4.2 Bonding, structure, and the properties of matter

Chemists use theories of structure and bonding to explain the physical and chemical properties of materials. Analysis of structures shows that atoms can be arranged in a variety of ways, some of which are molecular while others are giant structures. Theories of bonding explain how atoms are held together in these structures. Scientists use this knowledge of structure and bonding to engineer new materials with desirable properties. The properties of these materials may offer new applications in a range of different technologies.

4.2.1 Chemical bonds, ionic, covalent and metallic

4.2.1.1 Chemical bonds

There are three types of strong chemical bonds: ionic, covalent and metallic. For ionic bonding the particles are oppositely charged ions. For covalent bonding the particles are atoms which share pairs of electrons. For metallic bonding the particles are atoms which share delocalised electrons.

Ionic bonding occurs in compounds formed from metals combined with non-metals.

Covalent bonding occurs in most non-metallic elements and in compounds of non-metals.

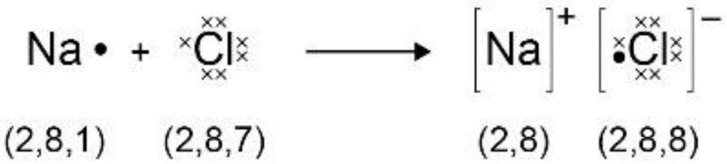
Metallic bonding occurs in metallic elements and alloys.

Students should be able to explain chemical bonding in terms of electrostatic forces and the transfer or sharing of electrons.

4.2.1.2 Ionic bonding

When a metal atom reacts with a non-metal atom electrons in the outer shell of the metal atom are transferred. Metal atoms lose electrons to become positively charged ions. Non-metal atoms gain electrons to become negatively charged ions. The ions produced by metals in Groups 1 and 2 and by non-metals in Groups 6 and 7 have the electronic structure of a noble gas (Group 0).

The electron transfer during the formation of an ionic compound can be represented by a dot and cross diagram, eg for sodium chloride



Students should be able to draw dot and cross diagrams for ionic compounds formed by metals in Groups 1 and 2 with non-metals in Groups 6 and 7.

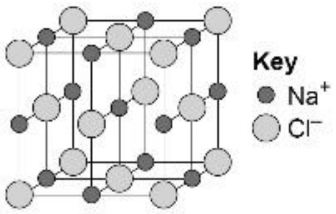
The charge on the ions produced by metals in Groups 1 and 2 and by non-metals in Groups 6 and 7 relates to the group number of the element in the periodic table.

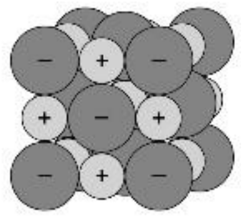
Students should be able to work out the charge on the ions of metals and non-metals from the group number of the element, limited to the metals in Groups 1 and 2, and non-metals in Groups 6 and 7.

4.2.1.3 Ionic compounds

An ionic compound is a giant structure of ions. Ionic compounds are held together by strong electrostatic forces of attraction between oppositely charged ions. These forces act in all directions in the lattice and this is called ionic bonding.

The structure of sodium chloride can be represented in the following forms:





Students should be able to:

• deduce that a compound is ionic from a diagram of its structure in one of the specified forms

• describe the limitations of using dot and cross, ball and stick, two and three-dimensional diagrams to represent a giant ionic structure

• work out the empirical formula of an ionic compound from a given model or diagram that shows the ions in the structure.

Students should be familiar with the structure of sodium chloride but do not need to know the structures of other ionic compounds.

4.2.1.4 Covalent bonding

When atoms share pairs of electrons, they form covalent bonds. These bonds between atoms are strong.

Covalently bonded substances may consist of small molecules.

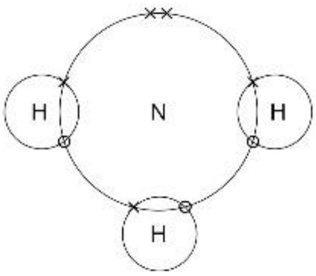
Students should be able to recognise common substances that consist of small molecules from their chemical formula.

Some covalently bonded substances have very large molecules, such as polymers.

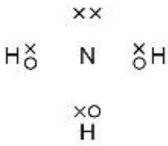
Some covalently bonded substances have giant covalent structures, such as diamond and silicon dioxide.

The covalent bonds in molecules and giant structures can be represented in the following forms:

For ammonia (NH_3)

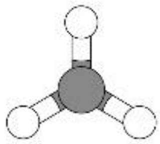


and/or

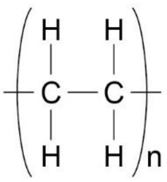


and/or

and/or



Polymers can be represented in the form:



poly(ethene)

where n is a large number.

Students should be able to:

• draw dot and cross diagrams for the molecules of hydrogen, chlorine, oxygen, nitrogen, hydrogen chloride, water, ammonia and methane

• represent the covalent bonds in small molecules, in the repeating units of polymers and in part of giant covalent structures, using a line to represent a single bond

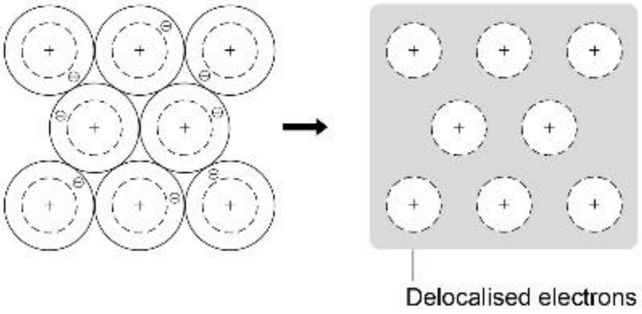
• describe the limitations of using dot and cross, ball and stick, two and three-dimensional diagrams to represent molecules or giant structures

• deduce the molecular formula of a substance from a given model or diagram in these forms showing the atoms and bonds in the molecule.

4.2.1.5 Metallic bonding

Metals consist of giant structures of atoms arranged in a regular pattern.

The electrons in the outer shell of metal atoms are delocalised and so are free to move through the whole structure. The sharing of delocalised electrons gives rise to strong metallic bonds. The bonding in metals may be represented in the following form:

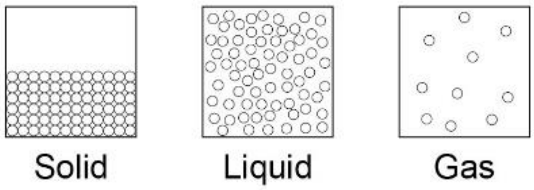


4.2.2 How bonding and structure are related to the properties of substances

4.2.2.1 The three states of matter

The three states of matter are solid, liquid and gas. Melting and freezing take place at the melting point, boiling and condensing take place at the boiling point.

The three states of matter can be represented by a simple model. In this model, particles are represented by small solid spheres. Particle theory can help to explain melting, boiling, freezing and condensing.



The amount of energy needed to change state from solid to liquid and from liquid to gas depends on the strength of the forces between the particles of the substance. The nature of the particles involved depends on the type of bonding and the structure of the substance. The stronger the forces between the particles the higher the melting point and boiling point of the substance.

(HT only) Limitations of the simple model above include that in the model there are no forces, that all particles are represented as spheres and that the spheres are solid.

Students should be able to:

• predict the states of substances at different temperatures given appropriate data

• explain the different temperatures at which changes of state occur in terms of energy transfers and types of bonding

• recognise that atoms themselves do not have the bulk properties of materials

• (HT only) explain the limitations of the particle theory in relation to changes of state when particles are represented by solid inelastic spheres which have no forces between them.

4.2.2.2 State symbols

In chemical equations, the three states of matter are shown as (s), (l) and (g), with (aq) for aqueous solutions.

Students should be able to include appropriate state symbols in chemical equations for the reactions in this specification.

4.2.2.3 Properties of ionic compounds

Ionic compounds have regular structures (giant ionic lattices) in which there are strong electrostatic forces of attraction in all directions between oppositely charged ions.

These compounds have high melting points and high boiling points because of the large amounts of energy needed to break the many strong bonds.

When melted or dissolved in water, ionic compounds conduct electricity because the ions are free to move and so charge can flow.

Knowledge of the structures of specific ionic compounds other than sodium chloride is not required.

4.2.2.4 Properties of small molecules

Substances that consist of small molecules are usually gases or liquids that have relatively low melting points and boiling points.

These substances have only weak forces between the molecules (intermolecular forces). It is these intermolecular forces that are overcome, not the covalent bonds, when the substance melts or boils.

The intermolecular forces increase with the size of the molecules, so larger molecules have higher melting and boiling points.

These substances do not conduct electricity because the molecules do not have an overall electric charge.

Students should be able to use the idea that intermolecular forces are weak compared with covalent bonds to explain the bulk properties of molecular substances.

4.2.2.5 Polymers

Polymers have very large molecules. The atoms in the polymer molecules are linked to other atoms by strong covalent bonds. The intermolecular forces between polymer molecules are relatively strong and so these substances are solids at room temperature.

Students should be able to recognise polymers from diagrams showing their bonding and structure.

4.2.2.6 Giant covalent structures

Substances that consist of giant covalent structures are solids with very high melting points. All of the atoms in these structures are linked to other atoms by strong covalent bonds. These bonds must be overcome to melt or boil these substances. Diamond and graphite (forms of carbon) and silicon dioxide (silica) are examples of giant covalent structures.

Students should be able to recognise giant covalent structures from diagrams showing their bonding and structure.

4.2.2.7 Properties of metals and alloys

Metals have giant structures of atoms with strong metallic bonding. This means that most metals have high melting and boiling points.

In pure metals, atoms are arranged in layers, which allows metals to be bent and shaped. Pure metals are too soft for many uses and so are mixed with other metals to make alloys which are harder.

Students should be able to explain why alloys are harder than pure metals in terms of distortion of the layers of atoms in the structure of a pure metal.

4.2.2.8 Metals as conductors

Metals are good conductors of electricity because the delocalised electrons in the metal carry electrical charge through the metal. Metals are good conductors of thermal energy because energy is transferred by the delocalised electrons.

4.2.3 Structure and bonding of carbon

4.2.3.1 Diamond

In diamond, each carbon atom forms four covalent bonds with other carbon atoms in a giant covalent structure, so diamond is very hard, has a very high melting point and does not conduct electricity.

Students should be able to explain the properties of diamond in terms of its structure and bonding.

4.2.3.2 Graphite

In graphite, each carbon atom forms three covalent bonds with three other carbon atoms, forming layers of hexagonal rings which have no covalent bonds between the layers.

In graphite, one electron from each carbon atom is delocalised.

Students should be able to explain the properties of graphite in terms of its structure and bonding.

Students should know that graphite is similar to metals in that it has delocalised electrons.

4.2.3.3 Graphene and fullerenes

Graphene is a single layer of graphite and has properties that make it useful in electronics and composites.

Students should be able to explain the properties of graphene in terms of its structure and bonding.

Fullerenes are molecules of carbon atoms with hollow shapes. The structure of fullerenes is based on hexagonal rings of carbon atoms but they may also contain rings with five or seven carbon atoms. The first fullerene to be discovered was Buckminsterfullerene (C_{60}) which has a spherical shape.

Carbon nanotubes are cylindrical fullerenes with very high length to diameter ratios. Their properties make them useful for nanotechnology, electronics and materials.

Students should be able to:

• recognise graphene and fullerenes from diagrams and descriptions of their bonding and structure

• give examples of the uses of fullerenes, including carbon nanotubes.

4.2.4 Bulk and surface properties of matter including nanoparticles (chemistry only)

4.2.4.1 Sizes of particles and their properties

Nanoscience refers to structures that are 1–100 nm in size, of the order of a few hundred atoms. Nanoparticles, are smaller than fine particles ($PM_{2.5}$), which have diameters between 100 and 2500 nm (1×10^{-7} m and 2.5×10^{-6} m). Coarse particles (PM_{10}) have diameters between 1×10^{-5} m and 2.5×10^{-6} m. Coarse particles are often referred to as dust.

As the side of cube decreases by a factor of 10 the surface area to volume ratio increases by a factor of 10.

Nanoparticles may have properties different from those for the same materials in bulk because of their high surface area to volume ratio. It may also mean that smaller quantities are needed to be effective than for materials with normal particle sizes.

Students should be able to compare 'nano' dimensions to typical dimensions of atoms and molecules.

4.2.4.2 Uses of nanoparticles

Nanoparticles have many applications in medicine, in electronics, in cosmetics and sun creams, as deodorants, and as catalysts. New applications for nanoparticulate materials are an important area of research.

Students should consider advantages and disadvantages of the applications of these nanoparticulate materials, but do not need to know specific examples or properties other than those specified.

Students should be able to:

• *given appropriate information, evaluate the use of nanoparticles for a specified purpose*

• *explain that there are possible risks associated with the use of nanoparticles.*