07 Structure and Properties

Introduction

The important theme in this chapter is the relationship between the properties of a substance and its structure. The physical properties of substances such as their melting points, boiling points, electrical conductivities and solubility can be explained using the theories of bonding and structures which were investigated in Chapter 6. The relationship between the properties and structures of substances is revisited throughout the course. For example, this relationship is mentioned again during the study of the properties of metals in Section 4.

Chapter Opener (page 101)

1. To open the chapter, the following questions could be discussed. Precise answers are not needed at this stage.

   What are some physical properties that substances have?

   Answer: E.g. State (at r.t.p.), melting and boiling point, solubility in water, heat and electrical conductivity.

   Name some substances that have (a) giant structures and (b) simple structures.

   Answer: (a) Ionic compounds, giant covalent structures (diamond / graphite / silicon dioxide, metals. (b) Simple molecular structures such as water, chlorine.

   Why does sodium chloride have a high melting point?

   Answer: Refer to Section 7.2 page 108.

2. Carry out an 'Inquiry Preview.'

Learning Outcomes

After completing this chapter, the students should be able to:

- relate physical properties of ionic compounds and covalent substances to their structure and bonding
- compare the structure of simple molecular substances with those of giant molecular substances in order to deduce their properties
- compare the bonding and structures of diamond and graphite in order to deduce their properties
- deduce physical properties of substances from their structures and bonding and vice versa
- relate physical properties of metals, including electrical conductivity, to the mobility of the electrons in the structure

Teaching notes for

7.1 Structure and Physical Properties (page 102)

Stimulation

Show the class some real substances covering the four types of structures (giant ionic structure, simple molecular structure, giant covalent structure, giant metallic structure) studied in Chapter 6. This could include the substances shown in Table 7.1 on page 102 of the Textbook. Without referring to their textbooks, ask students to list some properties of the substances and to state the type of structure of each substance. You could then tell the class that the purpose of this chapter is to study the relationship between the structures and the properties of substances. Carry out an 'Inquiry Preview' before beginning to teach the class.

Skills Practice (page 103)

1. The term 'structure' refers to the parts that make up a substance and how these parts are held or put together. In Chemistry, this includes the atoms used, the bonding between the atoms and the three-dimensional arrangement of the particles in the structure.
2. The kinds of structures studied in Chapter 6 are giant ionic structures, simple molecular structures, giant covalent structures and giant metallic structures.

   Examples of substances with a giant ionic structure are sodium chloride, calcium carbonate and copper(II) sulfate.

   Examples of substances with a simple molecular structure are hydrogen, chlorine, water and carbon dioxide.

   Examples of substances with a giant covalent structure are diamond and silicon dioxide.

   Examples of substances with a metallic structure are all the metals.
3. Sodium chloride has a high melting point and it dissolves in water to form a colourless solution. Water has a boiling point of 100 °C and a density of 1 g/cm^3. Diamond is very hard and has a very high melting point. Gold is shiny, soft and conducts heat.

Teaching pointers

7.2 Structure and Physical Properties of Simple Molecular Substances (page 103)

1. Substances with simple molecular structures consist of small covalent molecules. The forces within the molecules are strong while the forces between the molecules are weak and can be easily broken. Most covalent elements and compounds have molecular structures.
2. Iodine has a simple molecular structure and readily sublimes when heated. If this has not been demonstrated before, you could demonstrate this experiment now. (Refer to the notes on Chapter 2 of this Teacher's Resource File on how to carry out the demonstration.)
3. Students sometimes find it difficult to appreciate that when molecular substances melt, it is only the molecules only separate; the bonds within the molecules do *not* break. This can be compared with giant ionic structures, such as sodium chloride, in which *all* the bonds between the ions break on melting
4. Sweet-smelling substances (often esters) with molecular structures are added to soap powders. These are volatile and vaporise easily because of their low melting points.
5. To demonstrate the solubility of molecular substances, show the effect that water and an organic solvent such as tetrachloromethane have on iodine. This can be done by adding a crystal of iodine to a test tube containing both water and tetrachloromethane. (Water and tetrachloromethane are immiscible and form two separate layers.) Shake the test tube. Iodine is only slightly soluble in water but is readily soluble in tetrachloromethane to give a dark red solution.
6. Not all molecular substances have the typical properties given in the textbook. For example, both carbon monoxide and carbon dioxide are molecular substances; carbon monoxide is *insoluble* in water while carbon dioxide is *soluble* in water. Students investigate this in Exercise 7.2B.

(page 104)

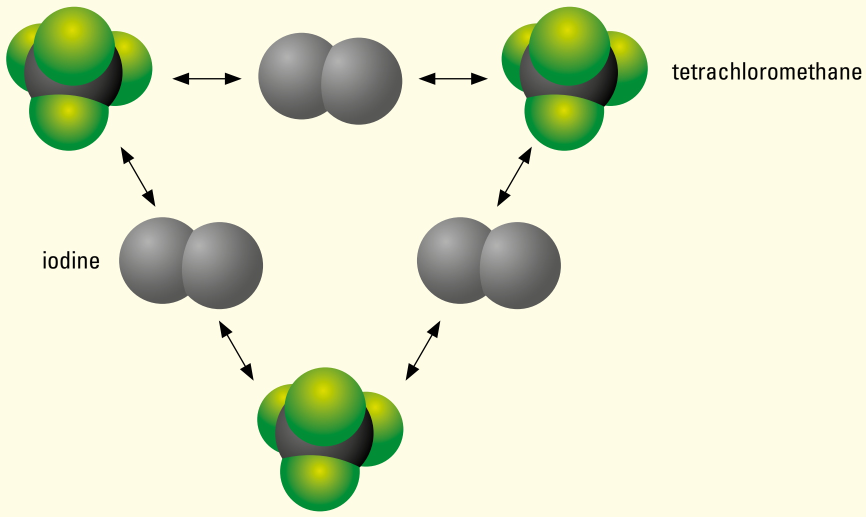
Mystery Clue

Iodine molecules made from I-131 or ordinary iodine have the same structure Both are volatile which is why the iodine easily escaped from the nuclear reactor.

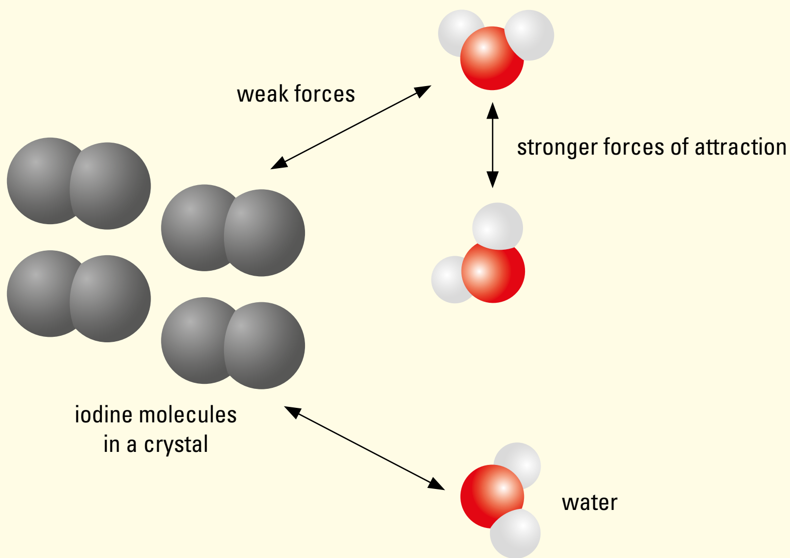
Notes for Teachers

Insolubility of molecular substances in water
Consider solid iodine. Iodine is insoluble in water. Iodine molecules are non-polar and have no overall electrical charge. Therefore they do not attract the polar water molecules. Instead, the water molecules tend to be attracted to each other. Thus the water molecules do not separate the molecules in the solid iodine. Iodine is therefore insoluble in water.

As both iodine and tetrachloromethane are molecular, they both have weak forces between the molecules. As a result, the iodine and tetrachloromethane molecules can mix together easily, causing the iodine molecules to separate and the solid to dissolve. As a result, iodine is soluble in tetrachloromethane.



Iodine dissolves in tetrachloromethane



Iodine is only slightly soluble in water

Teaching pointers

7.3 Structure and Physical Properties of Giant Molecular Substances (page 105)

1. Do not refer to giant covalent structures as giant molecules as this latter term is used to describe polymers such as plastics, starch and proteins. Although the term 'giant molecular structure' is an alternative to 'giant covalent/atomic structure', it is better not to use this term because it can be confused with giant molecules.
2. The element silicon, like diamond, has a giant covalent structure. Both have similar properties, e.g. they are hard, have high melting points and they do not conduct electricity (though, being a metalloid, silicon will conduct electricity when slightly impure or when heated).

3. If a diamond is available, use it to cut a (small) sheet of glass.

4. Demonstrate the electrical conductivity of graphite. This can be easily done by connecting a pencil lead to a battery and a light bulb. If graphite lubricant is available, get students to feel it and to note its slippery nature.

5. Even though weak forces/bonds exist between the layers in graphite, the covalent bonds *within* the layers are very strong. Thus graphite has a high melting point and boiling point because of the large amount of energy needed to break these bonds.

6. Different forms of an element are called **allotropes**. Diamond and graphite are allotropes of carbon. Allotropes have similar chemical properties but different physical properties because of their different structures. For example, both diamond and graphite burn in air to give carbon dioxide. (Other elements, such as tin and phosphorus, also show allotropy.)

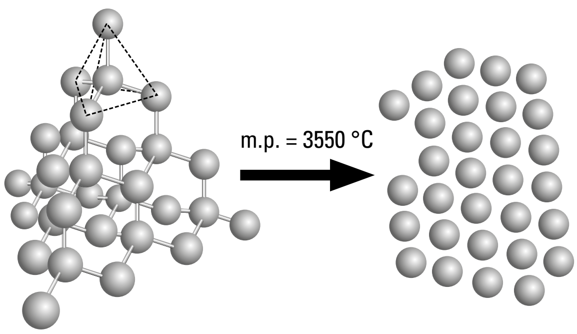
7. When discussing the properties and uses of diamonds, you may get the class to explain the analogies of diamonds in the advertisement "A diamond is a girl's best friend" and in the nursery rhyme "Twinkle, twinkle little star, ….. , like a diamond in the sky, … ." See 'Notes for Teachers' on the next page.

8. Pencils are made of graphite and have no lead in them. The connection between graphite and lead stems from the days of the Roman Empire (or even before that) when lead rods were used by scribes to write on papyrus. The term 'lead' continued to be used today.

9. For more able classes, discuss the structure of carbon nanotubes. The prefix 'nano' means 'divided by 1 billion (10^9).' A nanometre is 10^{-9} m which is the order of size of molecules. Nanotubes are tubes of molecular size.

Skills Practice (page 106)

1. The melting of diamond requires the breaking of strong covalent bonds within the structure. The structure breaks down into separate carbon atoms as shown in the diagram below. As this requires a lot of energy, the melting point of diamond is high.



2. Non-metals, as a rule, do not conduct electricity. Therefore graphite, which *does* conduct electricity, is not a typical non-metal.

3. (a) Hardness
   (b) Hardness
   (c) Electrical conductivity and high melting point
   Note: Students will *not* know the need for a high melting point as they have not studied electrolysis yet.
   (d) High melting point and is transparent

4.

Property	Diamond	Graphite
Appearance	Colourless, transparent crystal	Black, shiny solid
Hardness	Hard	Soft
Melting point	High (3550 °C)	High (3720 °C)
Electrical conductivity	Non-conductor	Conductor
Solubility in water	Insoluble	Insoluble
Uses	E.g. Jewellery	E.g. Pencil lead

Chemistry in Society (page 106)

Taking a Lift to Space!

This article provides further opportunities to discuss the relationship between structure and physical properties as follows:

(a) Discuss similarities and differences in the structures of ordinary graphite and graphite nanotubes. For example, both have C – C bonds arranged in layers. In graphite, the carbon layers are flat; in nanotubes they are in the shape of tubes. They have different properties: graphite is soft, whereas carbon nanotubes are strong. Carbon nanotubes have a variety of uses where graphite cannot be used.

(b) Discuss why ordinary graphite is soft and weak whereas graphite nanotubes are strong. Graphite consists of parallel layers of carbon atoms with weak forces between the layers; the layers can slide over each other, causing graphite to be soft. In nanotubes, there are no parallel layers. Instead, each layer is wrapped into a tube, which gives them strength.

Note: The idea of an elevator into space has been around for several decades and was popularised by Arthur C. Clarke, the science fiction writer, in his 1979 book *The Fountains of Paradise*. However the idea was never practical because there was no material strong enough to support its own weight over the large distance needed to reach space from Earth. The discovery of carbon nanotubes changed that. They are still being developed and, theoretically, when woven into fibres are strong enough to reach into space.

Exercise

Carbon nanotubes could be used as power cables to carry electricity to places that are very far away from the power source. They could also be used to make batteries and sporting equipment.

Notes for Teachers

Analogies with diamonds

The phrase "A diamond is a girl's best friend" is part of an advertisement for diamonds. It is an analogy as it compares a diamond with a friend. The advertisers hope that girls will make links between friends and diamonds. For example, both a diamond and a friend are always with her, both are important and valuable to her, both the possession of a diamond and a friendship can last a long time and neither of them will be given away.

In the nursery rhyme, "*Twinkle, twinkle, little star, ……*", the twinkling of stars is likened to the sparkling of diamonds.

Teaching pointers

7.4 Structure and Physical Properties of Ionic Compounds (page 107)

1. The structure of sodium chloride, and many other solids, was determined by X-ray diffraction/crystallography. Although this is not in the syllabus, you may mention that this process involves passing X-rays through crystals and interpreting the resulting photographs. This technique is referred to in Activity 7.1 of the Theory Workbook. See also 'Notes for Teachers' on the next page.
2. In discussing the structure of substances, again emphasise that the key aspect of all giant structures is a continuous three-dimensional network of particles with strong bonds between these particles.
3. Figure 7.14 shows the two kind of models that chemists use. Again discuss the advantages and disadvantages of each.

   Ball-and stick model: Shows clearly how the ions are arranged in rows, shows the relative sizes of the ions; the lines between the ions may be mistaken for covalent bonds, it does not show the full size of the ions.

   The *space filling model*: More realistic and shows how the ions are packed closely together; the arrangement of the ions in rows is less clear.
4. Crystals of copper(II) sulfate contain water of crystallisation. Its formula is written as $CuSO_4 \cdot 5H_2O$ and its full name is copper(II) sulfate pentahydrate. As the molecules of water are part of the crystal structure, the solid is dry to the touch. The dot in the formula indicates that the water molecules are loosely bonded and they come off on heating. The water molecules give the crystals their characteristic blue colour. When heated, the water evaporates and the crystals become white.
5. You could perform a demonstration to show that many ionic compounds have high melting points. Choose an ionic compound that will not decompose when heated and will not melt at Bunsen burner temperatures. An example is potassium chloride. (Do *not* use sodium chloride as students will get to heat this compound in Experiment 7.1 of the Practical Workbook).
6. The properties discussed in the Textbook are typical for ionic compounds. But not all ionic compounds fit into this pattern. For example, copper(II) chloride has the typical properties of an ionic compound whereas copper(II) oxide (insoluble in water) and copper(II) nitrate (low melting point) do not. Students will get to decide if substances fit into this pattern in Activity 7.2A of the Theory Workbook.
7. When ionic compounds dissolve in water, the ions become surrounded by water molecules to form *hydrated* ions. See the 'Notes for Teachers' on the next page. The websites provide simulations of the dissolving process and the formation of these hydrated ions.

(page 109)

Mystery Clue

Its physical properties are similar to those of sodium chloride as they have a similar structure. High melting point, which means it is a solid at room temperature, soluble in water.

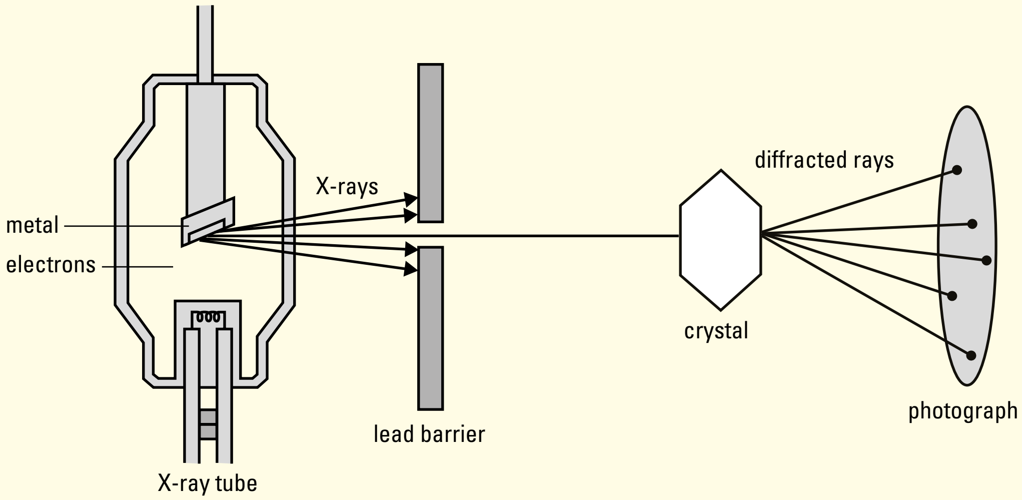
Skills Practice (page 109)

1. Salt is non-volatile (at room temperature) and will have a high melting point, suggesting a giant structure. (Note that lack of smell alone does not suggest the type of giant structure.) The compounds in durian and orange peel providing the smell are volatile and have a low boiling point, suggesting a molecular structure.
2. The ions cannot move in solid aluminium oxide, so it cannot conduct electricity. It will conduct when molten.

Notes for Teachers

X-ray diffraction

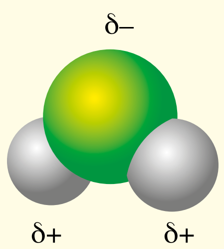
The diagram below shows, in a simplified way, how X-rays are used to determine the structure of a crystalline solid.



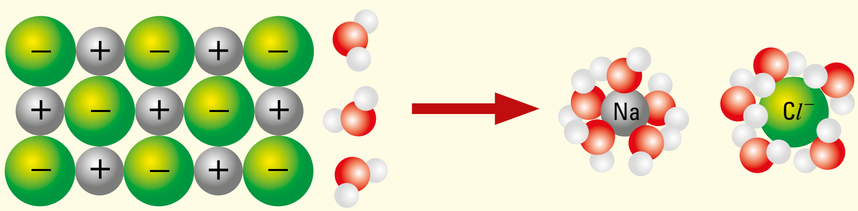
X-rays are produced when fast-moving electrons hit a metal surface. The X-rays are diffracted when they pass through a crystal and form a pattern of dots on a photographic film. From the pattern of dots, chemists deduce the arrangement of the particles in the solid.

Solubility of sodium chloride in water

When sodium chloride dissolves in water, the sodium and chloride ions attract water molecules because water is a polar substance. The oxygen atom in a water molecule has a slight negative charge (δ^-) while the hydrogen atoms have a slight positive charge (δ^+) as shown in the diagram below.



The Na^+ ions attract the negative ends of the water molecules while the Cl^- ions attract the positive ends. The process of forming the hydrated ions is shown in the following diagram:



IT Link

Simulations showing the process of dissolving sodium chloride:

http://www.chem.iastate.edu/group/Greenbowe/sections/projectfolder/flashfiles/thermochem/solutionSalt.html

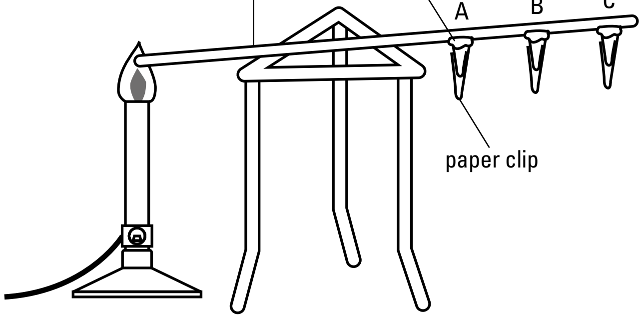
http://programs.northlandcollege.edu/biology/Biology1111/animations/dissolve.html

http://www.mhhe.com/physsci/chemistry/essentialchemistry/flash/molvie1.swf

Teaching pointers

7.5 Structure and Physical Properties of Metallic Structures (page 110)

1. Properties of metals. You could demonstrate some of the properties of metals as follows:
   - To show *malleability*, hammer a sheet of lead on a hard surface.
   - To show *ductility*, suspend a long, thin copper wire firmly to a hook in the ceiling and add heavy weights to a weight hanger attached to the bottom of the wire.
   - To show *heat conductivity*, set up the apparatus as shown below. The clips fall off in the order A, B and then C as heat is conducted along the rod.



2. You may also comment that most metals have high densities because atoms are closely packed. The mass of the metal is compacted into a small volume. Thus the mass of the metal per unit volume (i.e. density) is high.
3. When teaching the conduction of electricity, ask students to compare the movement of electrons when the metal is
   - conducting electricity, and
   - not conducting electricity.

   Emphasise that it is only the outer-shell electrons that are delocalised and move freely. When the metal is not conducting electricity, the free/delocalised electrons move about randomly throughout the metal. When conduction of electricity is taking place, electrons move into one end of the metal while the other electrons leave from the other end.
4. As the metallic bonds in most metals are strong, metals have high melting points. However, mercury (melting point –39 °C) and caesium (melting point 28 °C) have low melting points. Thus we can infer that the metallic bonds in these metals are much weaker.

Skills Practice (page 111)

1. **(a)** When one end of a piece of metal is heated, the electrons move faster and collide with neighbouring electrons. This transfers energy (which is detected as heat) along the metal.

   (b) Electrons move through the metal, from the end nearer the negative terminal of the power supply to the positive terminal.
2. Both ionic substances and metals have many strong bonds between the particles in the structures. Both require a lot of energy to separate break the bonds and separate the particles. So, both have high melting points.
3. **(a)** Substance A **(b)** Substance C **(c)** Substance A

Teaching pointers

7.6 Identifying the Structure of a Substance (page 112)

1. The identification key on page 112 of the Textbook can only identify the types of structures for the most typical substances. It is not suitable for mercury, graphite or for ionic compounds such as calcium carbonate that decompose on heating or are insoluble in water.
2. Experiment 7.1 in the Practical Workbook gets students to investigate the properties of some compounds and to use these properties to infer the types of structures and the kinds of particles present in each of these substances. Students then construct a key using the properties investigated and identify the type of structure present in an unknown compound. They are then given an unknown compound in which they are required to identify the types of structures present by carrying out the tests in their key. For Part C, the unknown solid compound could be anhydrous sodium carbonate.
3. Exercise 7.2B in the Theory Workbook gets students to predict the types of structures and bonding for several substances, given data for these substances.

Chemistry Inquiry (page 112)

What Structure and Properties Does the Compound Have?

Group Discussion

1. Because we are able to infer that the compound has an ionic structure and these properties are typical of ionic compounds.
2. For example: X – magnesium, calcium, zinc. Y – fluorine, chlorine, bromine, iodine. XY_2 – magnesium fluoride, calcium chloride, etc.
3. No, as the ionic model we are using is not perfect and is not able to predict the properties of all ionic compounds. (Refer to the comments on this at the end of Section 7.4 for ammonium nitrate and lead(II) sulfate.)

Skills Practice (page 113)

1. Mercury, which is a liquid at room temperature. The key would show it to have a simple molecular structure, whereas it actually has a metallic structure.
2. **(a)** A – solid. B – liquid. C – solid.
   (b) A – giant covalent structure. B – simple molecular structure. C – giant ionic structure.

Notes for Teachers

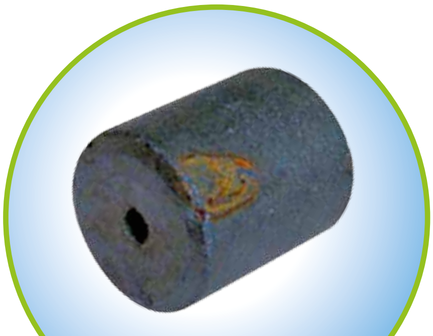
Alternative key for identifying structures
The key below uses just two properties to identify the structure of a substance: boiling point and electrical conductivity.

Low boiling point?* —Yes→ **Simple molecular structure**
↓ No
Conducts electricity when solid? —Yes→ **Metallic structure (or graphite)**
↓ No
Conducts electricity when molten? —Yes→ **Giant ionic structure**
↓ No
Giant covalent structure

*Low boiling points are usually taken as temperatures below 200 °C.

Solving the Mystery (page 114)

What role did iodine have in the Fukushima nuclear disaster?


uranium oxide fuel pellet

Iodine reacts easily with other chemicals, and isotopes of iodine are found as compounds rather than as a pure element. Thus, iodine–129 and–131 found in nuclear facilities quickly form compounds with the mixture of chemicals present. However, iodine released to the environment from nuclear power plants is usually a gas.

Iodine in air can combine with water particles and precipitate into water or soils. Iodine in soils will combine with organic matter and remain in the same place for a long time. Plants that grow on these soils may absorb iodine. Cattle and other animals will absorb iodine when they eat these plants.

The only naturally-occurring isotopes of iodine are I–127 and I–129, which are stable and radioactive respectively.

If radioactive iodine is breathed in or swallowed, it will concentrate in the thyroid gland and increase the risk of thyroid cancer. This risk can be lowered by taking potassium iodide pills to saturate the gland and help prevent the uptake of radioactive material when given before or shortly after exposure.

Iodide tablets must be taken at least an hour before exposure or within 24 hours of exposure, and then every 24 hours until the danger has passed. They only protect the thyroid, and offer no protection against other radioactive isotopes such as caesium.

Infer
After the first eight days, only 50% of the original amount of I–131 remains, after another eight days (16 days from the start), 25% remains, and so on.

Connect
I–137 remains in the environment longer as it has a longer half life.

Further Thought
- Radioactive iodine (and radioactive caesium) that are carried by the wind tend to stick like dust to large leafy vegetables such as spinach an cabbage but will not easily make their way inside. Experts in Japan have said that washing vegetables well with clean water can reduce levels. They also recommend that vegetables be washed after the outside leaves are removed. However washing vegetables will not remove any I–131 that has been absorbed by plants.
- On entering the body, caesium–137 concentrates in soft tissue such as muscles, where it can cause cancer.

07 Chapter Review

Self-Management

Misconception Analysis (page 115)

1. **False** Most ionic compounds are soluble in water. However, there are exceptions to this rule. For example, calcium carbonate and lead(II) chloride are ionic compounds but are insoluble in water.

2. **True** This is a typical property of simple molecular substances.

3. **False** Metals consist of positive ions in a 'sea' of electrons. Graphite consists of layers of covalently bonded carbon atoms with weak covalent bonds between the layers. Electrons in these weak bonds are able to move freely allowing graphite to conduct electricity.

4. **False** Diamond and graphite are two forms of carbon. Diamond is hard whereas graphite is soft.

5. **False** The molecules move apart on melting but do not separate into atoms.

6. **False** Conduction of electricity in metals is due to the movement of the free (delocalised) electrons in the metal.

7. **False** Mercury is a liquid at room temperature yet it has a metallic structure.

Practice

Structured Questions (page 116)

1. **(a)** **(i)** Substance D. Metals conduct electricity under all conditions.
(ii) Substance B. Substances with giant ionic structures typically have high melting points and boiling points and conduct electricity when molten but not when in the solid state.
(iii) Substance C. Substances with giant covalent structures have high melting points and boiling points and do not conduct electricity under any conditions.
(iv) Substance A. Substances with simple molecular structures have low melting points and boiling points and do not conduct electricity under any conditions.
(b) Substance A is sulfur. Substance B is potassium chloride. Substance C is diamond. Substance D is copper.

2. **(a)** Carbon tetrachloride, calcium chloride, iron(II) nitrate.
(b) **(i)** Calcium chloride, as there are ionic bonds between the calcium and chloride ions.
(ii) Carbon tetrachloride, which has a simple molecular structure with four C–Cl covalent bonds.
(iii) Iron(II) nitrate. There are ionic bonds between the iron(II) ion and the nitrate ions, but covalent bonds between the nitrogen and oxygen atoms within the nitrate ions.
(c) Carbon tetrachloride — low boiling point, volatile, insoluble in water — as it has a simple molecular structure.
Calcium chloride, iron(II) nitrate are ionic compounds — solids at room temperature, high melting points, soluble in water, conduct electricity when molten or in aqueous solution.

3. **(a)** NF_3.
(b) Simple molecular.
(c) Low.
(d) Insoluble.
(e) Will not conduct electricity.

4. **(a)** Carbon dioxide has a low melting point as it is a gas at room temperature.
(b) **(i)** The term 'to sublime' means to change from the solid state to the gaseous state without going through the liquid state.
(ii) Sublimation is a physical change as it does not change into another new substance.
(c) **(i)** Carbon dioxide has a low melting point. / Carbon dioxide is a gas at room temperature.
(ii) CO_2
Note: 'Stage smoke' is actually water vapour, condensed from water in the air by the cold dry ice.

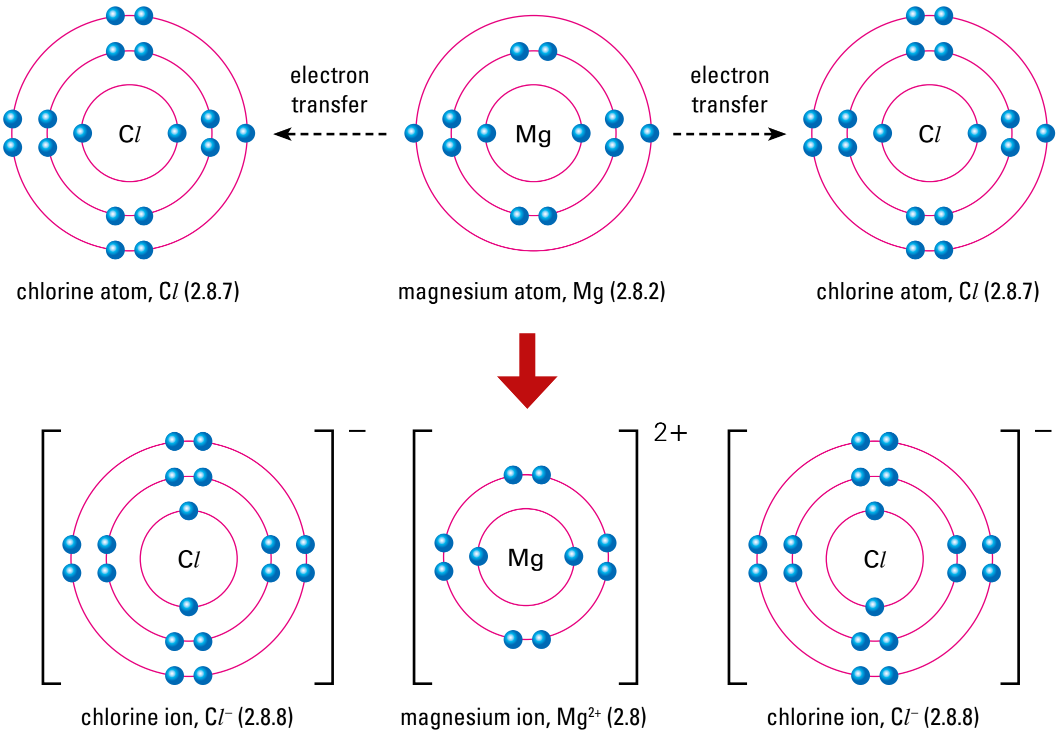
5. **(a)** The chemical formulae for potassium bromide and tin(IV) bromide are KBr and $SnBr_4$ respectively.
(b) Potassium bromide has ionic bonding as it has a high melting point (735 °C).
(c) Tin(IV) bromide has a simple molecular structure as it has a low melting point (30 °C).

Free Response Question (page 116)

The responses should contain the following points.

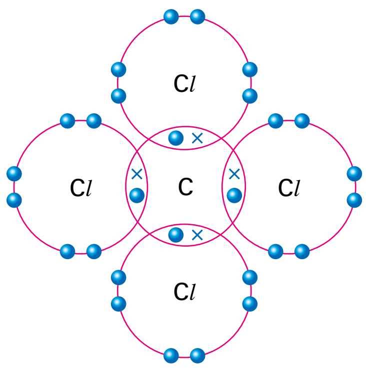
1. Oxygen is a gas. This is correct but the reason given is wrong. Oxygen molecules, O_2, have *strong* covalent bonds between the atoms in the molecules. But there are only weak attractive forces between the oxygen molecules. Therefore, only a little energy is needed to separate the molecules. As a result, oxygen has a low melting point and boiling point which explains why it is a gas (at room temperature).

2. *Magnesium chloride*: The electronic structures of magnesium and chlorine are 2.8.2 and 2.8.7 respectively. Each magnesium atom loses it two outer shell electrons to become a Mg^{2+} ion. The electrons are transferred to two chlorine atoms which form Cl^- ions.
The electron diagram for magnesium chloride is:



Tetrachloromethane: The electronic structures of carbon and chlorine are 2.4 and 2.8.7 respectively. The outer shell of a carbon atom needs four more electrons to obtain a noble gas structure while a chlorine atom needs one electron. Each outer shell electron in the carbon atom is shared with an outer shell electron in a chlorine atom to form a C – Cl covalent bond. Four C – Cl bonds are formed in tetrachloromethane.

Electron diagram for CCl_4:



Magnesium chloride has a higher melting point. Magnesium chloride has an ionic structure whereas tetrachloromethane has a simple molecular structure. Substances with ionic structures usually have high melting points.

Extension (page 117)

1. The modern pencil was first made in England in the 16th Century. This process required high-quality graphite which was suitable for writing. A later development in this process took place in France in 1795 when it was discovered that graphite could be mixed with clay and fired in a furnace to give pencils of varying degrees of hardness. The greater the proportion of clay to graphite, the harder the pencil lead is.

   Pencils graded 'B' consist of more graphite and less clay; these pencils are soft and give black writing but are brittle. Pencils graded 'H' are harder as they contain more clay and less graphite; these pencils are less brittle but give lighter writing. Pencils graded 'HB' are both hard and black and are the most common type of pencil for general use. Harder grades are used for drafting and engineering, whereas softer grades are usually used by artists.

2. (a) It conducts electricity and is slippery.
   (b) Copper as it is a very good conductor of electricity.

Blank