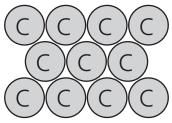
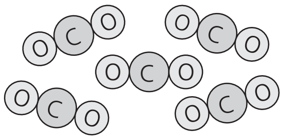
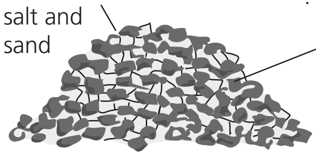
4 Bonding and structure

The big picture

- Atoms can join or 'bond' together. The purpose is to gain an outer shell of electrons like the noble gas atoms have, because that is a stable arrangement.
- There are three types of bonding: covalent, ionic, and metallic.
- The bonded atoms form a regular structure or lattice, in the solid state.
- The properties of a substance are influenced by both bonding and structure.

4.1 First, a review of some basic ideas

Elements, compounds and mixtures

Substance	What is in it?	Example
element	contains only one type of atom.	 the element carbon contains only carbon atoms
compound	contains more than one type of atom, held together by chemical bonds: ➤ the atoms are always bonded in the same ratio ➤ you cannot separate them by physical means.	 in the compound carbon dioxide, each carbon atom is always bonded to two oxygen atoms
mixture	can contain any number of different substances, in any ratio: ➤ the substances are just mixed, and *not* joined by chemical bonds. ➤ you can separate them using one of the separation methods in Section 2.	mixture of salt and sand  you can mix any amounts of salt and sand, and separate them by adding water to dissolve the salt, then filtering

Atoms and ions

Atoms and ions are closely related. What is the difference between them?

Atoms contain equal numbers of protons and electrons, so have no charge.	**Ions** are atoms or group of atoms that carry a charge, because they have gained or lost electrons.	
Examples of atoms A **sodium atom** has 11 protons and 11 electrons, so its charge is: from the protons 11+ from the electrons 11– total 0 A **chlorine atom** has 17 protons and 17 electrons, so its charge is: from the protons 17+ from the electrons 17– total 0	**Example of a positive ion** A **sodium ion** is a sodium atom that has *lost* an electron, so its charge is: from the protons 11+ from the electrons 10– total 1+ We show it as Na^+. It is called a positive ion because it has a positive charge.	**Example of a negative ion** A **chloride ion** is a chlorine atom that has *gained* an electron, so its charge is: from the protons 17+ from the electrons 18– total 1– We show it as Cl^-. It is called a negative ion because it has a negative charge.

Metals and non-metals

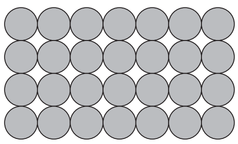
There are over 100 elements. They are all different. But they can be divided into two groups: **metals** and **non-metals**. As you will see later, the differences between the two groups are due to differences in bonding and structure.

Metals	Non-metals
readily conduct electricity and heat	do not conduct electricity or heat
are mostly malleable (can be hammered into shape) and ductile (can be drawn into wires)	are usually brittle when solid – they break up when they are hammered
tend to be shiny	look dull, when solid
tend to have high density (they are heavy)	have low density
usually have high melting points	have low melting points (many are gases at room temperature)
form positive ions, in reactions	when they form ions, these are negative (except for H^+)
usually form basic oxides (see page 88)	usually form acidic oxides (see page 88)

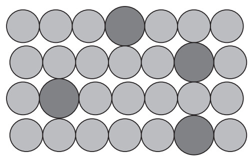
Some exceptions

- The metal mercury is a liquid at room temperature.
- Some metals, such as sodium and potassium, have low density and low boiling points.
- Hydrogen is a non-metal, but it forms positive ions, H^+.
- Diamond and graphite are two forms of carbon, a non-metal. Graphite is a soft greasy solid, and a good conductor of electricity. Diamond is very hard, with a very high melting point. Graphite and diamond have special structures, as you will see later.

Metals and alloys



Metals are **elements** so they contain only **one** type of atom.



Alloys are **mixtures**, where at least one other substance is added to the metal.

The added substances in alloys can be other metals, or non-metals such as carbon. They are chosen to improve on certain properties of a metal, and make it more useful.

Examples of alloys

Alloy	What is in it, and typical %	Special properties	Uses
brass	copper 70% zinc 30%	much harder than copper; and unlike copper it does not corrode	musical instruments, ornaments, door knobs and other fittings
stainless steel	iron 70% chromium 20% nickel 10%	unlike iron, it does not corrode	car parts, kitchen sinks, cutlery, tanks in chemical factories

✓

Quick check for 4.1 *(Answers start on page 164)*

1 Why is iron sulfide (FeS) classed as a compound?
2 Give three ways in which iron sulfide differs from a mixture of iron and sulfur.
3 Iron is a metal, and sulfur is a non-metal. Give three ways in which you expect them to behave differently.
4 Iron rusts (corrodes) easily. How would you improve on its properties?

4.2 An overview of bonding and structure

- Bonding is about how atoms are joined together.
- Structure is about how the bonded atoms are arranged.

Bonding

There are three types of bonding: covalent, ionic and metallic.

Type of bonding	covalent	ionic	metallic
Description	electrons are shared between atoms	electrons are transferred from one atom to another, forming ions	a lattice of positive ions in a sea of electrons
What kinds of atoms bond together in this way?	non-metal atoms: ➤ of the same element, or ➤ of different elements, giving compounds	metal atoms bond with non-metal atoms, to give compounds	➤ only metal atoms ➤ they are usually atoms of the same metal ➤ but an alloy has atoms of different metals
What holds the atoms together?	the bonds created by sharing electrons	the attraction between ions of opposite charge	the attraction between the positive ions and the electrons

Extended

Why do atoms bond?

Atoms bond to other atoms in order to gain the same arrangement of outer-shell electrons as a noble gas atom – because that is a stable arrangement. (See page 19.)

Remember

Outer shells of noble gas atoms:
helium – 2 electrons
neon – 8 electrons
argon – 8 electrons

Structure

In the solid state, the particles form a regular arrangement called a **lattice**.
There are two types of structure:

Structure	simple molecular	giant
Description	the lattice is built up of millions of separate small molecules	the lattice is built up of millions of particles, which can be: ➤ positive and negative ions, joined by ionic bonds, or ➤ metal ions in a sea of electrons, joined by metallic bonds, or ➤ non-metal atoms joined by covalent bonds
Example	in iodine (I_2) the lattice is made up of iodine molecules, each containing two atoms	in sodium chloride (NaCl) the lattice is made up of sodium and chloride ions
What holds the structure together?	strong covalent bonds within molecules, but weak forces between molecules	particles held together by a network of strong bonds
One result of this structure	the solid has a low melting point, since it does not take much heat energy to break up the lattice to form a liquid	the solid usually has a high melting point, since it takes a great deal of heat energy to break the bonds in the lattice

✓

Quick check for 4.2 *(Answers on page 165)*

1. Explain the difference between *bonding* and *structure*.
2. What is the main difference between an ionic bond and a covalent bond?
3. What is a *lattice*?
4. Give another name for a small group of atoms joined by covalent bonds.
5. Using information given above, describe the bonding in silver.

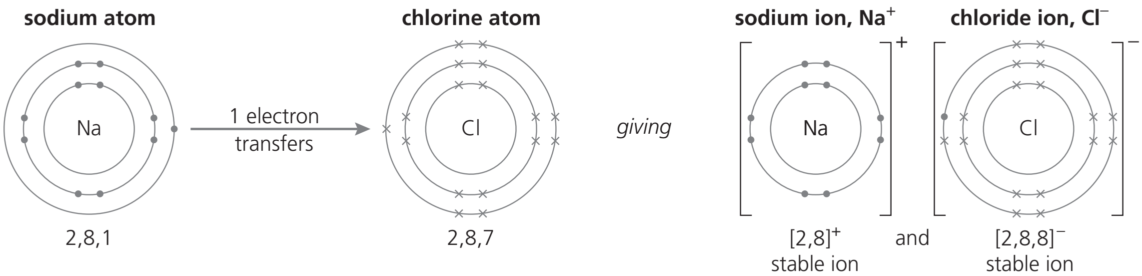
4.3 Ionic bonding

- Ionic bonds form only between metal and non-metal atoms.
- Electrons are transferred from the metal atom to the non-metal atom, to give ions of opposite charge.
- The ions are stable, because they have the same arrangement of outer-shell electrons as a noble gas atom does.
- The ions are then attracted to each other. (Opposite charges attract.)

Examples of ionic bonding

Sodium chloride

A sodium atom transfers its outer electron to a chlorine atom, giving a positive sodium ion and a negative chloride ion. These ions are stable because they have 8 electrons in their outer shells, like neon and argon atoms:

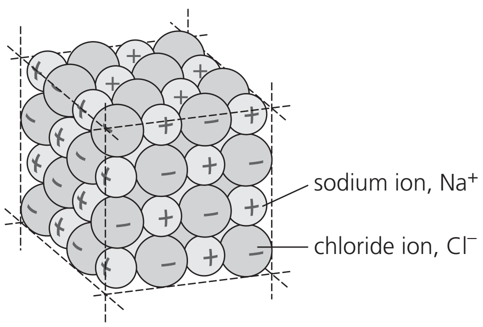


The bonding is the same in *any* compound formed between an alkali metal (Group I) and a halogen (Group VII). For example in lithium bromide (LiBr), and potassium iodide (KI).

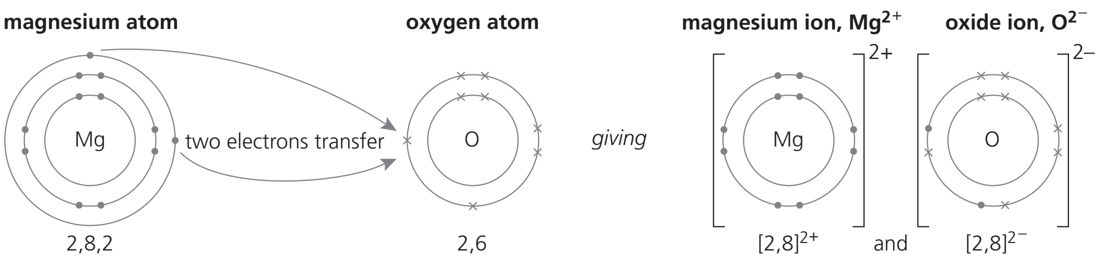
Extended

The structure of sodium chloride

Millions of ions group together to form a lattice. The lattice is a regular arrangement of alternating positive and negative ions. They are held together by the strong ionic bonds between ions of opposite charge:



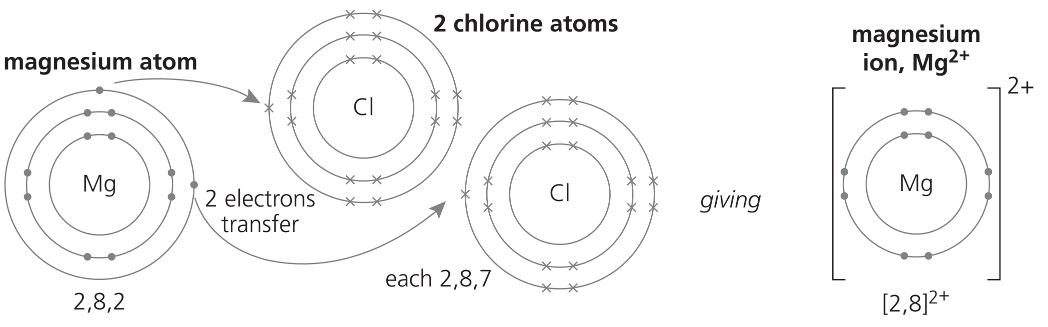
Magnesium oxide

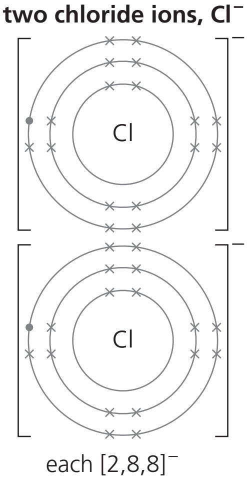


Bonding: the attraction between positive magnesium ions and negative oxide ions.
Structure: a lattice containing equal numbers of magnesium and oxide ions.

Extended

Magnesium chloride





Bonding: attraction between positive magnesium ions and negative chloride ions.
Structure: a lattice containing twice as many chloride ions as magnesium ions.

The properties of ionic compounds

- They have high melting and boiling points, because the bonds between ions are strong.
- They conduct electricity when melted or dissolved in water, because the charged ions are then free to move.
- They are usually soluble in water.

Writing the formula for an ionic compound

- An ionic compound has no overall charge.
- So the total positive charge must balance the total negative charge.
- So you adjust the number of ions in the formula, until the total charges on them balance.

Examples

Ionic compound	positive ion	negative ion	balancing their charges	so the formula is
magnesium oxide	Mg^{2+}	O^{2-}	they are balanced (2^+ and 2^-)	MgO
magnesium chloride	Mg^{2+}	Cl^-	two Cl^- ions are needed to balance one Mg^{2+} ion	$MgCl_2$
sodium oxide	Na^+	O^{2-}	two Na^+ ions are needed to balance one O^{2-} ion	Na_2O
aluminium hydroxide	Al^{3+}	OH^-	three OH^- ions are needed to balance one Al^{3+} ion	$Al(OH)_3$
calcium nitrate	Ca^{2+}	NO_3^-	two NO_3^- ions are needed to balance one Ca^{2+} ion	$Ca(NO_3)_2$

Look at the last two formulae above. They show how to use brackets, if there is more than one unit of the compound ion. (A compound ion contains atoms of different elements.)

✓

Quick check for 4.3 *(Answers on page 165)*

1 Explain *how* a sodium atom becomes a sodium ion, and *why*.
2 Draw a diagram to show the electron transfer when a lithium atom reacts with a fluorine atom.
3 Describe the structure of a solid ionic compound.
4 Draw a diagram to show the ionic bond formed between:
a calcium and oxygen atoms **b** calcium and chlorine atoms
5 Write the formula for: **a** sodium hydroxide **b** aluminium chloride
c magnesium hydroxide

4.4 Covalent bonding: simple molecules

Covalent bonds are formed when atoms share electrons.

- They are formed:
  - ➤ between the atoms in a non-metal element
  - ➤ between atoms of different non-metals, to give a compound.
- The purpose is to gain the same arrangement of outer-shell electrons as a noble gas atom – because that is a stable arrangement.
- The bonded atoms form a unit called a **molecule**.

Remember

Outer-shell electrons in the noble gases:
helium – 2 electrons (full shell)
neon – 8 electrons (full shell)
argon – 8 electrons

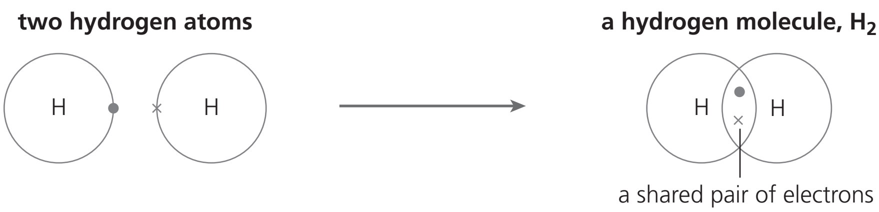
The molecules can be simple molecules with a small number of atoms, or giant molecules (macromolecules), with millions of atoms. In this section we concentrate on the simple molecules. Note that in the drawings below, only the outer electron shells are shown.

Molecular elements

Let's look first at the bonding in some non-metal elements.

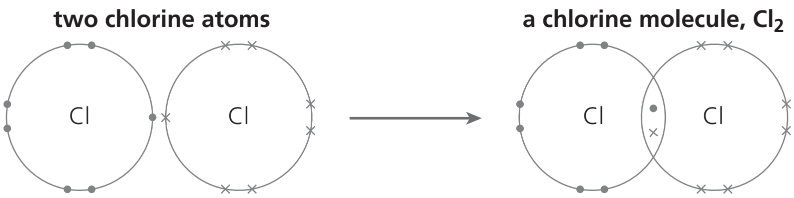
Hydrogen

A hydrogen atom has 1 electron, but needs 2 for a full shell, like a helium atom has.
So each shares its electron with another hydrogen atom, to form a hydrogen molecule, H_2.
The covalent bond is the attraction between the positive nuclei and the shared electrons.



Chlorine

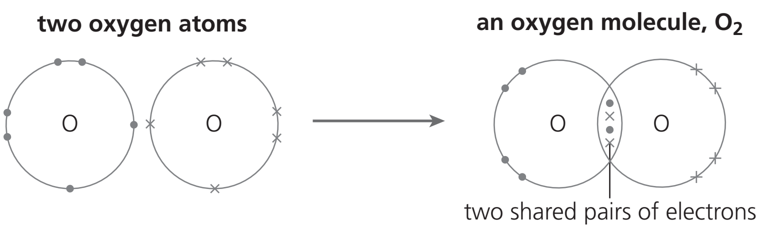
A chlorine atom shares an outer electron with another chlorine atom, to form a chlorine molecule, Cl_2. Each atom obtains an outer shell of 8 electrons, like an argon atom has.



Extended

Oxygen

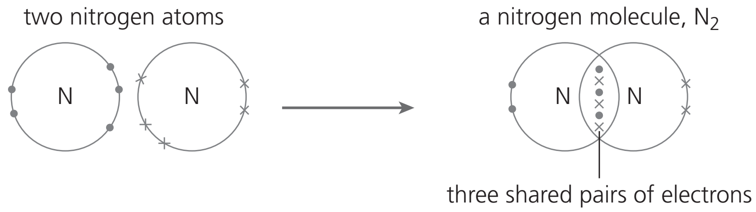
An oxygen atom shares two outer electrons with another oxygen atom, to form an oxygen molecule, O_2. Each atom obtains a full outer shell of electrons (8), like a neon atom has. Since two atoms are shared, the bond is called a **double** covalent bond (O=O).



Extended

Nitrogen

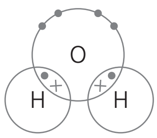
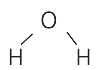
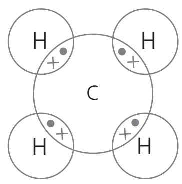
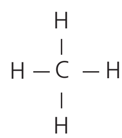
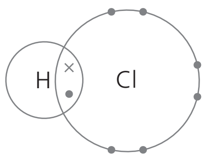
A nitrogen atom shares three outer electrons with another nitrogen atom to form a nitrogen molecule, N_2. Each atom obtains a full outer shell of electrons (8), like a neon atom has. Since three atoms are shared, the bond is called a **triple** covalent bond (N≡N).



Remember
If an atom has 4 electrons in its outer shell, they are not paired. But each extra electron after that pairs up. (Look at a nitrogen atom.)

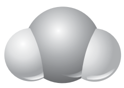
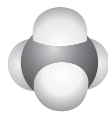
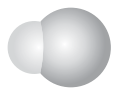
Molecular compounds

In a molecular compound, atoms share outer electrons with different atoms to form molecules. Each atom obtains an outer shell of electrons like a noble gas atom has. (Hydrogen obtains 2, others 8.) Look at these examples:

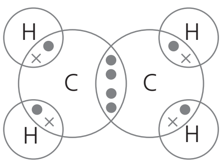
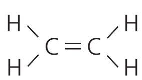
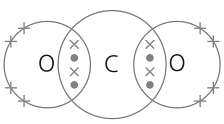
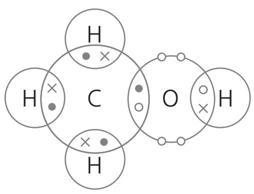
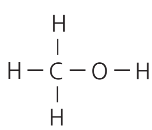
Water, H_2O	Methane, CH_4	Hydrogen chloride, HCl
 or, in a short way: 	 or 	 or H — Cl

Their shapes

Pairs of electrons repel each other, so they try to get as far apart as possible. That influences the shape of the molecule. Here are models of the three molecules above:

Water	Methane	Hydrogen chloride
 The atoms are not in a straight line because all the electron pairs (shared and unshared) repel each other.	 The four pairs of shared electrons have moved as far apart as possible, giving a tetrahedral shape.	 Here there are only two atoms, so only one possible shape: they lie in a straight line.

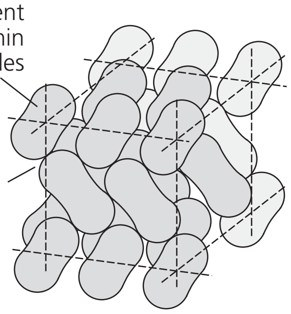
More examples of molecular compounds

Ethene, C_2H_4	Carbon dioxide, CO_2	Methanol, CH_3OH
 The molecule has a mix of single and double bonds. You can show it as: 	 The molecule has two double bonds. You can show it as: O=C=O	 The molecule has three different types of atom. You can show it as: 

Extended

Structure of simple molecular substances

In the solid, the molecules are arranged in a lattice. Look at the forces holding it together:



Properties of simple molecular substances

Substances with a simple molecular structure:

- have low melting and boiling points. This is because the intermolecular forces are weak. It does not take much heat energy to break up the lattice, and separate the particles from each other. (That is why many molecular substances are gases at room temperature.)
- do not conduct electricity, because they have no charge.
- are usually insoluble in water, but soluble in organic solvents (for example propanone).

Comparing ionic and molecular compounds

Molecular compounds (such as methane, CH_4)	Ionic compounds (such as sodium chloride, NaCl)
• have low melting and boiling points; many are gases or liquids at room temperature	• have high melting and boiling points, so they are solids at room temperature
• evaporate readily – they are volatile	• are not volatile
• do not conduct electricity	• conduct electricity
• are insoluble in water, but dissolve in organic solvents	• are usually soluble in water

✓

Quick check for 4.4 *(Answers on page 165)*

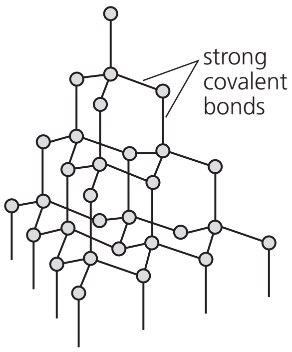
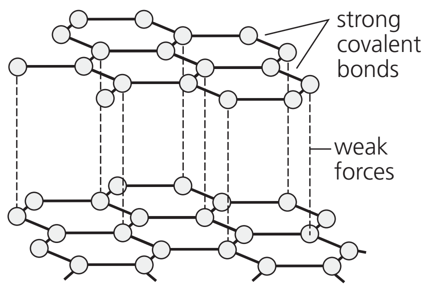
1 Explain how two hydrogen atoms become a hydrogen molecule.
2 Why are molecules stable?
3 Draw a diagram to show what happens to the electrons when carbon reacts with chlorine to form tetrachloromethane, CCl_4. (Show outer-shell electrons only.)
4 If you cool hydrogen gas down enough, it will become a liquid, and then freeze to a solid. Describe the structure of this solid.
5 Molecular compounds evaporate easily – they are *volatile*. Why is this?
6 Draw a diagram to show the covalent bonding in:
a carbon dioxide **b** nitrogen
7 Ammonia (NH_3) is a covalent compound. Draw a diagram to show the bonding in an ammonia molecule. (Show outer electrons only.)

4.5 Covalent bonding: macromolecules

Some substances with covalent bonding form **macromolecules**. A macromolecule is a giant structure (or lattice) of millions of atoms, all held together by covalent bonds.

Carbon: a macromolecular element

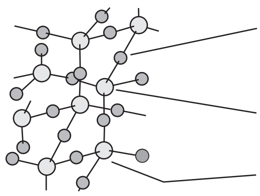
Carbon is a non-metal. It occurs in two forms or **allotropes**: diamond and graphite. Both are macromolecular. Compare them:

Form	diamond	graphite
Bonding	A carbon atom shares **all four** of its outer electrons with other carbon atoms, to form a three-dimensional lattice.	A carbon atom shares **three** of its outer electrons with other carbon atoms, to form a layer structure. The fourth electron exists between the layers and is free to move (like electrons in metals – see page 31).
Giant structure	 Each carbon atom forms a **tetrahedron** with four other carbon atoms.	 Each carbon atom becomes part of a **flat hexagonal ring**.
Forces	All the covalent bonds are identical, and strong. There are no weak forces.	The covalent bonds **within** the layers are strong. But the layers are held together by weak forces.
Properties	• very high melting point, because all the bonds are strong • very hard, for the same reason • non-conductor of electricity, because there are no electrons free to move • insoluble in water	• very high melting point, because the covalent bonds are strong • soft and slippery, because the layers slide over each other easily • good conductor of electricity, because the 'free' electrons between the layers can move • insoluble in water
Uses	cutting tools jewellery	lubricant for engines and locks electrodes for electrolysis in the lab and in industry

Extended

Silicon dioxide: a macromolecular compound

Silicon dioxide, SiO_2, is a macromolecular compound. It occurs naturally as sand and quartz.



- The bonds are strong, as in diamond. So silicon dioxide has similar properties to diamond:
  - ➤ it has a very high melting point, and is very hard
  - ➤ it is a non-conductor of electricity, and insoluble in water.
- It is used in sandpaper, and to line furnaces. (Since it occurs widely in nature, it is cheap.)

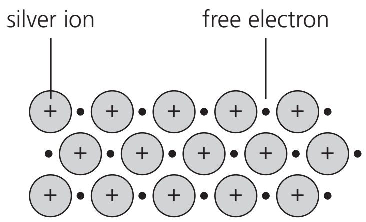
Quick check for 4.5 *(Answers on page 165)*

1 What holds the atoms together, in a macromolecule?
2 In which ways are molecules and macromolecules:
a the same? **b** different?
3 Graphite is soft and slippery, and a good conductor of electricity. Explain why it has these properties.
4 Silicon dioxide has similar properties to diamond – but not to graphite. Explain why.

4.6 Metallic bonding

Extended

- Metallic bonds are the bonds between metal atoms, in a metal or metal alloy.
- The outer electrons leave the metal atoms, giving metal ions with full outer shells. For example, in silver:



- The outer electrons form a sea of free electrons around the metal ions, in a giant lattice. (They are called 'free' electrons because they can move around freely.)
- Metallic bonds are the result of the attraction between the positive metal ions, and the free electrons.
- Metallic bonds are strong.

Explaining the properties of metals

This table shows how the bonding and structure in metals account for some of their properties:

Properties of metals	Reasons
They usually have high melting and boiling points.	They form a giant lattice, with strong bonds.
They conduct electricity, when solid and melted.	The 'free' electrons carry the electric charge through the metal.
They are malleable: they can be readily bent, pressed, or hammered into shape.	The layers of atoms can slide over each other, while the free electrons can also move (so the metallic bond is not broken).
They are ductile: they can be drawn into wires.	Same reason as above.

Quick check for 4.6 *(Answers on page 165)*

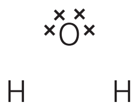
1 Describe the metallic bond.
2 What type of structure does a metal have?
3 All metals are good conductors of electricity. Why?

Questions on section 4

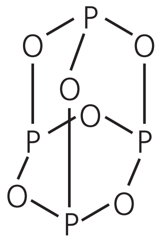
Answers for these questions are on page 165.

Core curriculum

1 **a** Complete the diagram to show the electronic structure of water:
show **hydrogen** electrons by o
show **oxygen** electrons by ×



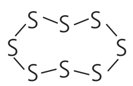
b The structure of phosphorus trioxide is shown below.



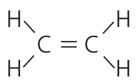
Write the simplest formula for phosphorus trioxide.

CIE 0620 November '07 Paper 2 Q1

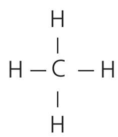
2 The structures of some elements and compounds are shown below.



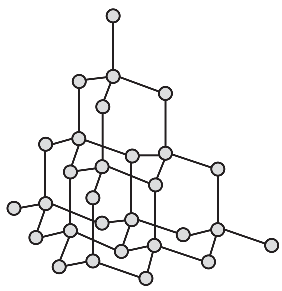
A



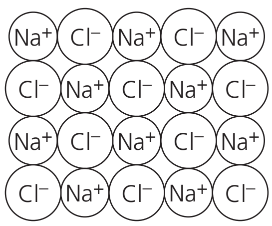
B



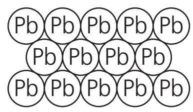
C



D



E



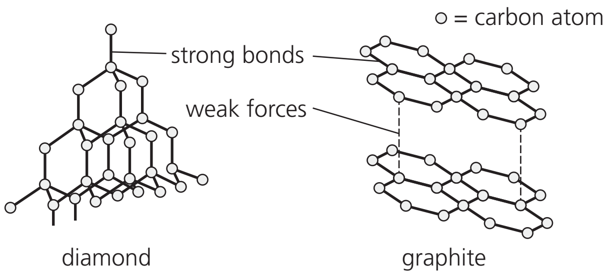
F

Answer these questions using the letters A to F.

i Which structure is methane?
ii Which structure contains ions?
iii Which structure is a metal?
iv Which structure is sodium chloride?
v Which structure is diamond?
vi Which structure contains a double covalent bond?
vii Which **three** structures are elements?

CIE 0620 June '07 Paper 2 Q1

3 Carbon exists in two forms, graphite and diamond.



Use ideas about structure and bonding to suggest:

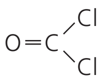
a why graphite is used as a lubricant,

b why diamond is very hard. *CIE 0620 November '07 Paper 3 Q6*

Extended

Extended curriculum

1 The structural formula of carbonyl chloride is given below.



Draw a diagram that shows the arrangement of the valency electrons in one molecule of this covalent compound.
Use x for an electron from a chlorine atom.
Use o for an electron from a carbon atom.
Use • for an electron from an oxygen atom. *CIE 0620 June '08 Paper 3 Q2*

2 Complete the following table.

Type of structure	Particles present	Electrical conductivity of solid	Electrical conductivity of liquid	Example
ionic	positive and negative ions	poor	**i**..........................	**ii**..........................
macromolecular	atoms of two different elements in a giant covalent structure	poor	poor	**iii**..........................
metallic	**iv**.......................... and **v**..........................	good	**vi**..........................	copper

CIE 0620 June '07 Paper 3 Q2

3 Magnesium reacts with bromine to form magnesium bromide.

a Magnesium bromide is an ionic compound. Draw a diagram that shows the formula of the compound, the charges on the ions, and the arrangement of outer electrons around the negative ion.
The electron distribution of a bromine atom is 2, 8, 18, 7.
Use x to represent an electron from a magnesium atom.
Use o to represent an electron from a bromine atom.

b In the lattice of magnesium bromide, the ratio of magnesium ions to bromide ions is 1:2.

i Explain the term *lattice*.

ii Explain why the ratio of the ions is 1:2. *CIE 0620 November '07 Paper 3 Q3*