestive system convert sucrose and water into simpler sugars like glucose.

\[
\text{C}_{12}\text{H}_{22}\text{O}_{11} + \text{H}_2\text{O} \rightarrow 2\text{C}_6\text{H}_{12}\text{O}_6
\]

Cellulose \((\text{C}_6\text{H}_{10}\text{O}_5)_n\) has the same formula as starch but a different structure. It consists of a few hundred to a few thousand glucose units firmly linked together in long, straight chains (as shown in the illustration below). Substances like this, with molecules that are long chains of repeating units, are called polymers. Cellulose is the most abundant of all organic compounds. It forms the cell walls in plant cells, including the walls of the xylem and phloem vessels (see Module 8.7), and it is a major constituent of wood. Because it is a polymer, cellulose is fibrous. The digestive system does not easily break it down, so cellulose provides the fibrous bulk needed for our faeces (see Module 12.3). In industry, we use cellulose (in the form of wood pulp and cotton pulp) to make paper and fibreboard. We also use it to produce plastics including cellophane for wrapping and cellulose acetate for making films and the frames of spectacles.

**Lipids** are oils (liquid) and fats (solid), and they contain carbon, hydrogen and oxygen only. The molecules are complex with most of the carbon atoms linked together in chains. Lipids provide stores of energy in plants and animals and are part of the structure of cell membranes. They are an important part of our diet and we use them in many ways when we prepare food. We use plant oils like canola, palm and coconut for heating (frying) food while others, like olive and sesame oils, provide flavour or carry the flavour of other foods such as spices and herbs. We use butter and other lipids to alter the texture and flavour of food. Most plant and fish oils are unsaturated. This means that at least one pair of carbon atoms in their molecules are joined by a double bond (a bond where two pairs of electrons are shared - like the bonds between C and O in \(\text{CO}_2\) - see Module 13.5). These oils are an important part of a healthy diet, but eating a lot of saturated fats, such as butter and other animal fats (which have no double bonds) is associated with heart disease. In addition to food, we use lipids to make soap, candles, perfumes and cosmetics.

**Proteins** contain nitrogen as well as carbon, hydrogen and oxygen. They are complex polymers of amino acids linked together into long chains. The structure of an amino acid is shown on the left. \(R\) is a variable radical based on a chain of carbon atoms. Proteins are the main components of living cells and (after water) they are the commonest molecules in the human body. Our bodies need proteins for growth and maintenance. We get proteins when we eat meat, fish, milk, eggs, grains and vegetables. They are key nutrients for success in sport! When we digest proteins, amino acids are released and used to build new tissue (including muscle) and to repair damaged tissue.

- 1. For what do our bodies use each of the following: (i) glucose, (ii) cellulose, (iii) lipids, (iv) proteins?
- 2. List the industrial uses of (i) cellulose, (ii) lipids.
- 3. Explain the following terms: (i) polymer, (ii) lipid, (iii) double bond, (iv) saturated fats, (v) amino acid.
- 4. Why do starch and cellulose behave differently?
13.12 FOSSIL FUELS 1 - COAL

Coal is called a fossil fuel because it is the buried remains of plants that lived in the geological past. About 350 to 250 million years ago, (in geological eras called the Carboniferous and the Permian), low-lying tropical forest swamps covered huge areas of the world. As trees and other vegetation died, they were buried under mud and water which stopped them from rotting quickly. As they were compressed under more and more vegetation, they gradually turned into a partly decayed form of vegetable matter called peat. Later, these low-lying areas were flooded by rising sea levels and the peat was compressed under layers of sand and other sediments. Over tens of millions of years, these sediments became sedimentary rocks, the peat becoming first lignite (soft, brown coal), and then ordinary hard, black coal.

**Peat.** In the past, some rural communities used dried peat as a fuel. Now it is sometimes used by farmers and gardeners to improve soils.

Most coal is classified as sedimentary rock. The picture below, on the left, shows the strata in a quarry with a coal seam lying below a bed of sandstone. The hardest kind of coal is called anthracite; this has been heated and compressed in the mantle and is classified as a metamorphic rock. Anthracite has a carbon content of more than 90%.

**Mineral methods.** Coal that is close to the surface is dug out in open cast mines which are huge pits in the ground. Most coal, however, is obtained from deep mines. A shaft is dug down into the coal seam. Men or machines then dig out the coal along the horizontal or gently sloping seams. Strong wooden posts are used to support the roof behind them. Trolleys carry the coal back to the shaft where heavy machinery lifts it to the surface.

**Uses of coal.** Coal burns well, producing a lot of heat. It has been an industrial fuel for more than 200 years. In 2010 over 6 billion tonnes of coal were used worldwide, mostly in power stations (for boiling water, to produce steam, to drive generators, to make electricity). Large amounts of coal are also used in the manufacture of steel and concrete, and in the production of fuel gases.

**Sustainability issues.** The coal we burn now is the product of about 100 million years of photosynthesis, and 200 million years of slow change under the ground. If we continue to use it at the present rate, we may run out of coal in about a hundred years. Using coal at the present rate is not sustainable because coal is non-renewable. We cannot wait 300 million years for nature to make more coal for us, so we urgently need to find new, sustainable (renewable) energy sources.

**Environmental issues.** When coal is burnt, the main product is CO₂; this is a greenhouse gas that traps heat in the atmosphere. The industrial combustion of coal (and oil) has already produced so much CO₂ that it has started to raise the Earth's temperature. Coal also contains sulphur and nitrogen as impurities. When coal is burnt, these two elements produce oxides that react with the atmosphere to make sulphuric and nitric acids. These acids, much diluted, fall as acid rain. Acid rain (pH=4) slowly destroys even stone buildings and kills plant life including trees.

- 1. Why is coal called (i) a fossil fuel, (ii) a sedimentary rock? What is the difference between lignite, coal and anthracite?
- 2. Describe two ways in which the burning of coal causes pollution. Try to find out how this problem is being mitigated.
13.13 FOSSIL FUELS 2 – OIL AND NATURAL GAS

Oil and natural gas are the remains of plankton, tiny animals, plants and algae that drifted in the upper waters of the oceans hundreds of millions of years ago. Dead plankton on the sea bed became buried under other sediments then, over geological periods of time, pressure and heat from the mantle slowly converted the dead organisms into oil and natural gas.

**Mining oil.** Mining geologists looking for oil, use reflected sound waves to help them build up a picture of the rock strata under the ground. Oil is usually trapped under a folded stratum of cap rock that will not allow it to pass through. When the geologists find suitable strata, oil companies can drill a hole from the surface, down through the cap rock, and insert a tube. If oil is present, the pressure of the natural gas above it is usually enough to force the oil to the surface, but if necessary the oil can be pumped out.

**The nature of oil.** The oil that comes out of an oil well is a thick, black liquid called crude oil or petroleum. Crude oil and natural gas are mainly mixtures of hydrocarbons, most of which belong to the alkane series. The table on the right lists some of the alkanes with their formulae and boiling points. The structure of one of them, propane, is shown here. You may notice that all the alkanes have the same general formula \( C_{2n+2}H_{4n+2} \) where \( n \) is a whole number. Natural gas is mostly methane, with smaller amounts of ethane, propane and butane. Most of the remaining alkanes are liquids. They are all present in crude oil, but those with 16 or more carbon atoms are waxy solids that are dissolved in the oil. Natural gas is used as a fuel in power stations and in the home. It is also used for making other chemicals including plastics and medicines. Crude oil has to be refined before it can be used.

**The refining of petroleum.** Crude oil is refined by fractional distillation as shown in the diagram. The oil is pumped through a furnace and it boils into a vapour. The vapour rises through a fractionating column and gradually cools as it does so. As it rises, it passes through bubble caps set in a number of trays. Different groups of alkanes called fractions, condense on each tray. Fractions with high boiling points condense on the hot, lower trays and fractions with low boiling points on the cooler trays higher up. Butane and other dissolved gases are collected from the top of the column. Petrol (gasoline) from the top tray is used as a fuel for cars, kerosene from the second tray is used mainly as a fuel for jet aircraft, diesel oil (diesel fuel) from the third tray is used in heavy motor vehicles, and fuel oil from the lowest tray is burnt to provide heat in industrial and domestic furnaces. The heavy fraction from the bottom of the column includes lubricating oil (used to reduce friction and wear in machines), paraffin wax, and asphalt or tar (used in road-making). The heavier fractions are often cracked (broken down by heat) to obtain more of the lighter fractions. Other chemicals obtained during the refining process are used for making plastics and medicines.

**Sustainability and environmental issues.** The world uses about 14 million litres of crude oil a day! This raises the same environmental and sustainability issues as for coal. The main differences are that (i) for the same output of energy, oil and gas create less greenhouse gasses and less pollution than coal, and (ii) oil and gas may run out sooner than coal, perhaps in less than 50 years. Another problem is that the accidental spillage of crude oil, or oil products, is very damaging to the environment, especially if it occurs in rivers and oceans. Spillage may happen when oil wells are sunk into the sea bed, and when ships carrying oil are damaged or wrecked.

- 1. What fuel is best for (i) a jet aircraft, (ii) a heavy truck, (iii) a domestic gas stove, (iv) a fast car, (v) a factory furnace?
- 2. When methane or ethane burn, the products are steam and carbon dioxide. Write the equations for these reactions.
13.14 PLASTICS

Plastics are man-made polymers. They have long chain molecules that contain 1 000 to 100 000 carbon atoms. Plastics are useful because they are cheap, tough, light in weight and easy to make, colour and mould. They also resist corrosion and chemicals. Plastics are classified as thermoplastics or thermosets. Thermoplastics soften on heating and can be remoulded to a new shape, but thermosets do not soften. Most everyday plastic objects are made of thermoplastics.

**Polyethylene** (polythene) is the most widely used thermoplastic. It is made from ethylene (ethene, C\textsubscript{2}H\textsubscript{4}) which is the first member of the **alkene series** of hydrocarbons. The alkены are **unsaturated** and each molecule contains one carbon-to-carbon double bond. An alkene has two hydrogen atoms less than the corresponding alkane and the general formula for the series is C\textsubscript{n}H\textsubscript{2n}. The double bond is sometimes shown by using a formula such as CH\textsubscript{2}=CH\textsubscript{2}.

Ethylene is made by **cracking** natural gas or the light fractions of refined crude oil. It is converted to polythene by heat and pressure. A special substance called an **initiator** has to be added to get the **polymerisation reaction** started. Depending on the conditions, the polythene may have upwards of 10 thousand carbon atoms in each long chain molecule (see the diagram on the right).

\[ n \text{C}_2\text{H}_4 \rightarrow \text{[-CH}_2\text{CH}_2\text{-]}_n \]

More than 80 million tonnes of polythene were produced in 2008. Polythene is used mainly to make packaging and plastic bags. Special, high density polythene is used to make machine parts and plastic toys.

**Polypropylene and polystyrene** are important plastics made from propylene (CH\textsubscript{3}CH=CH\textsubscript{2}) and styrene (C\textsubscript{6}H\textsubscript{5}CH=CH\textsubscript{2}). Their long chain molecules are like those of polythene except that one in four hydrogen atoms are replaced by methyl (CH\textsubscript{3}) radicals, or phenyl (C\textsubscript{6}H\textsubscript{5}) radicals (phenyl radicals consist of a ring of six carbon atoms). Polypropylene is used for packaging, and for making ropes, plastic chairs, small containers and plastic banknotes! Polystyrene is used in plastic mouldings such as CD/DVD cases, plastic razors and so on. It is also made into foam for packaging and insulation.

**Other important thermoplastics** include polyesters (used in fibres and fabrics), polyvinylchloride (PVC, used in water pipes), polycarbonate (used to make CDs and lenses in glasses), and nylon (used in fishing lines and fabrics).

**Thermosets** cure (harden or set) into their final shape at the time they are made; after that they can not be softened and remoulded by heat. The curing involves a reaction in which covalent bonds are formed between polymer chains so that the whole object becomes one huge molecule. The epoxy resins used in two-part glues and in fibreglass, are good examples of thermosets. These resins are made by mixing two liquid parts which react together. The mixture sets to a solid and cures over a period of a few minutes to a few days. In fibreglass, matted or woven fibres of glass or other materials are embedded in the plastic to increase its strength. Fibreglass has many uses, for example in the construction of boats, aircraft and storage tanks.

**Sustainability and environmental issues.** The present plastics industry is unsustainable because the raw materials come mostly from oil which is non-renewable and is increasing in price. Thermoplastics should be **recycled** and most products now carry recycling symbols like the one on the right (6 is for PVC). Scientists are trying to find new, renewable raw materials from plants. Plastics cause serious and permanent pollution. When we discard plastics they do not decay. Years later they still litter the environment and kill wildlife. Even in the middle of the ocean, we can find plastic bags and shoes floating alongside nylon fishing line, and broken polypropylene ropes and fishing nets.

---

1. Explain the meaning of: (i) polymer, (ii) alkene, (iii) unsaturated, (iv) initiator, (v) polymerisation reaction, (vi) thermoplastic, (vii) curing, (viii) recycling, (ix) PVC.

2. What is the structure of polystyrene?

3. Explain why we can’t remould thermosetting plastics.

4. List the advantages and disadvantages of plastics.
13.15 METALS FROM THE EARTH'S CRUST

The composition of the Earth's crust is shown in the diagram on the right. Most rocks contain silica (SiO$_2$) and silicates (with the SiO$_3$ radical) so it is no surprise that oxygen and silicon account for nearly 75% of the crust's mass. Aluminium and iron are next, mainly in the form of oxides or silicates, and calcium is fifth, mainly in the form of calcium carbonate (CaCO$_3$).

Of the 90 elements* found on Earth, 18 are non-metals and about 66 are metals with a few (called the metalloids) that are somewhere between the two. In this module we will focus on metals, and particularly on the two most common, aluminium and iron.

* Why are only 90 elements found on earth? The lightest element is hydrogen with one proton in the nucleus and an atomic number of 1. The heaviest element occurring naturally on Earth is uranium with 92 protons and an atomic number of 92. It looks as if there should be 92 elements, but the elements with atomic numbers 43 and 61 have never been found. These elements have been made in nuclear reactions but they are both radioactive and have short half-lives. That is why they are not found in the natural world.


germanium

which we extract a metal and the smelting process was probably found by accident. Perhaps a rock containing a metal ore was heated in a very hot fire that was being used to make pottery. The ore may have been an oxide, or the heat may have changed it into an oxide. Then carbon, from charcoal in the fire, would reduce the oxide to the metal. Reduction is the chemical process of removing oxygen from an oxide to produce the metal. A common red coloured ore of iron is called haematite and the equation for the reduction of haematite to iron metal is:

$$2\text{Fe}_2\text{O}_3 + 3\text{C} \rightarrow 4\text{Fe} + 3\text{CO}_2$$

Gold occurs in nature as a native metal and has been used in jewellery for at least 8000 years. Copper, sliver and iron (from meteorites) also occur as native metals and copper has been used to make tools and weapons from about -5000 CE. Between then and about -2000 CE people (at first in Mesopotamia and Egypt) learnt to make copper, silver, lead, tin and iron from mineral ores by smelting. An ore is a mineral from which we extract a metal and the smelting process was probably found by accident. Perhaps a rock containing a metal ore was heated in a very hot fire that was being used to make pottery. The ore may have been an oxide, or the heat may have changed it into an oxide. Then carbon, from charcoal in the fire, would reduce the oxide to the metal. Reduction is the chemical process of removing oxygen from an oxide to produce the metal. A common red coloured ore of iron is called haematite and the equation for the reduction of haematite to iron metal is:

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$$2\text{Fe}_2\text{O}_3 + 3\text{C} \rightarrow 4\text{Fe} + 3\text{CO}_2$$

Basically the same process can be used to obtain many metals from their ores. This process is still used today and the diagram below shows a modern blast furnace for the production of iron.

![Iron ore (haematite) Fe$_2$O$_3$](image-url)
Iron is the second most common metal in the Earth’s crust. Iron ores like haematite ($\text{Fe}_2\text{O}_3$) are reduced by carbon in a blast furnace like the one shown on the last page. Coal (1) is carried up a conveyor belt into an oven (2) where it is heated to change it into coke (3). Coke is almost pure carbon. The coke (4), and a mixture of iron ore ($\text{Fe}_2\text{O}_3$) and limestone ($\text{CaCO}_3$) (5), are carried up a new conveyor belt into the top of the blast furnace (6). Inside the blast furnace coke (7), and the haematite-and-limestone mixture (8), move slowly down until they reach the hottest part at the base (9). All around the base, very hot air (from heaters (10)) enters the furnace through a ring of openings called tuyeres (11). Hot waste gases come out from the top of the furnace (12). They are cleaned to remove dust (13) and then pass up a tall chimney (14) into the atmosphere.

Inside the base of the furnace, some of the coke burns in the hot air. This heats the furnace to a temperature of about 1500°C. The rest of the coke reduces the iron oxide to molten iron (see the equation on the last page). Molten iron collects in the base of the furnace and from there it runs off into special containers (15). The limestone acts as a flux to liquefy earthy impurities such as silica that are mixed with the ore. It converts these into a molten slag of calcium silicate. The slag floats on top of the iron and can be run off from time to time (16).

\[
\text{CaCO}_3 + \text{SiO}_2 \rightarrow \text{CaSiO}_3 + \text{CO}_2
\]

Iron from a blast furnace has about 5% of carbon dissolved in it; this has to be reduced by further processing to obtain steel. Steel is an alloy of iron containing between 0.2% and 2% of carbon. Varying amounts of other metals such as manganese, chromium, vanadium and tungsten are added to obtain steels with different properties for different purposes. Steel is used to make machinery, bridges, ships, railways, in buildings to reinforce concrete, and in many other ways. Over 2 billion tonnes of iron ore are processed into steel every year.

Aluminium is the commonest metal in the Earth’s crust. The main ore is called bauxite and this is refined to obtain pure aluminium oxide ($\text{Al}_2\text{O}_3$). This cannot be reduced to aluminium by carbon because the aluminium hangs onto the oxygen too tightly! Instead, the aluminium oxide is dissolved in a mineral called cryolite ($\text{Na}_3\text{AlF}_6$) and a huge electric current is passed through the solution. Aluminium oxide contains positive aluminium ions and negative oxygen ions and the electricity separates these, releasing aluminium metal and oxygen gas. The splitting up an ionic compound by passing electricity through it is called electrolysis.

\[
2\text{Al}_2\text{O}_3 \rightarrow 4\text{Al} + 3\text{O}_2
\]

Aluminium is much lighter than steel, and when alloyed with other metals such as copper, zinc, magnesium and manganese can be made very strong. Because of their light weight and strength, aluminium and its alloys are widely used in making aircraft, coaches for road and rail transport, cars, boats and bicycles. They are also used for electricity transmission lines, window frames and kitchen foil. About 40 million tonnes of aluminium were produced in 2010.

**Sustainability and environmental issues.** Aluminium and iron are common in the Earth’s crust so we are not likely to run out of either of them. However, a lot of fossil fuels are used in producing both these metals. This is a sustainability issue because fossil fuels are in short supply. Fortunately, both metals are easy to recycle and many objects made of aluminium now carry the recycling symbol illustrated on the right. When anything made of steel or aluminium is no longer needed, it should be melted down so that the metal can be used again. As regards pollution, it is the fossil fuels used to produce the metals that cause most of the problems. These problems include greenhouse gasses and acid rain (see Module 13.12).

- 1. What are (i) radicals, (ii) reduction, (iii) flux, (iv) slag, (v) ore, (vi) electrolysis, (vii) cryolite, (viii) native metals?
- 2. What is the 6th commonest metal in the earth's crust?
- 3. Use the equation on the previous page to calculate what weight of haematite and what weight of carbon are needed to make 1 tonne of iron.
13.16 CERAMICS, GLASS AND CONCRETE

**Ceramics** are solid objects like pottery and bricks made by heating and then cooling clay and related minerals. Clay is a mineral made of very tiny grains that are formed by the weathering of feldspars and other minerals in igneous and metamorphic rocks. It is composed mainly of aluminium silicate \((\text{Al}_2\text{Si}_3\text{O}_9)\) and is often coloured red by iron oxide \((\text{Fe}_2\text{O}_3)\). Ceramic products include domestic pottery and crockery, sanitary ware (sinks and toilets), and industrial products such as bricks, drain pipes and tiles. Pottery, bricks and tiles have been made from red clays, often mixed with silica sand \((\text{SiO}_2)\), since pre-historic times. At first these were just dried in the sun, but people soon learned that heating them, originally in a fire and later in special ovens called *kilns*, made them much harder and stronger. Modern ceramic products are fired at 1000 to 1400°C, and modern crockery is often made from a white clay called *kaolin*.

**Glass** is made by heating silica with various metal oxides or carbonates. Ordinary window glass is made by heating silica sand with sodium and calcium carbonates. It is called soda-lime glass and it contains sodium and calcium silicates mixed with some unchanged silica.

\[
\begin{align*}
\text{Na}_2\text{CO}_3 + \text{SiO}_2 & \rightarrow \text{Na}_2\text{SiO}_3 + \text{CO}_2 \\
\text{CaCO}_3 + \text{SiO}_2 & \rightarrow \text{CaSiO}_3 + \text{CO}_2
\end{align*}
\]

Glass is an *amorphous* solid; that means it does not contain crystals. The particles are not arranged in regular lattices but in a more random way like the particles in a liquid. For that reason, glass has been called a super-cooled liquid but that is no longer considered to be correct. Glass with different properties and different colours, can be made by adding different metal oxides when the glass is being made. For example copper oxide is added to make green glass and boron oxide is added to make borosilicate glass which resists cracking when it is heated or cooled suddenly. Glass is used to make windows, containers of many shapes and kinds, light bulbs, lenses for glasses, binoculars and microscopes, and glass fibres for fibreglass plastics and fibre optics.

**Concrete** is cheap and easy to make and use. It has become the most widely used building material in the world. Concrete is used to build office and apartment blocks in cities, in domestic houses everywhere, and in the construction of factories, roads, bridges and dams. Reinforcing rods of steel are often embedded in it to give increased strength. Concrete is a mixture of cement (1 part), sand (2 parts), gravel (3 parts) and water. The cement and water form a paste that *cures* (hardens) over time. Concrete feels hard after a few hours but takes several weeks to reach full strength.

In 2005, more than 2.3 billion tonnes of cement were manufactured worldwide. It is made by heating a mixture of limestone, sand and clay to about 1400°C as it slides down inside a sloping kiln that rotates. The resulting lumps of *clinker* are ground up fine to make cement powder. The composition of cement varies but most of the limestone is decomposed into calcium oxide.

\[
\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2
\]

The cement cures by *hydration*, that is by chemical reactions with water. For example, calcium oxide is hydrated to calcium hydroxide.

\[
\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2
\]

Concrete continues to gain strength over a number of years as the calcium hydroxide slowly reacts with carbon dioxide in the atmosphere to become calcium carbonate again.

\[
\text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O}
\]

**Sustainability and environmental issues.** Clay, sand and limestone are widespread and will not run out for a very long time. The main environmental issue is the release into the atmosphere of carbon dioxide (a greenhouse gas) by the glass and especially the cement industry.

- 1. What are they made of? (i) A tea cup, (ii) green glass, (iii) cement, (iv) a concrete block.
- 2. List all the advantages and disadvantages you can think of or find out about for building with concrete.
13.17 SOME MORE ELEMENTS

This is an extra page for those who may want to know about a few more of the elements.

**Sodium and potassium** are chemical twins. They occur mainly as chlorides in the oceans or in salt beds that are the remains of dried-up seas. Like aluminium, they can only be extracted by electrolysis. Sodium and potassium are silvery metals and both have a valency of one. They tarnish quickly in the air and are usually kept under oil. Both metals are soft, light and very reactive. They can easily be cut with a knife and they float on water and react with it violently. Sodium vapour is used in street lights like the one shown on the left. Sodium and potassium chlorides are found in all living organisms, and sodium carbonate, chloride and hydroxide are important industrial chemicals.

**Calcium and magnesium** have similar properties. They both occur as carbonates and are extracted by electrolysis of their chlorides. They are soft, light, reactive metals, but less so than sodium and potassium. They both have a valency of two. Magnesium burns with a bright, white light (as shown right). It is used in photography and flares, and for making light alloys with aluminium for the aircraft industry. Both elements are found in all living organisms and vertebrates need plenty of calcium for their bones and teeth. The average adult human contains about 4 kg of calcium. Calcium carbonate is an important industrial chemical.

**Transition metals.** 42 metal elements are classified by chemists as *transition metals*. The best known are iron, copper, zinc, silver, platinum and gold but there are many others that are important in industry including titanium, vanadium, chromium, manganese, cobalt, nickel and tungsten. Transition metals are extracted from their ores by reduction with carbon. They are typical metals – tough, malleable, good conductors of heat and electricity, and can be polished to a shiny surface. They have variable valencies (ranging from one in silver and sometimes in copper, to seven in some compounds of manganese), and their compounds tend to be coloured. They form many useful alloys with one another and especially with iron in different kinds of steel. The picture above shows an engine of a jumbo jet. The body and engines of this plane contain over 100 tonnes of titanium which is a very light and strong metal.

**The halogen family** of non-metal elements includes fluorine (F₂, a pale yellow gas), chlorine (Cl₂, a pale green gas), bromine (Br₂, a heavy red liquid with a brown vapour), and iodine (I₂, a black solid that gives off a violet vapour – as shown right). They occur as salts of metals in the ocean and in salt beds, and they are extracted mainly by electrolysis. They all have a valency of one and combine with hydrogen to form strong acids. The first three are poisonous, corrosive and highly reactive. Fluorine is the most reactive of all elements and is used in the production of uranium and a few organic chemicals. Chlorine is used for water purification, bleaching, and for many other purposes in the chemical industry, and iodine solution is a good antiseptic for wounds. Fluorides are poisonous but tiny amounts in toothpaste or drinking water (2 parts per million) help to stop tooth decay. Chlorides are found in all living organisms and we also need very small amounts of iodide for the functioning of the thyroid gland.