

# 3 Ionic bonding

To construct new substances such as smart materials, self-repairing materials and nanotubes, scientists and engineers need to understand the way atoms are put together and the limitations of the bonding models. The way that the atoms in a material are bonded together directly affects its properties and performance. The following three chapters investigate some of the types of bonding between the atoms that shape our world.

## YOU WILL EXAMINE:

- the formation of ions
- ionic bonding as the strong bonding found in solids such as sodium chloride and magnesium oxide
- the relationship between the structure and bonding of ionic materials and their properties
- the importance and limitations of the ionic bonding model
- chemical language: symbols and formulas
- data relating to the physical properties of ionic substances
- models that represent the ionic structure
- properties of ionic materials from a knowledge of their structure and bonding
- uses of ionic compounds.

Simplicity is the ultimate sophistication.

*Leonardo da Vinci*



Giant crystals of gypsum, some up to 11 metres long, found in the 'Cave of crystals' in Mexico. Note the size of the crystals compared with the human figure in the bottom right-hand corner.

## Introducing chemical bonds

Metal and non-metal atoms are joined by ionic bonding.

The forces between atoms in chemical bonds are electrostatic.

Collecting crystals of minerals and gemstones is one of the most popular and fastest growing hobbies in the world. These substances are admired for their perfect symmetry, brilliant colour, lustre and size. In ancient times, the early Egyptians gathered attractive crystals to use as household decorations and jewellery. Many of these crystals consist of **ionic compounds** in which metal and non-metal atoms are joined by **ionic bonding**.

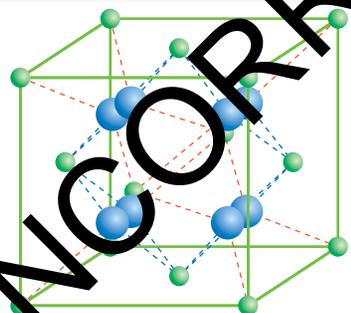
We are aware that all the varied substances around us are formed from atoms combining together. But what holds atoms together once they have combined? Why do some atoms join or bond with others, while some remain as individual atoms? Why do atoms combine in specific ratios?

The answers lie in the nature of the **chemical bond**. All forces of attraction leading to chemical bonding between atoms are electrostatic in nature: that is, an attraction between positive and negative charges. Studying the electron structure of the atom helps us understand not only how atoms bond but also the characteristic properties of the substances that are formed when they do.

Most spontaneous changes that take place in nature occur in order to reach a more stable state. For example, things tend to roll downhill, but come to rest when they reach a stable position.

We seldom find free atoms in nature because atoms undergo changes in structure to become more stable. They do this by joining together, or bonding. Sometimes they bond with atoms of the same kind (for example, hydrogen gas,  $H_2$ ) and sometimes with atoms of a different kind (for example, hydrochloric acid,  $HCl$ ). Only the noble gases may exist as free atoms. This behaviour can be explained by an atom's electron configuration.

The mineral fluorite contains the ionic compound calcium fluoride,  $CaF_2$ , as its main component. Its beautiful crystals are often cubic in shape and appear in a variety of colours, pink being the rarest. What causes its crystal structure to be so regular?



## Electron configuration and stability

We have already considered the electron configuration of atoms and have seen that the electrons may be found in certain shells around the nucleus. You may have noticed that some atoms have a complete outer shell of electrons. These atoms are helium, neon, argon, krypton and xenon, and are located in group 18 of the periodic table. They are known as the inert, or noble, gases because they





Non-metal atoms gain electrons to form anions.

The O atom has:

+++++++ 8 protons  
 ----- 8 electrons  
 = neutral charge.

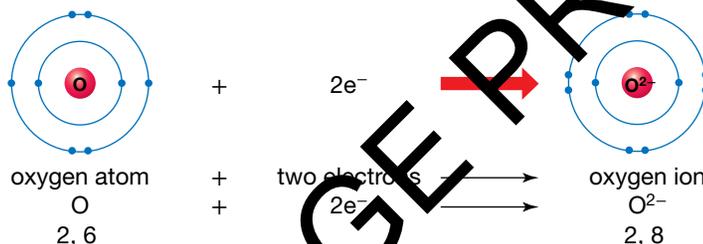
The O<sup>2-</sup> ion has:

+++++++ 8 protons  
 ----- 10 electrons  
 = 2 electrons unmatched  
 = 2- charge.

The oxygen atom has six valence electrons, and gains two electrons to form the oxide ion, which has a charge of 2-.

Non-metallic elements are shown on the right-hand side of the purple section in the periodic table on the previous page. These elements generally have high electronegativities. They gain electrons to achieve a noble gas configuration of eight electrons in their outer shells (with the exception of hydrogen).

For example, oxygen in group 16 has six outer shell electrons and has the electron configuration 2, 6. It is too difficult to remove all six electrons to achieve a full outer shell, so the oxygen atom gains two electrons instead to become a stable anion, as shown in the following figure. An anion has more electrons than a neutral atom of the same element; here, the oxygen ion has eight protons and ten electrons, resulting in a net charge of 2-. The electron configuration of the oxygen anion is now similar to that of a neon atom: 2, 8. The oxygen atom has become an oxide ion. (It is a convention in chemistry to indicate the ions of non-metallic elements with the suffix *-ide*.)



### Sample problem 3.1

Write the symbol, charge and name of the ions you would expect atoms of the following elements to form:

- (a) Mg (b) S

**Solution:**

- (a) Mg is a metal found in group 2. It has electron configuration 2, 8, 2. In order to become stable the Mg atom needs to lose two electrons. The charge of the resultant ion would therefore be 2+ and its symbol Mg<sup>2+</sup>. It is called the magnesium ion.
- (b) S is a non-metal found in group 16. In order to become stable the S atom needs two more electrons to complete its outer shell. The charge of the resultant ion would therefore be 2- and its symbol S<sup>2-</sup>. It is called the sulfide ion.

### Revision questions

- Explain why atoms such as Ca and Al form ions.
- Use electron shell diagrams and simple equations to show how the following atoms form their corresponding ions:
  - the metal atoms Ca and Al
  - the non-metal atoms N and F.
- For each of the following atoms, predict the charge of the ion formed, and write its name and symbol:
  - Ba
  - K
  - P
  - Cl
  - S.
- Copy and complete the following table, predicting the general electrovalencies for period 2 and period 3 ions in each group.

Period	Group 1	Group 2	Group 13	Group 15	Group 16	Group 17
2	1+					
3						

A transfer of electrons from a metal to a non-metal results in an ionic bond.



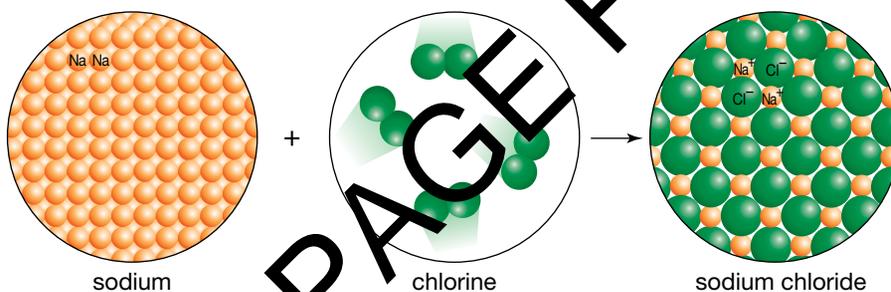
A small piece of sodium is melted in a metal spoon before being thrust into a flask containing chlorine. This produces an extremely violent reaction that releases a large amount of heat as the stable product, salt, is formed.

## Ionic bonding

Metals and non-metals can react together because the electrons lost by the metals can be taken up by the more electronegative non-metals. This transfer of electrons results in an ionic bond between the metal cations and the non-metal anions.

For example, when a small piece of sodium metal is added to a flask containing chlorine gas, a chemical reaction occurs, as shown below. The sodium ignites, and the solid ionic compound sodium chloride forms. This involves a transfer of one electron from the sodium atom to the chlorine atom. The ways in which we can represent this process are shown in the solution to sample problem 3.2.

Sodium ions and chloride ions are oppositely charged and therefore they attract each other by **electrostatic attraction**. This strong force of attraction between positive and negative ions is what produces an ionic bond.



The formation of sodium chloride from solid sodium and gaseous chlorine

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Reaction of sodium with chlorine

A salt is the general name for a compound formed from a metal and a non-metal.

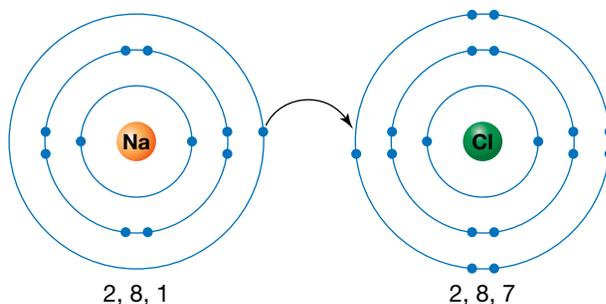
Note that the bonded form is more stable than the unbonded form and has different properties from those of the original elements. Sodium is a very reactive metal; chlorine is a poisonous gas. Sodium chloride, however, is a non-toxic ionic compound familiar to us as table salt. The term 'salt', however, has a wider meaning in chemistry. The general name for an ionic compound, a substance formed from the reaction between a metal and a non-metal, is a **salt**.

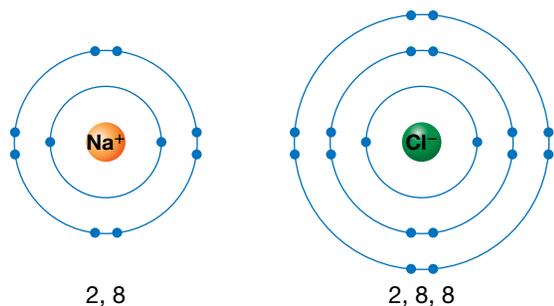
### Sample problem 3.2

Consider the reaction between sodium and chlorine and explain it using:

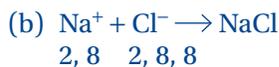
- electron shell diagrams
- a simple equation.

**Solution:** (a) Sodium and chlorine can be represented as follows:





In bonding ionically with a chlorine atom, the sodium atom loses one electron (its entire outer shell) to become a positive ion, or cation. The chlorine atom gains one electron to complete its outer shell. It is now a negative ion, or anion. The sodium and chloride ions form the substance called sodium chloride, and can be represented as follows:

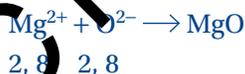
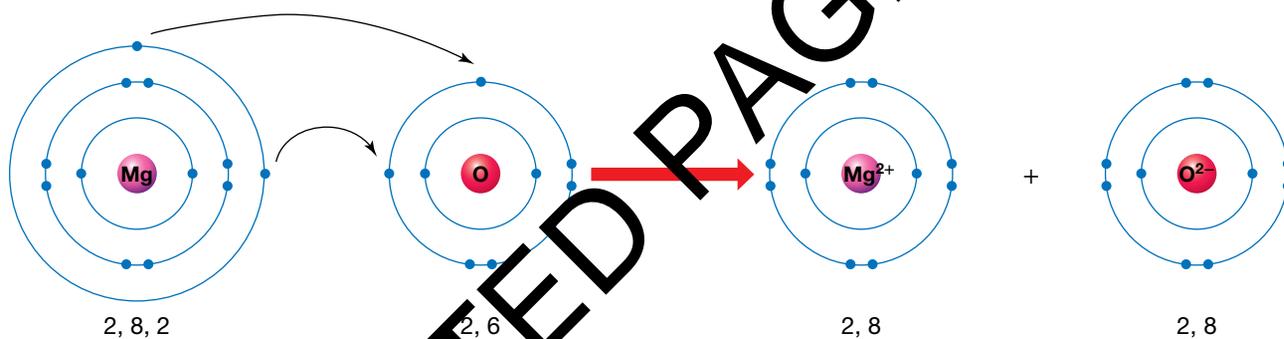


### Sample problem 3.3

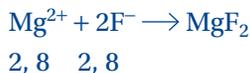
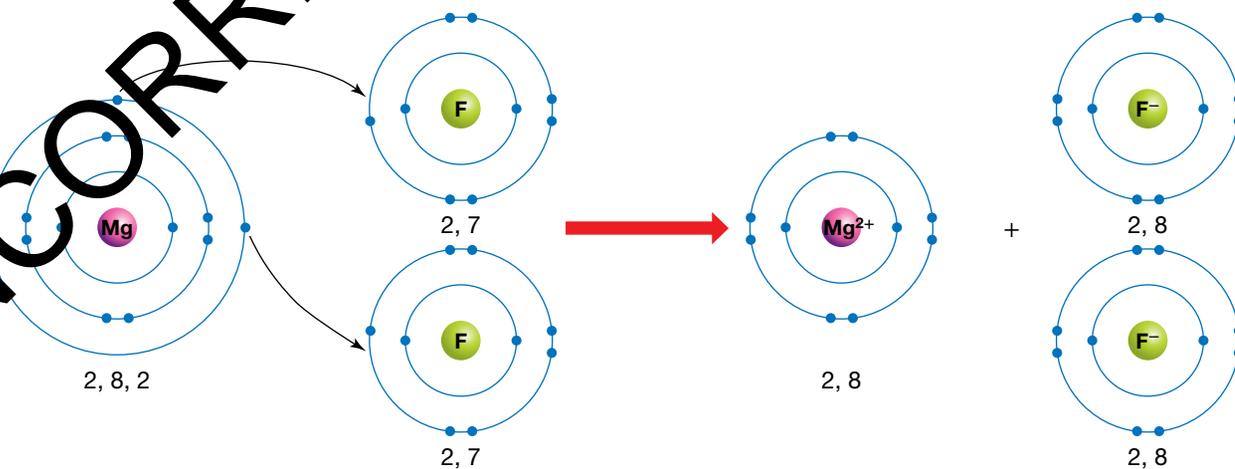
Consider the following ionic compounds and explain the bonds between their atoms using electron shell diagrams and simple equations.

- (a) magnesium oxide  
(b) magnesium fluoride.

**Solution:** (a) A magnesium atom needs to lose two electrons to gain a stable noble gas configuration. In doing so, it becomes a doubly charged ion  $\text{Mg}^{2+}$ . The two resulting electrons can be gained by a *single* atom, such as oxygen, which requires two electrons to complete its outer shell.



- (b) Each of the two electrons from the magnesium atom are accepted by *separate* fluorine atoms, which each require only one electron to fill their outer shells.



## study on

Unit 1

AOS 1

Topic 4

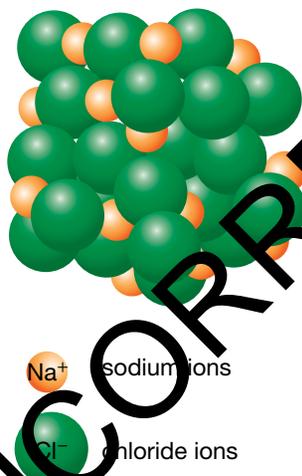
Concept 2

**Ionic bonding model**  
Summary screen and practice questions

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Animation of NaCl structure

Ionic network lattices are three-dimensional arrays of cations and anions.



NaCl is represented here using both the space-filling and ball-and-stick molecular models.

- Which model is which?
- Which model do you consider more useful for the discussion of ionic network lattices?

## Revision questions

5. Draw electron shell structures and write simple equations to show the ionic bonding between the following:
  - (a) calcium and oxygen
  - (b) beryllium and chlorine
  - (c) lithium and fluorine
  - (d) aluminium and sulfur
  - (e) sodium and nitrogen
  - (f) magnesium and sulfur.
6. Write the electron configurations of:
  - (a) the cations potassium, calcium and aluminium
  - (b) the anions fluoride, oxide and nitride.
7. Name the noble gas that has the same electron configuration as the anions in question 6(b).

## Structure and properties of ionic substances

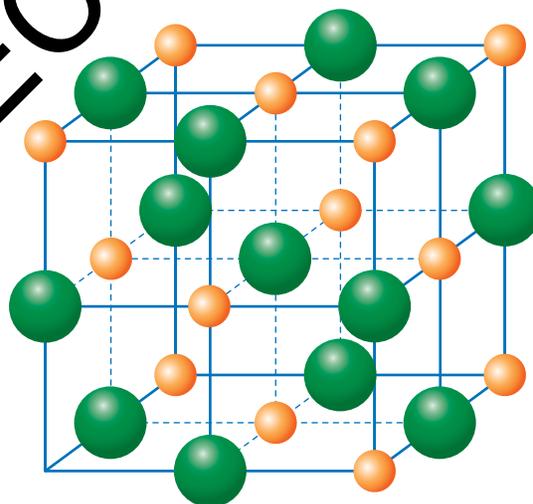
Like most ionic substances, sodium chloride is a hard, brittle crystalline solid at room temperature. It has a high melting point (800 °C). This indicates that its particles are arranged in repeating three-dimensional patterns and are strongly held together. When sodium chloride is dissolved in water or is melted, its crystal structure breaks down and in both these states it is able to conduct electricity, indicating that charged particles (ions) are free to move.

How can we explain the distinctive composition, melting point and conductivity characteristics of ionic substances? What is it about the structure of these substances that makes them behave so uniquely?

### Ionic lattices

The major features of the current theory of the structure of ionic substances are as follows.

- Ionic compounds form crystals that are composed of three-dimensional arrays of positive metal ions and negative non-metal ions.
- These arrays are called ionic network lattices and are held together by the strong electrostatic attraction — the ionic bond — between the oppositely charged ions.
- The ions are arranged in a regular repeating pattern throughout the crystal. They pack together in the way that will achieve the most stable arrangement, with oppositely charged ions as close together as possible, and similarly charged ions as far apart as possible. Each cation is thus surrounded by anions and each anion by cations.



Na<sup>+</sup> sodium ions

Cl<sup>-</sup> chloride ions

## Interactivities

Ionic models

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Pass the salt

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## study on

Unit 1

Crystal structure

AOS 1

Summary screen

Topic 4

and practice

Concept 3

questions

- The relative numbers of cations and anions are fixed by the requirement that the solid is neutral.
- The relative sizes and numbers of the ions present determine the actual lattice structure.

Sodium chloride is a typical ionic compound. Its appearance and ionic structure are shown below. Its crystals are cubic, reflecting the regular arrangement of the ions in the lattice. Each sodium ion is surrounded by six chloride ions and each chloride ion is surrounded by six sodium ions. In this arrangement, each ion is strongly attracted to each of its neighbours. The large attractive forces result in a very stable structure.



Sodium chloride crystals are cube-shaped owing to the regular cubic arrangement of the sodium and chloride ions. Each chloride ion is surrounded by six sodium ions, and each sodium ion is surrounded by six chloride ions.

The formula of the ionic substance sodium chloride is NaCl, which means that the ratio of positive to negative ions is 1:1. The formula NaCl does not represent a distinct molecule of sodium chloride but simply means that a sample of sodium chloride contains equal numbers of sodium ions and chloride ions. The formula  $\text{MgBr}_2$  signifies that a sample of magnesium bromide contains twice as many bromide ions as magnesium ions.

A chemical formula given for an ionic compound is called an empirical formula. This refers to the simplest ratio of ions in the lattice.

## Revision question

8. Magnesium chloride,  $\text{MgCl}_2$ , and potassium chloride, KCl, are typical ionic compounds.
- Describe how their ionic lattice structure is formed from their respective atoms.
  - Show why their empirical formulas have ratios of 1:2 and 1:1 respectively.
  - Explain what holds the ions close together in their lattice structures.

The empirical formula is the simplest ratio of ions in the ionic lattice.

The properties of ionic compounds can be explained by their structures.

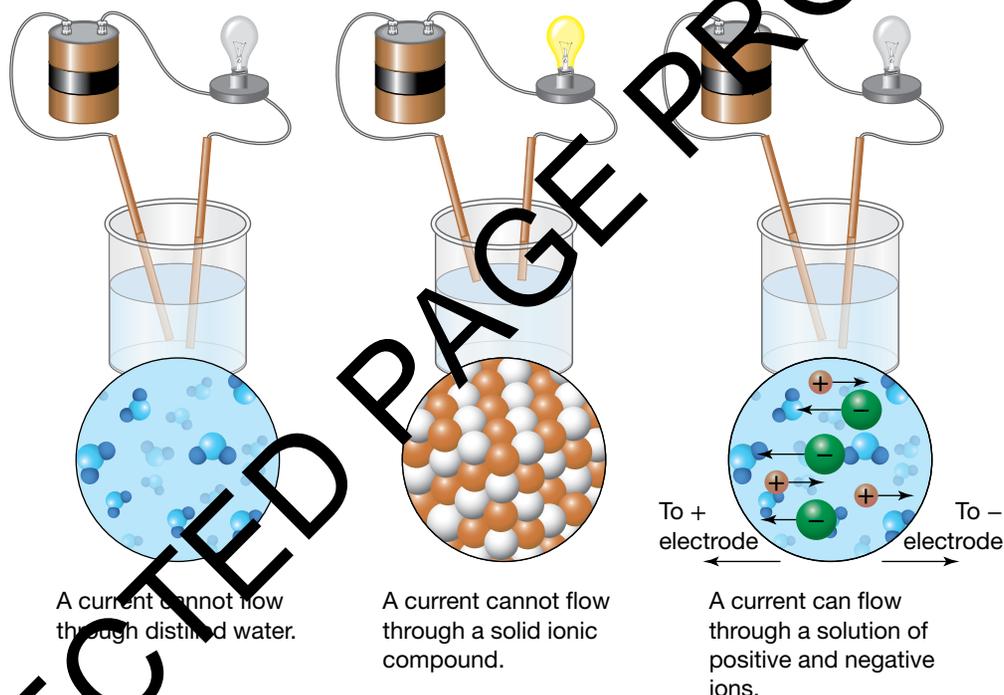
**study on**

- Unit 1 **Properties of ionic compounds**
- AOS 1 Summary screen and practice questions
- Topic 4
- Concept 1

## Connecting properties of ionic compounds to structure

Ionic compounds are composed of two or more different kinds of ions that have opposite charges. The electrostatic forces of attraction holding them together are strong. As a result of this, ionic compounds:

- are usually crystalline solids, owing to the arrangement of ions in repeating three-dimensional patterns
- have high melting and boiling points, as a large amount of energy is needed to separate the ions
- do not conduct electricity in the solid form, as the charged particles (ions) are not able to move (to conduct electricity, a substance must contain mobile charged particles)



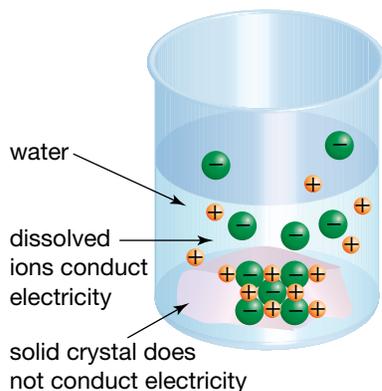
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Experiment 3.1 Investigating electrical crystals  
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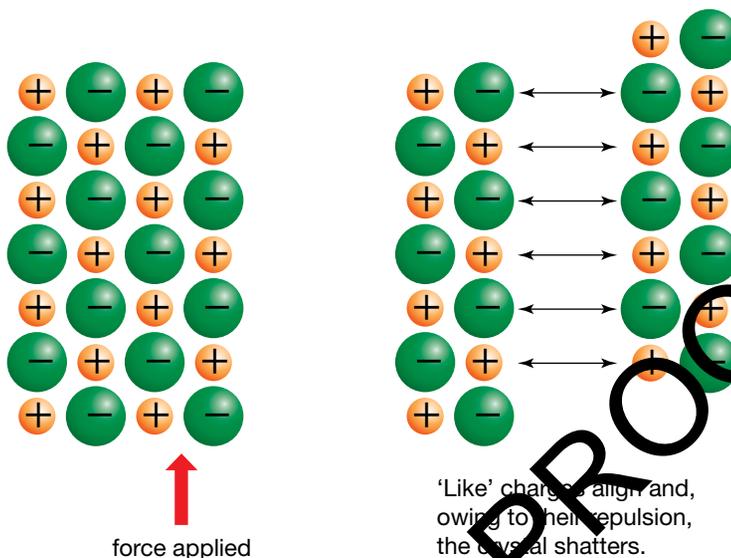
An electrolyte has ions that are free to move. It can be a molten ionic compound or an aqueous solution of an ionic compound.

- are hard, since the surface of the crystal is not easily scratched due to the strong ionic bond holding the ions together
- often dissolve in water to form ions, because water molecules are able to move between ions and free them by disrupting the rigid crystal structure
- conduct electricity when molten or in aqueous solution (dissolved in water). In the molten form, ions are able to slide past one another and can therefore conduct electricity. When an ionic substance is dissolved in water, the ions



Dissociation of sodium chloride to form a conducting solution called an electrolyte

- dissociate from the lattice and can move freely to conduct an electric current. The solution is called an **electrolyte**.
- are brittle, since distortion of the crystal causes ions of like charge to come close together and the repulsion between these ions cleaves or shatters the crystal, as shown in the figure on the next page. If the distortion of the crystal is caused by a sharp blow along the plane of ions, cleavage (a clean split) along the plane occurs. If the blow is along different planes of ions, the crystal lattice shatters.



The brittle nature of an ionic compound, which cleaves or shatters when distorted

### Revision questions

9. Calcium chloride is a crystalline substance at room temperature. Predict whether it:
- has a low or high melting point
  - shatters when pressure is applied
  - conducts electricity in the solid or liquid state.
- Justify your predictions.
10. (a) Compare the ratio of positive to negative ions in the lattice of:
- sodium chloride
  - magnesium oxide.
- (b) Which of these compounds would you expect to have the higher melting point? Give a reason for your choice.
11. A solid substance has a high melting point, conducts electricity only in molten form and cleaves when struck with a sharp knife. However, it does not readily dissolve in water. Is this enough data to predict the chemical bonding in this substance? Explain in terms of the limitations of the bonding model.
12. Atom X, having one electron in its outer shell, combines with atom Y, which has six electrons in its outer shell.
- Write the formula of the compound formed.
  - Name the type of bonding in the compound.
  - Predict three general properties of the compound.

## Naming ionic compounds

Knowing how to write formulas is a skill that all chemists require. There are many known compounds and to memorise them all would be impossible. Chemists have developed a set of rules that allow us to predict the formulas of many compounds. Some compounds that have been known for many years also have common names, as listed in table 3.2.

**TABLE 3.2** Common ionic compounds

Common name	Systematic name	Formula	Used to manufacture
salt	sodium chloride	NaCl	chlorine
soda ash	sodium carbonate	Na <sub>2</sub> CO <sub>3</sub>	glass
baking soda	sodium hydrogen carbonate	NaHCO <sub>3</sub>	cake raising agent
lime	calcium oxide	CaO	mortar
limestone	calcium carbonate	CaCO <sub>3</sub>	cement
potash	potassium nitrate	KNO <sub>3</sub>	gunpowder
milk of magnesia	magnesium hydroxide	Mg(OH) <sub>2</sub>	laxative or antacid
gypsum	calcium sulfate	CaSO <sub>4</sub>	plaster
caustic soda	sodium hydroxide	NaOH	soap or drain cleaner

## Formulas of binary ionic compounds

A binary compound contains only two elements.

In a **binary** ionic compound, only two elements are present. Examples include sodium chloride, NaCl, calcium fluoride, CaF<sub>2</sub>, and potassium nitride, K<sub>3</sub>N. Note that the word 'binary' does not refer to the relative number of ions or subscripts. When writing empirical formulas for binary ionic compounds, the following rules should be followed:

- Write the symbol for the cation first, followed by the symbol for the anion.
- Determine the lowest whole number ratio of ions that provides a net charge of zero.

The 'cross over' method is another way to determine formulas, using the charges of the ions. For example, to obtain the formula for aluminium sulfide, the symbol for the cation is written first, followed by the symbol for the anion: Al<sup>3+</sup>S<sup>2-</sup>. The charges are then crossed over so that the charge of the anion becomes the subscript of the cation and the charge of the cation becomes the subscript of the anion.



The formula is then written showing only the subscripts. Note that subscripts must always be reduced to the smallest possible whole numbers. (For example, the formula of magnesium oxide is MgO, not Mg<sub>2</sub>O<sub>2</sub>.)

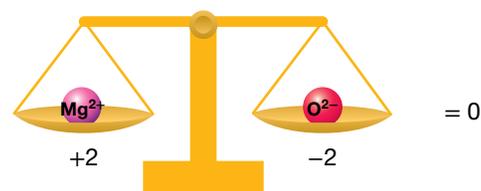
### Sample problem 3.4

Write formulas for the following compounds:

- magnesium oxide
- potassium oxide
- aluminium sulfide.

**Solution:**

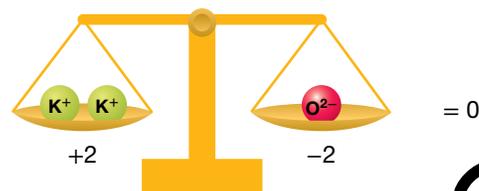
- The symbols for the cation and anion in the compound are Mg<sup>2+</sup> and O<sup>2-</sup> respectively. In order to have a net charge of zero, the number of positive charges must be balanced by an equal number of negative charges. Thus one Mg<sup>2+</sup> ion is balanced by one O<sup>2-</sup> ion and the ratio of ions is 1 : 1.



The formula is written as MgO.

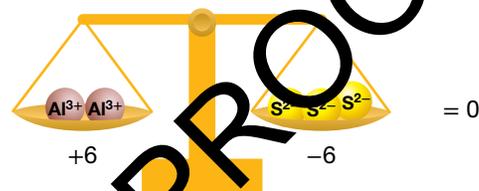
The number of positive charges must be balanced by an equal number of negative charges.

(b) The symbols for the cation and anion in the compound are  $K^+$  and  $O^{2-}$  respectively. In order to have a net charge of zero, two positively charged potassium ions are needed to balance the two negative charges of the oxide ion. The ratio of ions is 2 : 1.



The formula is written as  $K_2O$ . The subscript numeral '2' indicates that there are two potassium ions for every oxide ion.

(c) The symbols for the cation and anion in the compound are  $Al^{3+}$  and  $S^{2-}$  respectively. In order to have a net charge of zero, two  $Al^{3+}$  ions, with a total charge of 6+, are needed to balance three  $S^{2-}$  ions, with a total charge of 6-. The ratio of ions is 2 : 3.



The formula is written as  $Al_2S_3$ .

### Sample problem 3.5

Name the compound  $MgF_2$ .

**Solution:** First name the cation from the metallic element it came from: magnesium. Then add the name of the anion with the ending *-ide*: fluoride. The compound  $MgF_2$  is known as magnesium fluoride.

### Revision questions

13. Write the formula for the ionic compound formed between each of the following sets of ions:
- (a) aluminium and chlorine                      (c) sodium and sulfur  
(b) barium and oxygen                              (d) magnesium and phosphorus.
14. Complete the table below by writing the formulas for the compounds formed when each cation is bonded to each anion.

Ions	$K^+$	$Ca^{2+}$	$Al^{3+}$
$F^-$			
$O^{2-}$			
$N^{3-}$			

15. Name the nine compounds formed in question 14.
16. Name the following compounds:
- (a)  $KCl$     (c)  $Na_3N$ .  
(b)  $Ag_2S$

### Sample problem 3.6

Write the formula for the ionic compound formed between magnesium and chlorine (use table 3.3 on page 57).

**Solution:** Magnesium ions have a charge of 2+ and chloride ions have a charge of 1-, so two chloride ions are needed to balance the charge on magnesium. Therefore, the formula is  $MgCl_2$ .

Atoms of transition metals can form ions with different charges: for example,  $\text{Fe}^{2+}$  and  $\text{Fe}^{3+}$ .

## Ions of variable charge

As the atomic number increases, atoms become larger and have more electrons. Some transition metals have quite complicated arrangements of electrons and may be able to form more than one type of ion. Such ions have different charges. This is very significant as ions of the same element with different charges have different physical and chemical properties. For example, a solution of  $\text{Cr}^{6+}$  is orange, whereas a solution of  $\text{Cr}^{3+}$  is yellow, as shown below.

Elements that have ions of variable charge can form two or more different binary ionic compounds containing the same element. Iron, for example, can form black  $\text{FeO}$  and brown  $\text{Fe}_2\text{O}_3$ , each with different physical and chemical properties. This means we must name them differently, since simply saying iron oxide is ambiguous. Therefore, we use roman numerals in brackets after the cation's name to denote its charge. For example, the black  $\text{FeO}$  contains  $\text{Fe}^{2+}$  ions, and so it is called iron(II) oxide. The brown  $\text{Fe}_2\text{O}_3$  contains  $\text{Fe}^{3+}$  ions and is named iron(III) oxide.

Metal ions that form more than one cation include iron(II) and (III), copper(I) and (II), and mercury(I) and (II). Note that the roman numerals do not indicate the numbers of ions present in the compound, only the charge of the ion.



These solutions are different in colour. The orange flask contains  $\text{Cr}^{6+}$  ions, and the yellow flask contains  $\text{Cr}^{3+}$  ions. When chromium reacts with other chemicals, often  $\text{Cr}^{3+}$  changes to  $\text{Cr}^{6+}$ . The colour change can indicate that a reaction has occurred.

### Sample problem 3.7

- Name the compound  $\text{CuO}$ .
- Give the formula for iron(II) chloride.

**Solution:**

- In order to determine the charge on the metal ion, we work backwards from the known charge on the anion. The charge on the oxide ion is  $2-$ . Therefore, for a net charge of zero, the charge on the Cu ion must be  $2+$ . The compound is therefore named copper(II) oxide.
- Iron(II) means that the  $\text{Fe}^{2+}$  ion is present in the compound. The chloride ion has a charge of  $1-$ . To balance the  $2+$  of the Fe ion for a net charge of zero, two chloride ions are needed. The formula is  $\text{FeCl}_2$ .

## Revision questions

17. Name the following compounds:
- |                                    |                       |                       |
|------------------------------------|-----------------------|-----------------------|
| (a) FeS                            | (c) CuCl <sub>2</sub> | (e) Cu <sub>2</sub> O |
| (b) Fe <sub>2</sub> S <sub>3</sub> | (d) SnO               | (f) PbBr <sub>2</sub> |
18. Give the formula for each of the following compounds:
- |                       |                       |
|-----------------------|-----------------------|
| (a) tin(IV) fluoride  | (d) iron(III) nitride |
| (b) lead(II) sulfide  | (e) copper(I) sulfide |
| (c) mercury(II) oxide | (f) tin(II) oxide.    |

## Polyatomic ions

A polyatomic ion is a bound group of atoms with an overall charge.

A **polyatomic ion** is a group of tightly bound atoms that behave as a single unit and carries an overall charge. It may be a positively or negatively charged ion. The carbonate ion, for example, is composed of one carbon atom and three oxygen atoms. The *whole group* of four atoms carries a negative two charge.

<p>(a)  2-</p> <p>This group of four atoms carries a 2- charge and is written:</p> <div style="display: flex; align-items: center; gap: 10px;"> <div style="border: 1px dashed black; padding: 5px;">C</div> <div style="border: 1px dashed black; padding: 5px;">O<sub>3</sub></div> <div style="border: 1px dashed black; padding: 5px;">2-</div> </div> <p>one carbon atom joined to three oxygen atoms</p> <p>one carbon atom    three oxygen atoms    2- charge on the ion</p>
<p>(b)  +</p> <p>This group of five atoms carries a 1+ charge and is written:</p> <div style="display: flex; align-items: center; gap: 10px;"> <div style="border: 1px dashed black; padding: 5px;">N</div> <div style="border: 1px dashed black; padding: 5px;">H<sub>4</sub></div> <div style="border: 1px dashed black; padding: 5px;">+</div> </div> <p>one nitrogen atom joined to four hydrogen atoms</p> <p>one nitrogen atom    four hydrogen atoms    1+ charge on the ion</p>

These diagrams show two polyatomic ions: (a) the anion carbonate and (b) the cation ammonium.

Ionic compounds consist of arrays of cations and anions. A table of charges may be used to help write the empirical formula of an ionic compound (see table 3.3).

### Sample problem 3.8

Write the formula for the compound ammonium phosphate.

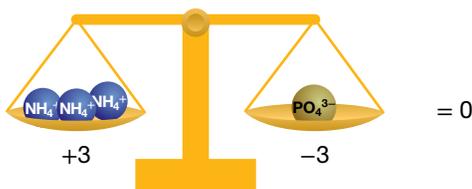
**Solution:** The method for writing the formula for this compound is the same as that for a binary ionic compound.

#### STEP 1

Write the symbol for the cation followed by the symbol for the anion. The cation is NH<sub>4</sub><sup>+</sup> and the anion is PO<sub>4</sub><sup>3-</sup>.

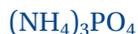
#### STEP 2

Since the net charge must be zero, we need three NH<sub>4</sub><sup>+</sup> ions for every PO<sub>4</sub><sup>3-</sup> ion.



### STEP 3

Place brackets around the entire ammonium ion so that the subscript 3 applies to all of it. The formula is:



Note that brackets need to be used whenever more than a single polyatomic ion is needed to balance a formula. This is the only time they are used.

**TABLE 3.3** Anions and cations

Cations					
+1		+2		+3	
lithium	Li <sup>+</sup>	magnesium	Mg <sup>2+</sup>	aluminium	Al <sup>3+</sup>
sodium	Na <sup>+</sup>	calcium	Ca <sup>2+</sup>	chromium(III)	Cr <sup>3+</sup>
potassium	K <sup>+</sup>	barium	Ba <sup>2+</sup>	iron(III)	Fe <sup>3+</sup>
caesium	Cs <sup>+</sup>	iron(II)	Fe <sup>2+</sup>		
silver	Ag <sup>+</sup>	nickel	Ni <sup>2+</sup>		
copper(I)	Cu <sup>+</sup>	chromium(II)	Cr <sup>2+</sup>		
ammonium	NH <sub>4</sub> <sup>+</sup>	copper(I)	Cu <sup>2+</sup>		
		zinc	Zn <sup>2+</sup>		
		tin(II)	Sn <sup>2+</sup>		
		lead(II)	Pb <sup>2+</sup>		
		manganese(II)	Mn <sup>2+</sup>		
		mercury(II)	Hg <sup>2+</sup>		
		strontium	Sr <sup>2+</sup>		

Anions					
-1		-2		-3	
hydride	H <sup>-</sup>	oxide	O <sup>2-</sup>	nitride	N <sup>3-</sup>
fluoride	F <sup>-</sup>	sulfide	S <sup>2-</sup>	phosphide	P <sup>3-</sup>
chloride	Cl <sup>-</sup>	sulfate	SO <sub>4</sub> <sup>2-</sup>	phosphate	PO <sub>4</sub> <sup>3-</sup>
bromide	Br <sup>-</sup>	carbonate	CO <sub>3</sub> <sup>2-</sup>		
iodide	I <sup>-</sup>	sulfite	SO <sub>3</sub> <sup>2-</sup>		
hydroxide	OH <sup>-</sup>	dichromate	Cr <sub>2</sub> O <sub>7</sub> <sup>2-</sup>		
nitrate	NO <sub>3</sub> <sup>-</sup>	chromate	CrO <sub>4</sub> <sup>2-</sup>		
hydrogen carbonate	HCO <sub>3</sub> <sup>-</sup>	thiosulfate	S <sub>2</sub> O <sub>3</sub> <sup>2-</sup>		
hydrogen sulfate	HSO <sub>4</sub> <sup>-</sup>	hydrogen phosphate	HPO <sub>4</sub> <sup>2-</sup>		
chlorate	ClO <sub>3</sub> <sup>-</sup>				
hydrogen sulfite	HSO <sub>3</sub> <sup>-</sup>				
nitrite	NO <sub>2</sub> <sup>-</sup>				
permanganate	MnO <sub>4</sub> <sup>-</sup>				
hypochlorite	OCl <sup>-</sup>				
dihydrogen phosphate	H <sub>2</sub> PO <sub>4</sub> <sup>-</sup>				
cyanide	CN <sup>-</sup>				

### Revision questions

19. Refer to table 3.3. Write the formula and name of each of the polyatomic ions that contains sulfur.
20. Using the charges provided in table 3.3, copy and complete the table below.

Name of ionic compound	Valency of cation	Valency of anion	Empirical formula
silver chloride			
potassium sulfide			
magnesium oxide			
aluminium bromide			
iron(III) carbonate			
barium phosphate			
ammonium sulfate			

21. Give the formulas for the following compounds:
- sodium sulfite
  - calcium nitrite
  - copper(II) hydrogen carbonate.
22. Name the compound formed when each of the following pairs of ions is bonded, and write its formula.
- $\text{Al}^{3+}$  and  $\text{CO}_3^{2-}$
  - sodium and nitrate
  - $\text{Hg}^{2+}$  and  $\text{PO}_4^{3-}$
  - lead(II) and sulfate.

### Uses of ionic compounds

Ionic compounds have a wide range of uses, as can be seen in table 3.2. Many metals are obtained from ionic compounds that have been extracted from different ores. Sodium hydrogen carbonate is used in cooking and also as an environmentally friendly cleaning agent. Ammonium nitrate is used to manufacture fertilisers as well as explosives. Compounds containing nitrate, nitrite and sulfite ions are used to preserve food. Our bodies can function only because of the presence of particular ions.

### Revision question

23. Write the formulas for the compounds and ions described in the paragraph above.

### Why do athletes take sports drinks?

An electrolyte is a substance that dissociates to form ions. Athletes sometimes take electrolyte drinks after exercise to rehydrate, boost energy and replace important ions in the body that are lost during sweating. Adequate water consumption is essential but there is much discussion about the need for these drink supplements if individuals have an adequate diet. Table 3.4 provides a list of some ions that are essential for optimum functioning of our bodies.

As we sweat, we also lose valuable electrolytes (water-soluble ionic compounds); these may be replaced by sports drinks.

**TABLE 3.4** Common ions needed in the body

Name	Symbol	Functions in the body
sodium	Na <sup>+</sup>	regulates fluid balance transmission of nerve impulses controls blood pressure by controlling blood volume acid–base balance of blood
potassium	K <sup>+</sup>	controls the level of body fluids transmission of nerve impulses and muscle contraction including heartbeat important in reactions within cells
calcium	Ca <sup>2+</sup>	needed for building teeth and bones involved in blood clotting transmission of nerve impulses and muscle contraction
magnesium	Mg <sup>2+</sup>	needed for bone formation assists in energy production functioning of muscle and nerve tissue component of enzymes
chloride	Cl <sup>-</sup>	acid–base balance of blood fluid balance in the body formation of hydrochloric acid in stomach

**Revision question**

24. Research which foods are the main sources of each of the ions listed in table 3.4.

Hydrated ionic compounds contain water molecules bonded within the crystal.

Note:

<i>mono-</i> = 1	<i>hexa-</i> = 6
<i>di-</i> = 2	<i>hepta-</i> = 7
<i>tri-</i> = 3	<i>octa-</i> = 8
<i>tetra-</i> = 4	<i>nona-</i> = 9
<i>penta-</i> = 5	<i>deca-</i> = 10

**Hydrated ionic compounds**

A number of ionic compounds, called **hydrates**, release water, which is part of their structure, when they decompose upon heating. When the formula of a hydrated compound is written, the number of water molecules is also included. For example, the formula for iron(II) sulfate octahydrate is written as FeSO<sub>4</sub>·8H<sub>2</sub>O. This formula indicates that eight molecules of water are bonded within the ionic crystal for every one formula unit of FeSO<sub>4</sub>.

The prefixes on the left are used to indicate the number of water molecules in a hydrated compound.

**Sample problem 3.9**

- (a) Name the compound ZnCl<sub>2</sub>·4H<sub>2</sub>O.  
(b) Give the formula for the compound calcium sulfate dihydrate.

**Solution:**

- (a) Name the binary ionic compound in the usual way, and then use the prefix *tetra-* for four followed by the word 'hydrate'. The name of the compound is zinc chloride tetrahydrate.

- (b) **STEP 1**

Write the symbols for the cation and anion, Ca<sup>2+</sup> and SO<sub>4</sub><sup>2-</sup>.

**STEP 2**

Balance the charges so the net charge is zero, keeping the polyatomic sulfate ion intact. Since the ions are equally charged, the formula for calcium sulfate is CaSO<sub>4</sub>.

**STEP 3**

Determine how many water molecules there are from the prefix; *di-* means 'two', so the formula is CaSO<sub>4</sub>·2H<sub>2</sub>O.

### Revision question

25. The table below shows the uses and formulas of some hydrated ionic compounds. Copy the table and fill in either the formula for the compound or its name. The first one is done for you.

Name of hydrated ionic compound	Common name(s); use; description	Formula
copper(II) sulfate pentahydrate	blue vitriol; copper plating; blue solid	$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$
sodium carbonate decahydrate	washing soda, soda ash; water softener; white solid	(a)
(b)	Epsom salts; explosives, matches; white solid	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$
magnesium chloride hexahydrate	disinfectants, parchment paper; white solid	(c)
(d)	dyeing fabrics, tanning leather; white solid	$\text{BaCl}_2 \cdot 2\text{H}_2\text{O}$

## Growing ionic crystals

Ionic compounds form crystals of many interesting shapes depending on the arrangement of ions in the lattice, but the different sizes of crystals are caused by the diverse conditions in which they are formed. The largest natural crystals found have been in Chihuahua, Mexico, and these are over 12 metres long; the smallest fit into the nanoscale range.

Crystals of a more manageable size can be prepared in a school laboratory from saturated solutions, which are solutions in which no more solid (solute) will dissolve. To form a saturated solution, it is heated while the solute is added; this assists the dissolving process. As the solution cools, the water (or

other solvent) evaporates and small crystals appear.

To produce a larger crystal, a regularly shaped crystal can be selected and suspended by a thread in a saturated solution and the crystal will grow. This crystal is called the seed crystal, and it provides a nucleation site, a point where crystallisation can begin. Dust particles or scratches on a glass container can also act as nucleation sites. The rate of evaporation affects the size of the crystal formed.

Recrystallisation processes are very useful to chemists for purifying substances, because impurities cannot form part of the growing crystal structure.



These vanadinite crystals are hexagonal in shape and are a source of the element vanadium.

# Chapter review

## Summary

- Ions are formed when atoms lose or gain electrons to achieve the stable electron configuration of a noble gas.
  - Metals lose electrons in order to gain a full outer shell and become positively charged ions called cations.
  - Non-metals gain electrons to obtain a full outer shell and become negatively charged ions called anions.
  - Whether an atom gains or loses electrons depends on its electronegativity, or electron-attracting power.
- In the periodic table, the group numbers 1, 2, 13, 15, 16 and 17 have the charge 1+, 2+, 3+, 3-, 2- and 1- respectively. Group 14 and group 18 elements do not readily form ions.
- There are three types of chemical bond:
  - ionic bond
  - metallic bond
  - covalent bond.
- Ionic bonding is produced by the strong electrostatic attraction that results between ions when a metallic atom transfers electrons to a non-metallic atom. The ionic compound formed:
  - is known as a salt
  - is made up of an ionic network lattice of positive cations and negative anions
  - is neutrally charged; that is, the total positive charge of the cations must equal the total negative charge of the anions
  - can be represented by a formula unit, which shows the smallest whole number ratio of cation to anion, when charges are balanced. This is also called the empirical formula.
- The structure and bonding of ionic compounds has a direct influence on their properties. Ionic network lattices are rigid structures of cations bonded to anions. Ionic compounds:
  - do *not* conduct electricity in the solid state but become electrolytes when in aqueous or molten states, when their rigid structures have broken down sufficiently to allow free movement of their ions
  - are brittle as pressure causes like charges to align, resulting in the structure shattering
  - are often soluble in water, whose molecules disrupt the lattice and allow free mobile ions to form
  - are usually crystalline solids due to the close-packed, three-dimensional lattice structure
  - have high melting and boiling points due to the strong force of attraction between the ions.

- The key rules in naming ionic compounds and writing their formulas are:
  - When naming a binary ionic compound, always name the metal ion in full first and then add the non-metal ion with the ending *-ide* (e.g. lithium oxide).
  - To find the correct formula for an ionic compound, determine the lowest whole number ratio of ions that gives a net charge of zero.
  - When naming ionic compounds that contain metal ions with more than one charge, such as iron(II) and (III), copper(I) and (II), lead(II) and (IV), mercury(I) and (II), and tin(II) and (IV), use roman numerals to indicate which ion is present (CuS is copper(II) sulfide.) Note that the Roman numerals indicate the charge of the ion rather than the number of ions present in the compound.
  - When there is more than one polyatomic ion in the formula of an ionic compound, the usual rules of naming apply, but use brackets to separate the ions in the formula (e.g. ammonium carbonate is  $(\text{NH}_4)_2\text{CO}_3$ ).  
For hydrates, use the prefixes *mono-*, *di-*, *tri-*, *tetra-*, *penta-*, *hexa-*, *hepta-*, *octa-*, *nona-* and *deca-* to indicate the number of water molecules in the compound (e.g.  $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$  is copper(II) sulfate pentahydrate).
- The size of a crystal depends on the conditions during its formation.

## Multiple choice questions

1. When an atom loses an electron:
  - A a positive ion is formed
  - B a negative ion is formed
  - C the atomic number changes
  - D the atomic mass changes.
2. Sodium atoms and sodium ions:
  - A are identical in their chemical properties
  - B have the same number of electrons
  - C have the same number of protons
  - D have the same number of protons and electrons.
3. The elements sodium, caesium and lithium form ions with the charge in their compounds of:
  - A 1+ only
  - B 2+ only
  - C 3+ only
  - D 1+ or 2+ only.
4. Which of the following ions does not have the same electron configuration as an oxide ion,  $\text{O}^{2-}$ ?
 

A $\text{N}^{3-}$	C $\text{S}^{2-}$
B $\text{F}^-$	D $\text{Al}^{3+}$



2. (a) What is the electron configuration of the calcium atom?
  - (b) What is the electron configuration of the fluorine atom?
  - (c) Describe what happens when the calcium and fluorine atoms react chemically.
  - (d) Use an electron shell diagram to illustrate your answer to part (c).
  - (e) What holds the ions together in a crystal?
  - (f) What is the ratio of calcium ions to fluoride ions?
3. Cations form from metallic elements. Using an example, show how this occurs.

### Ionic bonding

4. In a sample of potassium chloride (an important electrolyte in the human body), the number of  $K^+$  ions and  $Cl^-$  ions are equal. In a sample of potassium oxide, however, the numbers of each ion are not equal. State the ratio of each ion in the potassium oxide and explain why they are not equal.
5. Write simple equations and electron shell diagrams to show what happens when the following pairs of atoms bond.
 

(a) K and F	(c) Be and Cl
(b) Al and O	

### Properties and structure of ionic substances

6. Explain why ionic salts conduct electricity in the molten and aqueous states but not in the solid state.
7. Draw diagrams to illustrate the brittle nature of salt.
8. Explain why ionic substances have high melting points and are usually crystalline solids at room temperature.
9. A compound made up of X and Y atoms has the following properties:
  - It has a high melting point and boiling point.
  - It is very soluble in water but not in kerosene.
  - It conducts electricity in the liquid or aqueous state but not in the solid state.
  - The electron configuration of an atom of X is  $2, 8, 2$ , while that of Y is  $2, 6$ .
  - (a) What is the formula for the compound?
  - (b) What type of bonding must it have?
  - (c) Write a simple equation showing how the bonding is attained.

### Binary and polyatomic ionic compounds

10. Using table 3.3, write the formulas for the following compounds.
  - (a) magnesium sulfate
  - (b) zinc oxide
  - (c) iron(II) hydroxide
  - (d) silver chloride

- (e) aluminium nitride
- (f) calcium carbonate
- (g) calcium hydrogen carbonate
- (h) lead(II) iodide
- (i) potassium hydrogen sulfate
- (j) ammonium carbonate
- (k) silver sulfate
- (l) tin(II) chloride
- (m) potassium sulfate
- (n) sodium fluoride
- (o) barium nitrate
- (p) iron(III) hydroxide
- (q) sodium sulfide
- (r) aluminium oxide
- (s) calcium hydride
- (t) copper(II) sulfate
- (u) ammonium hydroxide
- (v) chromium(III) oxide
- (w) calcium nitrate
- (x) lithium chloride
- (y) potassium cyanide
- (z) sodium hydrogen phosphate

11. Give the names of the following compounds.

- |                    |                    |
|--------------------|--------------------|
| (a) $Fe_2O_3$      | (g) $Al_2(CO_3)_3$ |
| (b) $Al_2(SO_4)_3$ | (h) $Na_2SO_4$     |
| (c) $CaCl_2$       | (i) $AgNO_3$       |
| (d) $Mg(NO_3)_2$   | (j) $NaOH$         |
| (e) $BaSO_4$       | (k) $KNO_3$        |
| (f) $ZnCl_2$       | (l) $PbCl_2$       |

12. Give the chemical name and formula for each of the following compounds.

- (a) Soda ash is the common name of a compound containing sodium ions and carbonate ions.
- (b) Baking soda is commonly used in baking cakes and is composed of sodium and hydrogen carbonate ions.
- (c) Chalk, marble and limestone are all composed of calcium ions and carbonate ions.

### Hydrated ionic compounds

13. Write the formulas for the following compounds.

- (a) magnesium sulfate heptahydrate
- (b) sodium carbonate decahydrate
- (c) zinc chloride hexahydrate
- (d) barium chloride dihydrate

14. Name the following compounds.

- (a)  $BaCl_2 \cdot 3H_2O$
- (b)  $LiCl \cdot 4H_2O$
- (c)  $CoCl_2 \cdot 5H_2O$

15. Sodium chloride is used as a typical example of an ionic compound. Research the effects of too little or too much sodium chloride on the body.

16. Prepare a fact sheet outlining the advantages and disadvantages of sports drinks.

17. Find out about other ions and their importance to human health.



## Exam practice questions

In a chemistry examination, you will be required to answer a number of short and extended response questions.

### Multiple choice questions

- Potassium chloride is an ionic compound. Which one of the following statements about potassium chloride is *incorrect*?
  - It has a high melting point.
  - It conducts electricity in all physical phases.
  - It is soluble in water.
  - Its ions are fixed in a crystal lattice that is brittle.

1 mark
- $X$  and  $Y$  are elements. The ionic compound  $XY_2$  is known to exist. If  $X^{2+}$  and  $Y^-$  both have the same electron configuration as the neon atom, then  $XY_2$  is:
  - magnesium fluoride
  - magnesium chloride
  - magnesium bromide
  - calcium fluoride.

1 mark

### Extended response questions

- Predict the charges on the ions formed when the following atoms react with other atoms.
  - Ca
  - P
  - Al

3 marks
- Oxygen gas, which forms about 20% of the Earth's atmosphere and is essential to life, exists as  $O_2$  molecules. Explain why ionic bonding does not exist between two atoms of oxygen.

2 marks