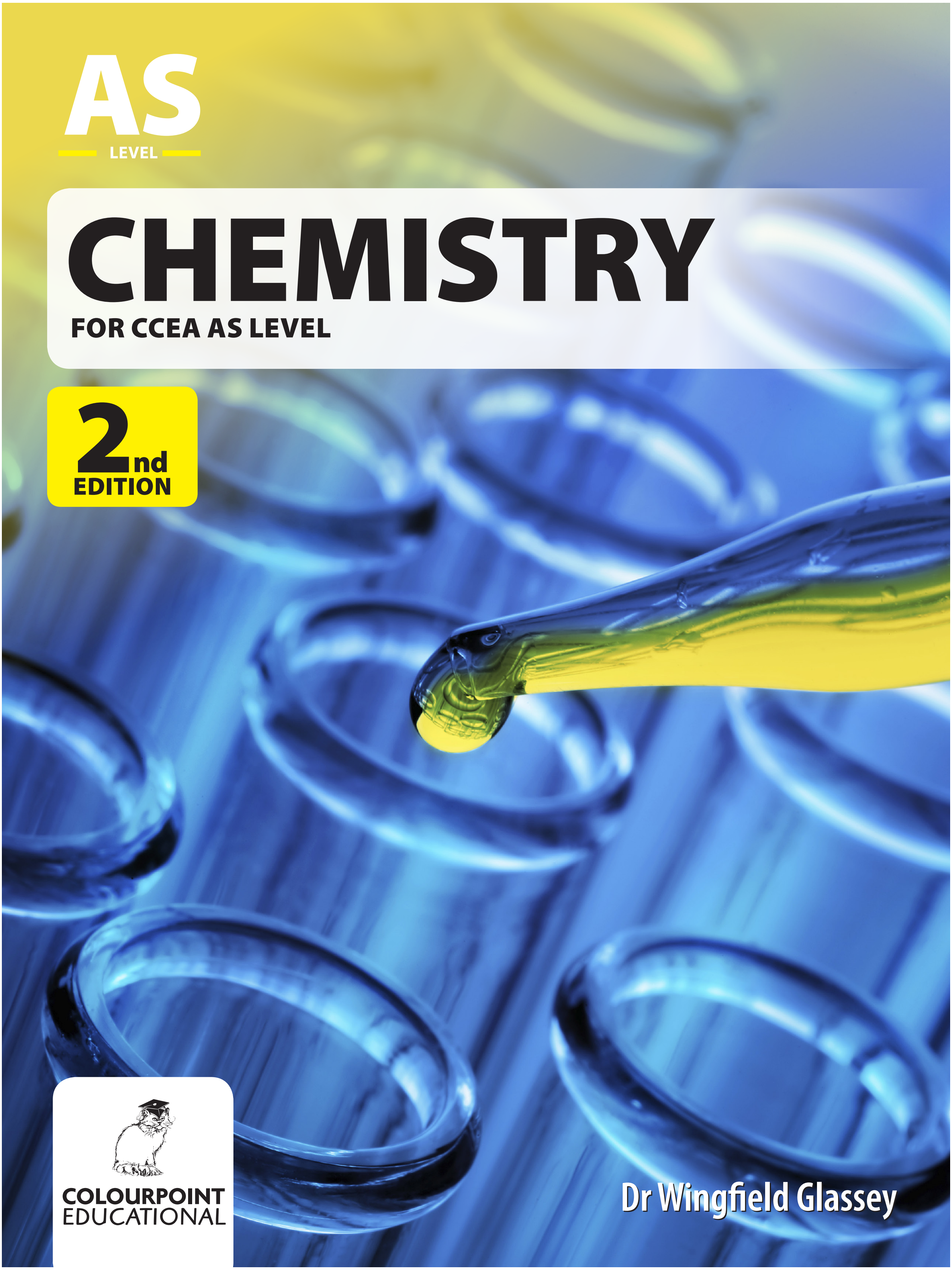


AS LEVEL

CHEMISTRY

FOR CCEA AS LEVEL

2nd EDITION

COLOURPOINT EDUCATIONAL

Dr Wingfield Glassey

Print ISBN: 978-1-78073-101-8
eBook ISBN: 978-1-78073-292-3

Second Edition
Second Impression 2018

Layout and design: April Sky Design

Colourpoint Educational

Colourpoint Educational
An imprint of Colourpoint Creative Ltd
Colourpoint House
Jubilee Business Park
Jubilee Road
Newtownards
County Down
Northern Ireland
BT23 4YH

Tel: 028 9182 6339
E-mail: sales@colourpoint.co.uk
Web site: www.colourpoint.co.uk

The Author

Dr. Wingfield Glassey teaches Chemistry at Friends' School Lisburn, and is an examiner for GCE AS and A2 Chemistry. Dr. Glassey also maintains a professional interest in the teaching and learning of science, and has published scholarly articles in a number of peer-reviewed journals including *The Journal of Chemical Education*.

Copyright

CONTENTS

Unit AS 1:

Basic Concepts in Physical and Inorganic Chemistry

1.1 Formulas, Equations and Amounts of Substance

CONNECTIONS

- All matter is made from around 100 elements.
- Almost all life on earth is based on the element carbon.
- Hydrogen is the most abundant element in the universe.

Elements and Compounds

In this section we are learning to:

- Use the terms element and compound to classify pure substances.
- Recall examples of elements with metallic, molecular and giant structures.
- Distinguish between ionic compounds and nonmetal compounds.
- Recall examples of compounds with ionic, molecular and giant structures.
- Describe the structure of an ionic compound.
- Use the terms atom, molecule, monatomic and diatomic to describe the structure of molecular materials.
- Recall the effect of molecular size on the melting and boiling points of molecular materials.

Plastics, medicines, and the other materials in the world around us are made of matter. The matter within any material is a combination of elements and compounds. An element is the simplest type of pure substance. A compound is also a pure substance and contains two or more elements bonded together. Water and carbon dioxide are examples of compounds. Water is a compound of the elements hydrogen and oxygen, and carbon dioxide is a compound of the elements carbon and oxygen.

A mixture contains a combination of compounds and elements. Crude oil, paint and air are all mixtures. Approximately 99% of air is made up of the elements nitrogen and oxygen. The remaining 1% is principally a mixture of water vapour, carbon dioxide and the element argon. The relationship between elements, compounds and mixtures is summarised in Figure 1.

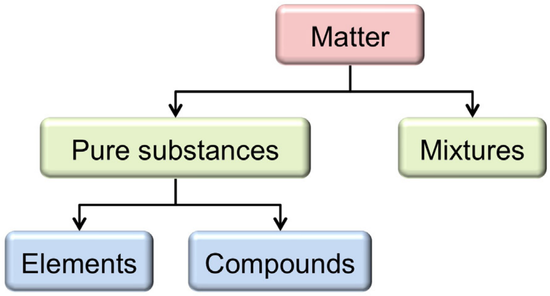


Figure 1: The relationship between elements, compounds and mixtures.

Elements

There are approximately 100 elements. The properties of one element can be quite different to those of another. Relationships between the properties and behaviour of different elements are best understood by constructing a Periodic Table. The form of the modern Periodic Table is shown in Figure 2. In the modern Periodic Table each element is represented by a chemical symbol and is assigned an atomic number. The atomic number of the elements increases from left to right across each row and down each column. When arranged in this way the properties of the elements are similar within each group (column), and vary in a predictable way from left to right across each period (row). For example, the distribution of metals and nonmetals in Figure 2 suggests that the elements behave less like metals and more like nonmetals from left to right across a period, and towards the top of each group.

Metals and nonmetals have very different properties. This results from differences in the arrangement of matter within each element. If we define an **atom** to be the smallest amount of an element, we can define an **element** to be a pure substance that contains only one type of atom. The atoms in a metal such as iron or silver are tightly packed together in an ordered arrangement. The resulting metallic structure is shown in Figure 3a. In contrast the atoms in nonmetals bond together to form molecules as in oxygen (Figure 3b),

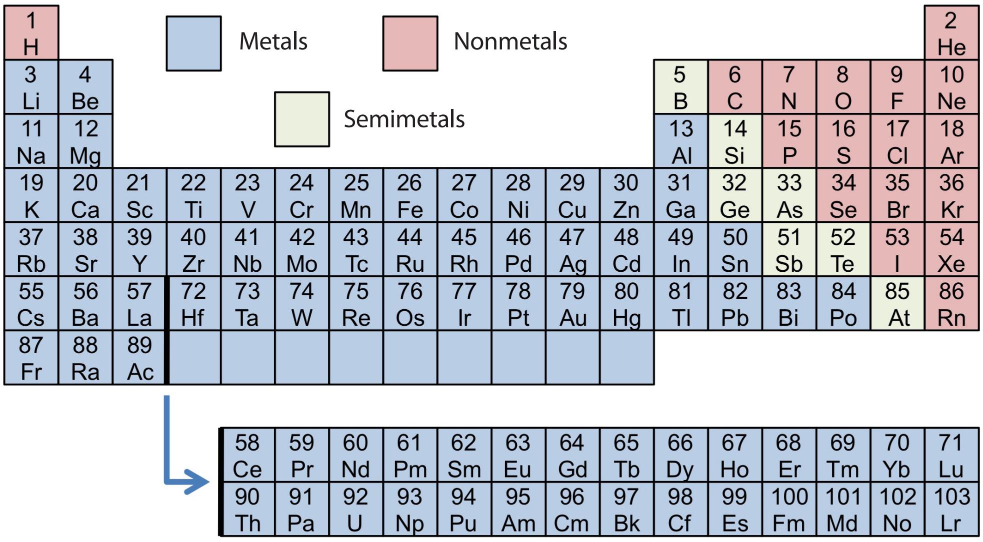


Figure 2: Classification of the elements as metals, nonmetals and semimetals. The term semimetal refers to elements that have properties in common with metals and nonmetals.

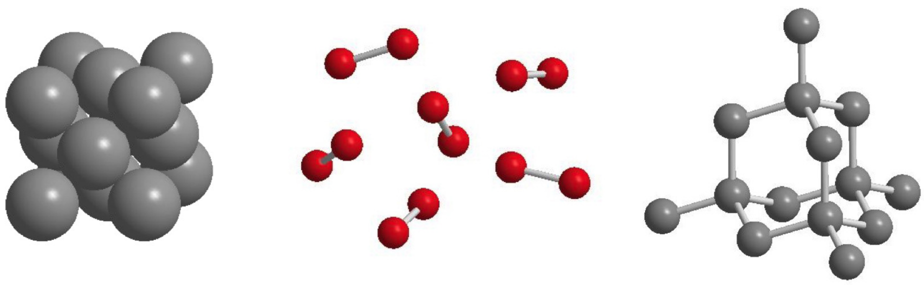
or to create giant structures such as the network of carbon atoms in diamond (Figure 3c).

The term **molecule** is used when referring to two or more atoms bonded together to form a single uncharged particle. Substances that are made of molecules are referred to as **molecular materials**. The elements oxygen and nitrogen are both molecular materials. They are also examples of **diatomic elements** as the molecules in oxygen and nitrogen each contain two atoms. Molecules containing two atoms are referred to as **diatomic molecules**.

Substances with giant structures such as diamond (Figure 3c) are held together by strong bonds between the atoms. As a result, they have high melting points and are solids under normal conditions. Graphite - the major component in pencil 'lead' - is a different form of carbon that also contains a network of carbon atoms. Like diamond, graphite has a high melting point and is a solid under normal conditions. Diamond and graphite are examples of allotropes where the term **allotrope** is used to refer to different physical forms of the same element.

In contrast, molecular materials may be solids, liquids or gases under normal laboratory conditions. Elements containing heavier atoms such as bromine and iodine are more likely to be liquids or solids. For example, under normal laboratory conditions oxygen is a gas, bromine is a liquid, and iodine is a solid.

Oxygen, bromine and iodine are diatomic elements. Elements containing larger molecules are even more likely to be liquids or solids. Rhombic sulfur and white phosphorus are examples of allotropes containing large molecules. Both are solids. Molecules of rhombic sulfur and white phosphorus are shown in Figure 4.

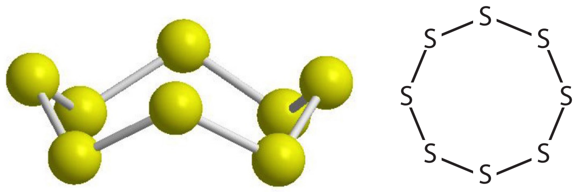


(a) Atoms in iron
Formula: Fe

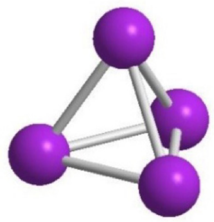
(b) Oxygen molecules
Formula: O_2

(c) Atoms in diamond
Formula: C

Figure 3: The arrangement of (a) atoms in iron, (b) molecules in oxygen gas and (c) carbon atoms in diamond



(a) Sulfur molecule
Formula: S_8



(b) Phosphorus molecule
Formula: P_4

Figure 4: A molecule of (a) rhombic sulfur and (b) white phosphorus.

The relationship between the size of the molecules in a substance and its melting point is further illustrated by the elements in Group VIII; a group of unreactive gases known as the noble gases. The noble gases are examples of **monatomic elements**. A substance is described as monatomic if the particles in the substance each contain a single atom. The fact that heavy noble gases such as krypton (Kr) and xenon (Xe) are gases, while much lighter elements such as sulfur are solids, demonstrates that the melting point of a molecular material is determined by the size of the molecules in the material.

Exercise 1.1A

1. Which of the following is (a) a diatomic element, (b) a gas, and (c) solid?

   nitrogen bromine silver sulfur iodine

Before moving to the next section, check that you are able to:

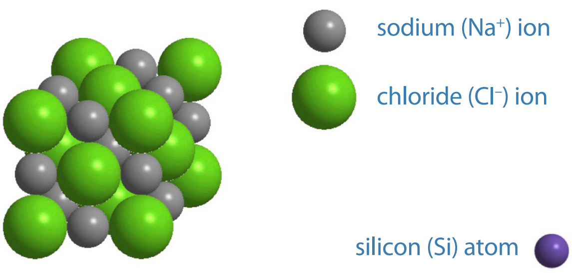
- Use the terms atom, molecule, monatomic and diatomic to describe elements.
- Recall examples of elements with metallic, molecular and giant structures.
- Recall the effect of molecular size on melting and boiling point.

Compounds

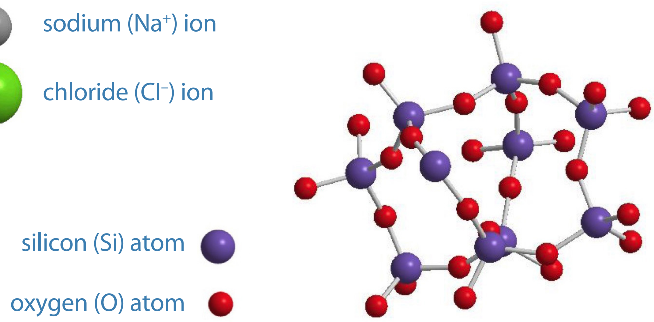
The term **compound** refers to a pure substance that contains two or more elements bonded together. A compound cannot be easily separated into its constituent elements. Water, carbon dioxide and sodium chloride (table salt) are all examples of compounds.

The compounds formed when metals combine with nonmetals are known as **ionic compounds** and are very different to the compounds formed when nonmetals combine. For example, sodium chloride is an ionic compound formed by the reaction between sodium metal (Na) and the nonmetal chlorine (Cl). Ionic compounds such as sodium chloride contain ions packed tightly together in a regular pattern known as a lattice. The lattice in sodium chloride is held together by attractive forces between sodium (Na^+) ions and chloride (Cl^-) ions. The packing of the ions in the sodium chloride lattice is shown in Figure 5a.

Ionic compounds are solids. The ions in the lattice separate and move independently when the solid dissolves or melts. Similarly, the molecules in nonmetal compounds separate and move independently when the compound dissolves or changes state. As in elements, compounds containing small molecules such as hydrogen chloride, HCl and sulfur dioxide,



(a) Sodium chloride



(b) Quartz

Figure 5: The structure of (a) sodium chloride and (b) quartz.

SO_2 are gases. Compounds made of larger molecules such as phosphorus(III) chloride, PCl_3 and dichloromethane, CH_2Cl_2 are liquids, and compounds containing even larger molecules such as phosphorus(V) chloride, PCl_5 and phosphorus(V) oxide, P_4O_{10} are solids.

Many nonmetal compounds such as the mineral quartz – an allotrope of silicon dioxide, SiO_2 – have a giant structure held together by strong bonds between the atoms. The structure of quartz is shown in Figure 5b. The strong bonding between atoms in giant structures such as quartz does not break easily and explains why substances with a giant structure have very high melting points, and tend to be insoluble in water and other solvents.

Exercise 1.1B

1. Which of the following (a) is an ionic compound, (b) is a molecular material, and (c) has a giant structure.

   NO_2 $NaNO_3$ $MgBr_2$ CCl_4 SiO_2

2. Which one of the following is a molecular substance?

   A CaO B CO C Cr_2O_3 D CuO

   (CCEA June 2013)

3. Which one of the following compounds is not molecular?

   A carbon dioxide
   B calcium chloride
   C hydrogen chloride
   D phosphorus trichloride

   (Adapted from CCEA June 2011)

Before moving to the next section, check that you are able to:

- Recall the definition of a compound.
- Distinguish between ionic compounds and nonmetal compounds.
- Describe the structure of an ionic compound.
- Recall examples of compounds with ionic, molecular and giant structures.

Chemical Formulas

In this section we are learning to:

- Use the formula for a substance to deduce its composition and structure.
- Write the formula for ionic compounds and nonmetal compounds, including those containing an element with variable valency.

Interpreting Formulas

The **chemical formula** or ‘formula’ of a substance describes the amount of each element in the substance. The formula of a substance also represents the smallest amount of the substance that can participate in a chemical reaction. For example, the formula of sodium chloride is NaCl and indicates that there is one sodium (Na^+) ion for every chloride (Cl^-) ion in the compound. Similarly the formula for magnesium chloride, $MgCl_2$ indicates that there are two chloride (Cl^-) ions for every magnesium (Mg^{2+}) ion in the compound.

In molecular materials such as water and carbon dioxide, the formula of the compound describes the number of atoms in each molecule of the substance. For example, the formula of water, H_2O indicates that each molecule of water contains two hydrogen atoms and one oxygen atom. Similarly, the formula for carbon dioxide, CO_2 indicates that each molecule of carbon dioxide contains one carbon atom and two oxygen atoms.

The formula of an element is determined by how the atoms in the element are organised. In a metal such as iron, the atoms are closely packed in an ordered array (Figure 3a) and are indistinguishable. As a result, a single metal atom can be used to represent any one atom in the structure, and the formula of a metal such as iron (formula: Fe) or gold (formula: Au) represents one atom of the element. Similarly, a single atom can be used to represent any atom in a monatomic element such as helium (formula: He) or neon (formula: Ne), and any atom in giant structures such as diamond (formula: C).

In elements with a molecular structure the formula of the element represents the atoms in one molecule of the element. For example, the formulas of hydrogen (formula: H_2) and chlorine (formula: Cl_2) represent two atoms of the element, indicating that the element is made up of diatomic molecules. Similarly, formulas can be used to indicate that the molecules in white phosphorus contain four phosphorus atoms (formula: P_4), and the molecules in rhombic sulfur contain eight sulfur atoms (formula: S_8).

Writing Formulas

The formula of a compound is determined by the **valency** or 'combining power' of the elements in the compound. The valency of many elements can be determined from their location in the Periodic Table. This relationship is illustrated in Figure 6.

When a metal combines with one or more nonmetals to form an ionic compound such as NaCl, the metal loses electrons to form a positive ion and the nonmetal gains electrons to form a negative ion. From Figure 6 we see that sodium (Na) belongs to Group I and has a valency of 1. The valency of sodium tells us that when sodium combines with nonmetals each sodium atom will lose one electron to form a sodium ion (Na^+). Similarly, chlorine belongs to Group VII and has a valency of 1. The valency of chlorine tells us that when chlorine reacts with a metal such as sodium, each chlorine atom will gain one electron to form a chloride ion (Cl^-). In this way the relationship between the location of an element in the Periodic Table and its valency can be used to deduce the charges on the ions in an ionic compound.

An ionic compound does not have a charge and, as a result, *the charges on the ions in one formula of an ionic compound add to zero*. This idea can be used to construct the formula for any ionic compound. For example, magnesium (Mg) belongs to Group II and has a valency of 2. The valency of magnesium tells us that magnesium forms Mg^{2+} ions when it combines with nonmetals to form an ionic compound. We have already seen that chlorine (Group VII) has a valency of 1 and forms chloride (Cl^-) ions when it combines with metals. If the charges on the ions in magnesium chloride add to zero the compound must contain two chloride (Cl^-) ions for each magnesium (Mg^{2+}) ion.

This explains why the formula of magnesium chloride: $MgCl_2$

represents one Mg^{2+} ion and two Cl^- ions

Worked Example 1.1i

Write the formula for (a) magnesium oxide, (b) sodium oxide and (c) aluminium bromide.

Strategy

- Use the valency of each element to calculate the charges on the ions.
- Deduce the number of positive and negative ions needed to balance the charge in one formula.

Solution

(a) Magnesium (Group II) has a valency of 2 and forms Mg^{2+} ions. Oxygen (Group VI) has a valency of 2 and forms O^{2-} ions. Magnesium oxide contains one Mg^{2+} ion for every O^{2-} ion. The formula of magnesium oxide is MgO.

(b) Sodium (Group I) has a valency of 1 and forms Na^+ ions. Oxygen (Group VI) has a valency of 2 and forms O^{2-} ions. Sodium oxide contains two Na^+

Group:	I	II	III	IV	V	VI	VII	VIII
Valency:	1	2	3	4	3	2	1	0
	H							He
	Li	Be	B	C	N	O	F	Ne
	Na	Mg	Al	Si	P	S	Cl	Ar
	K	Ca	Ga	Ge	As	Se	Br	Kr
	Rb	Sr	In	Sn	Sb	Te	I	Xe
	Cs	Ba	Tl	Pb	Bi	Po	At	Rn

Figure 6: The relationship between the valency of an element and its location in the Periodic Table.

ions for every O^{2-} ion. The formula of sodium oxide is Na_2O.

(c) Aluminium (Group III) has a valency of 3 and forms Al^{3+} ions. Bromine (Group VII) has a valency of 1 and forms Br^- ions. Aluminium bromide contains three Br^- ions for every Al^{3+} ion. The formula of aluminium bromide is $AlBr_3$.

Exercise 1.1C

1. Write the chemical formula for (a) lithium fluoride, (b) potassium chloride, (c) magnesium bromide, (d) magnesium sulfide, and (e) aluminium oxide.

In nonmetal compounds such as carbon dioxide (formula: CO_2) and water (formula: H_2O), the atoms are held together by covalent bonds. The valency of an element tells us how many covalent bonds can be formed by an atom of the element when it combines with other elements to form a compound. For example, carbon belongs to Group IV and has a valency of 4. This tells us that a carbon atom can form up to four covalent bonds when bonding with other nonmetals. When carbon combines with oxygen (Group VI, valency 2) two oxygen atoms (total valency 2 + 2 = 4) are needed to equal the combining power of one carbon atom (valency 4). As a result, a molecule of carbon dioxide contains 2 oxygen atoms and 1 carbon atom.

This explains why the formula of carbon dioxide:

CO_2

represents one carbon atom and two oxygen atoms

one molecule of carbon dioxide

Compounds of Hydrogen

Hydrogen, H is a nonmetal. It has a valency of 1 and combines with metals to form ionic compounds known as metal hydrides. Sodium hydride, NaH and calcium hydride, CaH_2 are examples of metal hydrides. Hydrogen also has a valency of 1 when it combines with nonmetals to form molecular compounds such as water, H_2O and ammonia, NH_3.

Worked Example 1.1ii

Deduce the formula of the compounds (a) H_xF, (b) H_xS, (c) NH_x and (d) CH_x.

Strategy

- Determine the valency of each element.
- Deduce the value of x needed to balance the combining power of each element.

Solution

(a) Hydrogen (H) and fluorine (F) both have a valency of 1. One hydrogen atom is needed to combine with one fluorine atom. Formula: HF

(b) Hydrogen (H) has a valency of 1 and sulfur (S) has a valency of 2. Two hydrogen atoms are needed to combine with one sulfur atom. Formula: H_2S

(c) Hydrogen (H) has a valency of 1 and nitrogen (N) has a valency of 3. Three hydrogen atoms are needed to combine with one nitrogen atom. Formula: NH_3

(d) Hydrogen (H) has a valency of 1 and carbon (C) has a valency of 4. Four hydrogen atoms are needed to combine with one carbon atom. Formula: CH_4

Elements with Variable Valency

A number of metals and nonmetals have the ability to vary their valency when forming compounds. For example, carbon can combine with oxygen to form carbon monoxide, CO in which the valency of carbon is 2 and carbon dioxide, CO_2 in which carbon has a valency of 4. Similarly iron can combine with chlorine to form iron(II) chloride, $FeCl_2$ in which iron has a valency of 2, and iron(III) chloride, $FeCl_3$ in which the valency of iron is 3.

Worked Example 1.1iii

Tin is a 'poor metal' and will behave in a similar way to carbon and other nonmetals in Group IV when bonding with other elements. Write the formula for (a) tin(II) chloride, (b) tin(IV) chloride, (c) copper(II) oxide and (d) copper(I) oxide.

Strategy

- Roman numerals are used to indicate the valency of tin and copper in each compound.

Solution

(a) Tin has a valency of 2 and chlorine has a valency of 1. Two chlorine atoms are needed to equal the combining power of tin. Formula: $SnCl_2$

(b) Tin has a valency of 4 and chlorine has a valency of 1. Four chlorine atoms are needed to equal the combining power of tin. Formula: $SnCl_4$

(c) The ions in copper(II) oxide are copper(II), Cu^{2+} and oxide, O^{2-}. One oxide ion is needed to balance the charge on one copper(II) ion. Formula: CuO

(d) The ions in copper(I) oxide are copper(I), Cu^{+} and oxide, O^{2-}. Two copper(I) ions are needed to balance the charge on one oxide ion. Formula: Cu_2O

Exercise 1.1D

1. Write the chemical formula for
(a) phosphorus(III) bromide, (b) nitrogen(IV) oxide, (c) sulfur(IV) fluoride and
(d) mercury(II) chloride.

2. Write the chemical formula for (a) sulfur(IV) oxide, (b) phosphorus(V) chloride,
(c) manganese(IV) oxide and (d) xenon(II) fluoride.

Before moving to the next section, check that you are able to:

- Use formulas to deduce the composition and structure of compounds.
- Determine the valency of an element from its location in the Periodic Table.
- Write the formula for ionic and nonmetal compounds, including those containing an element with variable valency.

Naming Compounds

In this section we are learning to:

- Name ionic compounds, including those containing molecular ions.
- Use prefixes to name nonmetal compounds.
- Name ionic and nonmetal compounds, including those containing an element with the ability to vary its valency.

Ionic Compounds

When a metal combines with a nonmetal to form an ionic compound the metal loses electrons to form a **cation** and the nonmetal gains electrons to form an **anion**. For example, when sodium reacts with oxygen to form sodium oxide, Na_2O each atom of sodium forms a sodium cation, Na^+ and each oxygen gains electrons to form an oxide anion, O^{2-}. Ionic compounds are named by following the name of the cation with the name of the anion. In the case of sodium oxide, Na_2O the name indicates that the compound contains sodium cations and oxide anions.

Sodium oxide, Na_2O contains

sodium cations and oxide anions

The names and formulas of common cations and anions are summarised in Table 1. Ions such as ammonium (NH_4^+), carbonate (CO_3^{2-}) and sulfate (SO_4^{2-}) are listed separately under the heading **molecular ions** as they are *positively or negatively charged ions that contain two or more atoms held together by covalent bonds*. The atoms in a molecular ion remain bonded together when the compound containing the molecular ion melts, reacts, or dissolves to form a solution.

Worked Example 1.1iv

Name the following ionic compounds.

(a) Na_2S (b) $MgBr_2$ (c) Na_2CO_3
(d) KNO_3 (e) $(NH_4)_2CO_3$ (f) K_2SO_4

Strategy

- Use the formula to identify the cations and anions in each compound.
- Use the names of the cation and anion to name the compound.

Solution

(a) Na_2S contains sodium cations (Na^+) and sulfide (S^{2-}) anions. Na_2S is the formula for sodium sulfide.

(b) $MgBr_2$ contains magnesium cations (Mg^{2+}) and bromide (Br^-) anions. $MgBr_2$ is the formula for magnesium bromide.

Cations	Anions	Molecular Ions
Hydrogen, H^+	Hydride, H^-	*Cations:*
		Ammonium, NH_4^+
Group I:	*Group V:*	*Anions:*
Lithium, Li^+	Nitride, N^{3-}	Peroxide, O_2^{2-}
Sodium, Na^+		Hydroxide, OH^-
Potassium, K^+	*Group VI:*	Nitrate, NO_3^-
	Oxide, O^{2-}	Nitrite, NO_2^-
Group II:	Sulfide, S^{2-}	Sulfate, SO_4^{2-}
Magnesium, Mg^{2+}		Thiosulfate, $S_2O_3^{2-}$
Calcium, Ca^{2+}	*Group VII:*	Hydrogensulfate, HSO_4^-
Barium, Ba^{2+}	Fluoride, F^-	Sulfite, SO_3^{2-}
	Chloride, Cl^-	Carbonate, CO_3^{2-}
Other metals:	Bromide, Br^-	Hydrogencarbonate, HCO_3^-
Aluminium, Al^{3+}	Iodide, I^-	Phosphate, PO_4^{3-}
Copper(II), Cu^{2+}		Chlorate, ClO_3^-
Iron(II), Fe^{2+}		Hypochlorite, ClO^-
Iron(III), Fe^{3+}		*Anions containing metals:*
Zinc, Zn^{2+}		Chromate, CrO_4^{2-}
Silver, Ag^+		Dichromate, $Cr_2O_7^{2-}$
		Permanganate, MnO_4^-

Table 1: Common cations and anions

(c) Na_2CO_3 contains sodium cations (Na^+) and carbonate (CO_3^{2-}) anions. Na_2CO_3 is the formula for sodium carbonate.

(d) KNO_3 contains potassium cations (K^+) and nitrate (NO_3^-) anions. KNO_3 is the formula for potassium nitrate.

(e) $(NH_4)_2CO_3$ contains ammonium (NH_4^+) cations and carbonate (CO_3^{2-}) anions. $(NH_4)_2CO_3$ is the formula for ammonium carbonate.

(f) K_2SO_4 contains potassium cations (K^+) and sulfate (SO_4^{2-}) anions. K_2SO_4 is the formula for potassium sulfate.

Exercise 1.1E

1. Name the following ionic compounds.
   (a) $CaCl_2$ (b) Al_2O_3 (c) AgBr
   (d) LiH (e) ZnS
2. Name the following ionic compounds.
   (a) $ZnCO_3$ (b) $ZnSO_4$ (c) $Mg(NO_3)_2$
   (d) Mg_3N_2 (e) $KMnO_4$
3. Name the following ionic compounds.
   (a) $AgNO_3$ (b) NH_4NO_3 (c) $NaNO_2$
   (d) $Al_2(SO_4)_3$ (e) Na_2SO_3
4. Name the following ionic compounds.
   (a) Na_2O (b) Na_2O_2 (c) $Ca(HCO_3)_2$
   (d) NaClO (e) K_2CrO_4

Nonmetal Compounds

When naming nonmetal compounds the amount of each element in the compound can be described by using a prefix such as *di* or *tri*. For instance, the prefixes *mon*, *di* and *tri* could be used to distinguish carbon monoxide, CO from carbon dioxide, CO_2 and sulfur dioxide, SO_2 from sulfur trioxide, SO_3. Similarly, the prefixes *tri* and *penta* could be used to distinguish phosphorus trichloride, PCl_3 from phosphorus pentachloride, PCl_5. The use of prefixes is further illustrated by the examples in Table 2.

Element Ratio in Compound	Prefix	Example
1:1	mon	nitrogen **mon**oxide, NO
1:2	di	nitrogen **di**oxide, NO_2
1:3	tri	boron **tri**fluoride, BF_3
1:4	tetra	carbon **tetra**chloride, CCl_4
1:5	penta	phosphorus **penta**chloride, PCl_5
1:6	hexa	sulfur **hexa**fluoride, SF_6

Table 2: Using prefixes to name nonmetal compounds