SURFING

UNIT 2

QCE CHEMISTRY

UNIT 2 MOLECULAR INTERACTIONS AND REACTIONS

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Science Press

First published 2019

Science Press
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Introduction

This book covers the Chemistry content specified in the Queensland Certificate of Education Chemistry Syllabus. Sample data has been included for suggested experiments to give you practice to reinforce practical work in class.

Each book in the *Surfing* series contains a summary, with occasional more detailed sections, of all the mandatory parts of the syllabus, along with questions and answers.

All types of questions – multiple choice, short response, structured response and free response – are provided. Questions are written in exam style so that you will become familiar with the concepts of the topic and answering questions in the required way.

Answers to all questions are included.

A topic test at the end of each topic contains an extensive set of summary questions. These cover every aspect of the topic, and are useful for revision and exam practice.

Words To Watch

account, account for State reasons for, report on, give an account of, narrate a series of events or transactions.

analyse Interpret data to reach conclusions.

annotate Add brief notes to a diagram or graph.

apply Put to use in a particular situation.

assess Make a judgement about the value of something.

calculate Find a numerical answer.

clarify Make clear or plain.

classify Arrange into classes, groups or categories.

comment Give a judgement based on a given statement or result of a calculation.

compare Estimate, measure or note how things are similar or different.

construct Represent or develop in graphical form.

contrast Show how things are different or opposite.

create Originate or bring into existence.

deduce Reach a conclusion from given information.

define Give the precise meaning of a word, phrase or physical quantity.

demonstrate Show by example.

derive Manipulate a mathematical relationship(s) to give a new equation or relationship.

describe Give a detailed account.

design Produce a plan, simulation or model.

determine Find the only possible answer.

discuss Talk or write about a topic, taking into account different issues or ideas.

distinguish Give differences between two or more different items.

draw Represent by means of pencil lines.

estimate Find an approximate value for an unknown quantity.

evaluate Assess the implications and limitations.

examine Inquire into.

explain Make something clear or easy to understand.

extract Choose relevant and/or appropriate details.

extrapolate Infer from what is known.

hypothesise Suggest an explanation for a group of facts or phenomena.

identify Recognise and name.

interpret Draw meaning from.

investigate Plan, inquire into and draw conclusions about.

justify Support an argument or conclusion.

label Add labels to a diagram.

list Give a sequence of names or other brief answers.

measure Find a value for a quantity.

outline Give a brief account or summary.

plan Use strategies to develop a series of steps or processes.

predict Give an expected result.

propose Put forward a plan or suggestion for consideration or action.

recall Present remembered ideas, facts or experiences.

relate Tell or report about happenings, events or circumstances.

represent Use words, images or symbols to convey meaning.

select Choose in preference to another or others.

sequence Arrange in order.

show Give the steps in a calculation or derivation.

sketch Make a quick, rough drawing of something.

solve Work out the answer to a problem.

state Give a specific name, value or other brief answer.

suggest Put forward an idea for consideration.

summarise Give a brief statement of the main points.

synthesise Combine various elements to make a whole.

Surfing QCE CHEMISTRY

UNIT 2

UNIT 2

Molecular Interactions and Reactions

In this unit you will:

- Develop your understanding of the physical and chemical properties of materials such as gases, water, aqueous solutions, acids and bases.
- Explore the properties of water.
- Investigate the solubility of substances.
- Investigate how to predict and control reaction rates.
- Understand the relationship between the kinetic theory and chemical reactions.
- Use contexts, experiments and technology to help understand intermolecular forces and chemical reactions and develop skills.

SURFING QCE CHEMISTRY

UNIT 2

TOPIC 4

Intermolecular Forces and Gases

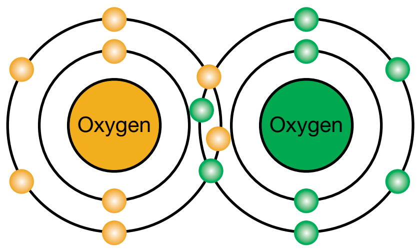
In this topic you will:

- Apply VSEPR theory to predict, draw and explain shapes of molecules.
- Use molecular shape, symmetry and electronegativity to explain and predict polarity.
- Explain the relationship between observable properties and forces.
- Construct 3-D models of molecules.
- Use chromatography techniques to determine composition and purity of substances.
- Use the kinetic theory of gases to explain their behaviour.
- Solve problems related to the ideal gas concept and the ideal gas equation.
- Solve problems about moles, mass and volume of chemicals.
- Determine molar volume of a gas.

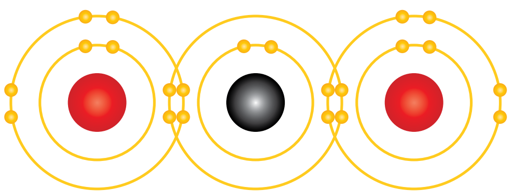
1 Molecular Substances

You will recall that **molecular substances** contain **covalent bonds** which are formed by the sharing of electrons between atoms. The electron configurations of the **non-metals in groups 4 to 7** of the periodic table leads to the sharing of electrons in their outer valency shell in order to form stable structures.

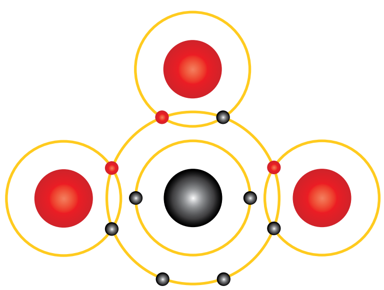
Atoms may share one or more electrons with identical atoms or with different atoms.



(a) Oxygen molecule O_2 – two identical oxygen atoms share electrons and form a small covalent molecule.



(b) Carbon dioxide molecule CO_2 – a carbon atom shares electrons with two oxygen atoms and forms a molecule of a compound.



(c) An ammonia molecule NH_3 – a nitrogen atom shares electrons with three hydrogen atoms.

Figure 1.1 Atoms bonding by sharing electrons and forming molecules.

When covalent bonds hold atoms together in a small grouping, we call the group of atoms a molecule. A **molecule** means the smallest particle of a substance that can exist and move independently.

Many substances with covalent bonds – both elements and compounds – exist as small molecules, but others can form large covalent network structures and macromolecules.

Elements as molecules

Originally a molecule was defined as two or more atoms joined by a covalent bond. However, as it is now defined as the smallest particle of a substance that can exist and move independently, the term molecule can also be used to describe the noble gases (group 18) which consist of only one atom. These are referred to as **monatomic molecules**.

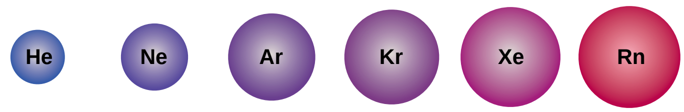


Figure 1.2 Monatomic molecules – group 18 elements.

Other non-metals that exist as groups of two atoms are referred to as **diatomic molecules**. The two atoms in these molecules are held together by sharing electrons and this gives them stable valency shells.

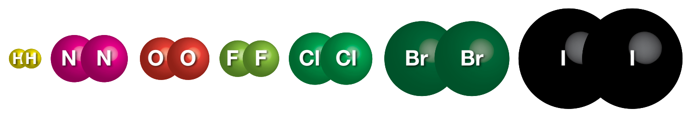


Figure 1.3 Diatomic molecules of elements.

Elements as covalent network structures

The group 4 elements, silicon and carbon, exist as large numbers of atoms held together by covalent bonds in a **large lattice** called a **covalent network structure**. The atoms of these elements each have four electrons in their outer shells. All of these four outer shell electrons can be shared with other atoms of the same element. The atoms join together to form a very large lattice or network in which all of the atoms are held tightly by the strong, covalent bonds that extend throughout the lattice.

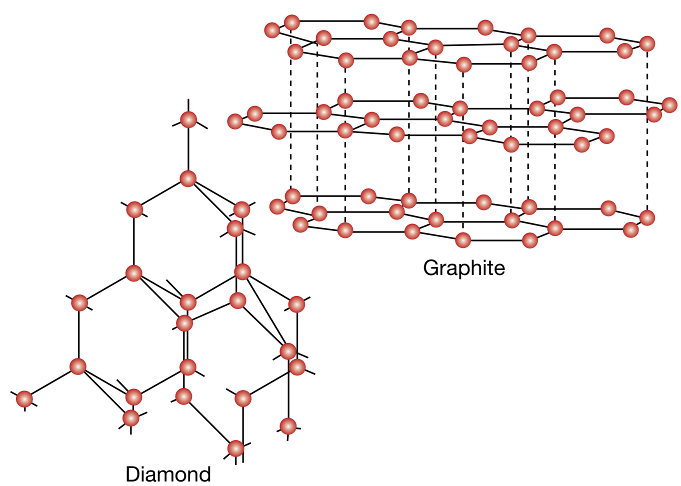


Figure 1.4 Two different forms (allotropes) of carbon which exist as covalent networks.

Compounds as molecules

Compounds composed of two or more non-metal atoms mostly occur as small molecules – small groupings of two or more different atoms.

Diatomic molecules have two atoms in each molecule such as hydrogen chloride HCl, hydrogen iodide HI, and carbon monoxide CO.

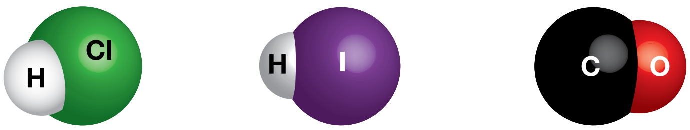


Figure 1.5 Diatomic molecules of compounds.

Larger molecules have more atoms in each molecule such as ammonia NH_3, carbon dioxide CO_2, sulfur dioxide SO_2, sulfur tetraiodide SI_4, carbon disulfide CS_2, phosphorus trihydride PH_3, methane CH_4 and hydrogen oxide (water) H_2O.

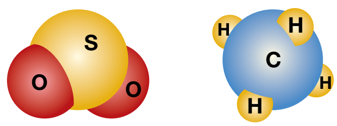


Figure 1.6 Larger molecules of compounds – sulfur dioxide and methane.

Compounds as large networks

A few compounds occur as large networks. Silicon dioxide (which makes up quartz and sand) is a giant 3-D network of silicon and oxygen atoms in the ratio 1 : 2. These are joined by strong covalent bonds throughout the network structure.

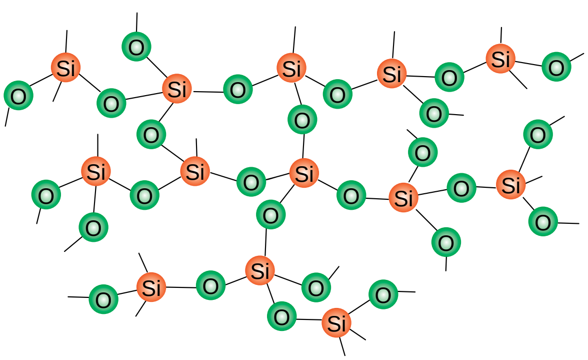


Figure 1.7 Silicon dioxide, a covalent network compound.

Compounds as macromolecules or polymers

A **macromolecule** is a very large molecule. Carbohydrates, proteins and fats tend to be macromolecules. **Polymers** are macromolecules that consist of large chains of repeating, smaller units joined together with covalent bonds. For example, starch is a polymer of glucose ($C_6H_{12}O_6$) and polyethene is a polymer of ethene (C_2H_4).

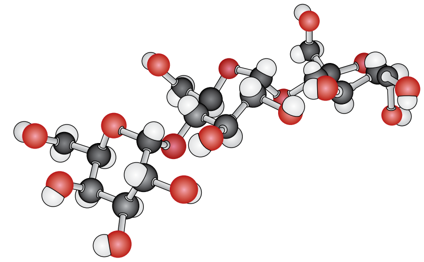
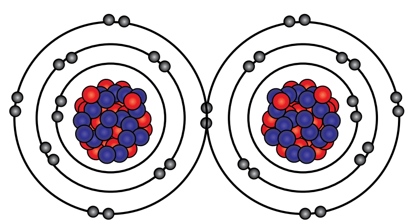


Figure 1.8 Part of a starch macromolecule.

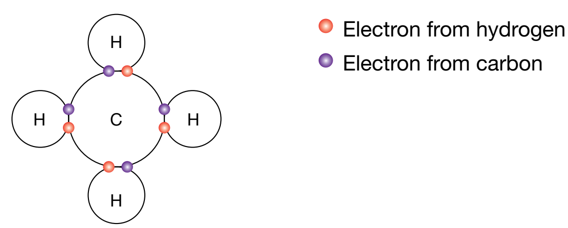
You have already looked at intramolecular and intermolecular forces in Unit 1. They will be repeated here in the next few chapters for convenience.

QUESTIONS

1. Define the following terms.
   (a) Covalent bond. (b) Covalent compound.
   (c) Covalent lattice. (d) Molecule.
   (e) Intermolecular forces.
2. Identify two elements that exist as molecules containing:
   (a) One atom. (b) More than one atom.
3. Identify two compounds that exist as molecules containing:
   (a) Two atoms. (b) More than two atoms.
4. State whether each of the following substances exists as small covalent molecules or as a covalent lattice.
   (a) Carbon. (b) Carbon dioxide.
   (c) Nitrogen. (d) Ammonia (NH_3).
   (e) Phosphine (PH_3). (f) Silicon dioxide (sand).
5. Describe what is illustrated by each of the following diagrams.
   (a)



   (b)



6. Check your knowledge with this quick quiz.
   (a) Covalent bonds involve the .... of electrons.
   (b) A molecule containing two atoms is called a .... molecule.
   (c) Name an element that exists as a covalent network structure.
   (d) Name a compound that occurs as a macromolecule.

2 Representing Molecular Substances

There are many ways in which we can represent molecular substances, all of which have limitations. We can use electron dot formulas, structural formulas, valence structures, ball and stick models and space-filling models.

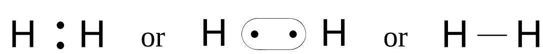
We have already seen how **electron dot structures** use dots to show only the outer valence shell of electrons around an atom. These structures can provide a helpful tool in working out bonding between atoms and we can see at a glance if a stable outer shell will be formed when the atoms lose, gain or share electrons.

(a) Nitrogen. (b) Hydrogen.

Figure 2.1 Electron dot structures for single atoms.

When electrons are shared we can either use just the dots close together, or draw a line to represent the shared pair of electrons or else draw a circle around the shared pair of electrons.

(a) Hydrogen gas.



(b) Ammonia.

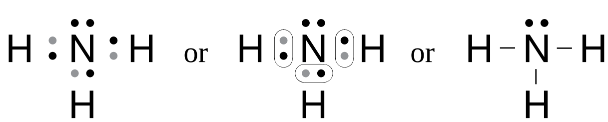
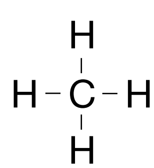


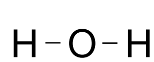
Figure 2.2 Electron dot structures when electrons are shared.

Structural formulas use sticks to join atoms of elements, such as in this structural formula of methane (CH_4).

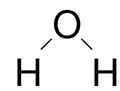


These sticks are always used to represent a covalent bond with shared electrons – you should never draw a stick model to represent an ionic compound.

Structural formulas do provide some information about how atoms are bonded in covalent molecules, but they tell us nothing about the **shape of a molecule**. For example, the structural formula for water can be written as follows.



This suggests the molecule is a linear (straight line) shape whereas it is actually a bent shape.



Bent water molecule.

A problem with using diagrams as models is that they show molecules as **two-dimensional structures** and they are actually usually three-dimensional. This can be seen in the ammonia molecule.

(a) 2-D model. (b) 3-D model.

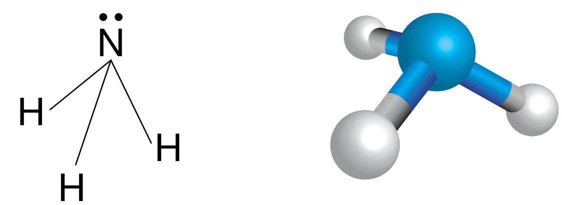


Figure 2.3 Ammonia (NH_3).

Space-filling models can give a more accurate idea of the three-dimensional structure of molecules, including the relative sizes of atoms, for example this molecule of water.

Water molecule

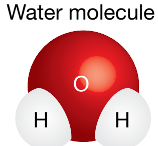


Figure 2.4 Space-filling model of water (H_2O).

Ball and stick models such as this model of ethanol (C_2H_5OH) can give an idea of the relative sizes of atoms and also provide some information about bond length and angle.

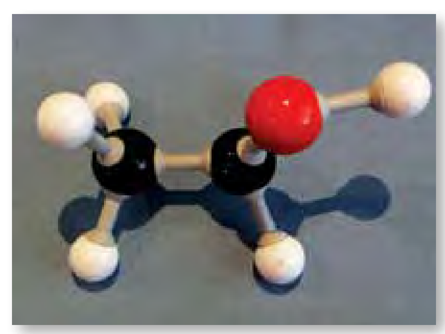
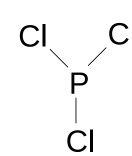


Figure 2.5 Ball and stick model of ethanol.

QUESTIONS

1. Describe different types of models you have constructed for elements and compounds and explain why some are preferable to others.
2. Explain why it is not correct to show sodium chloride as Na – Cl, yet it is correct to show phosphorus trichloride as:



3. All these models have limitations. Discuss this statement.

3 Intramolecular Forces

You already know that:

- Atoms of covalent substances share electrons.
- Most covalent substances exist as molecules.
- The atoms within these molecules are held together by strong covalent bonds – intramolecular forces.
- The whole molecules are attracted to each other by weaker forces – intermolecular forces.

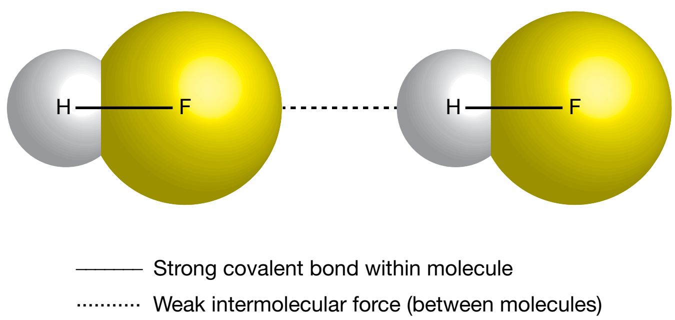


Figure 3.1 Forces within and between molecules of hydrogen fluoride.

The nature and strength of intermolecular forces can explain observable properties such as vapour pressure, melting point, boiling point and solubility. However, to understand this, **we first need to look at bonds and forces in more detail**.

Covalent bonds – non-polar bonds

When atoms share valence electrons to form covalent bonds the shared pair of electrons orbits both nuclei. Covalent bonds are very strong bonds.

In a molecule such as hydrogen (H_2), the two atoms are identical hydrogen atoms, so the bonding electrons are attracted equally to each nucleus and shared equally between them. The two shared electrons spend equal time in the area around each atom and this sharing of electrons forms the covalent bond which holds the atoms together. Such bonds are referred to as **non-polar covalent bonds**. Figure 3.2 shows two different types of models which can be used to illustrate this.

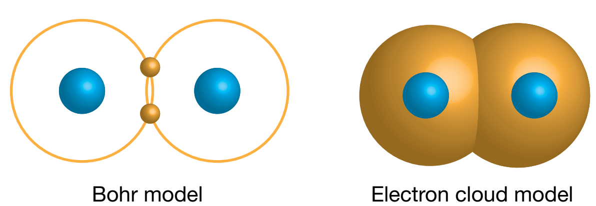


Figure 3.2 Molecule of hydrogen gas with non-polar bond between its atoms.

Covalent bonds – polar bonds

When the atoms joining together are not identical, then their electrons are not shared equally. For example, this happens when hydrogen and chlorine atoms share a pair of electrons to form hydrogen chloride (HCl). The shared electrons are more strongly attracted to the chlorine nucleus than to the hydrogen nucleus, so the electrons spend more time near the chlorine. This makes the chlorine end slightly more negative than the hydrogen end. A bond with unequal sharing of electrons is called a **polar covalent bond**. The bond forms a **dipole**, a structure with two oppositely charged ends and it can be shown as follows.

$$\delta^+ \mathbf{H} - \mathbf{Cl}\ \delta^-$$

The Greek lower case delta (δ) is used to represent a partial (small amount of) electrical charge, a much smaller charge than that on a proton or an electron. δ^+ and δ^- symbols indicate the areas on the molecule surface which are slightly more positive or slightly more negative due to unequal sharing of electrons.

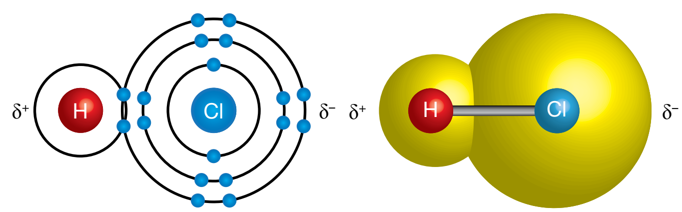
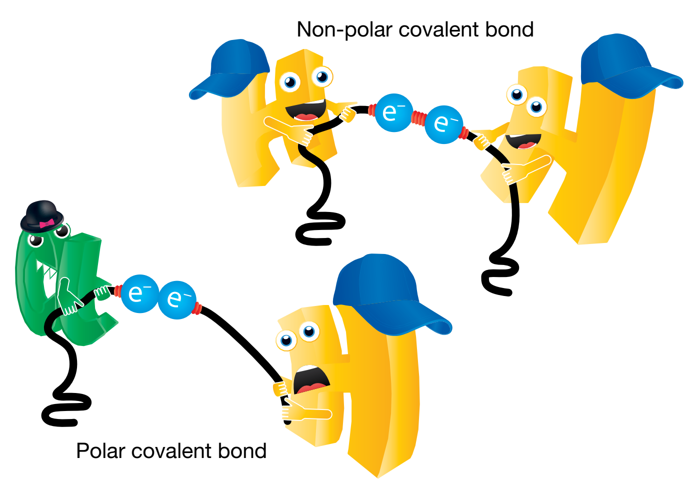


Figure 3.3 Electron dot and electron cloud diagrams to illustrate the polar bond in hydrogen chloride.

Polar and non-polar molecules

You could think about polar and non-polar bonds like this:



A molecule which consists of **only non-polar bonds**, e.g. H_2, Cl_2 will be called a **non-polar molecule**.

A molecule which contains **one polar bond**, e.g. HCl will have an unequal charge distribution so it will form a **polar molecule** with a slightly positive area at one end and a slightly negative area at the other end.

A molecule which has **more than one polar bond** may have **polar molecules**, such as in water H_2O, or **non-polar molecules** such as in tetrachloromethane CCl_4 (which used to be called carbon tetrachloride). Molecules such as CCl_4 have non-polar molecules because the way that the polar bonds are arranged means that they cancel each other out.

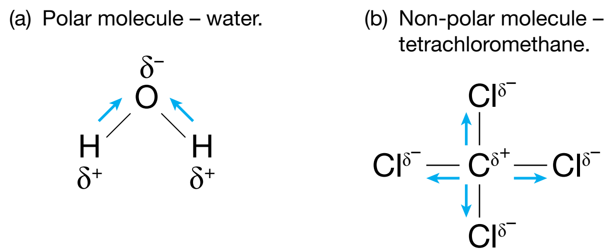


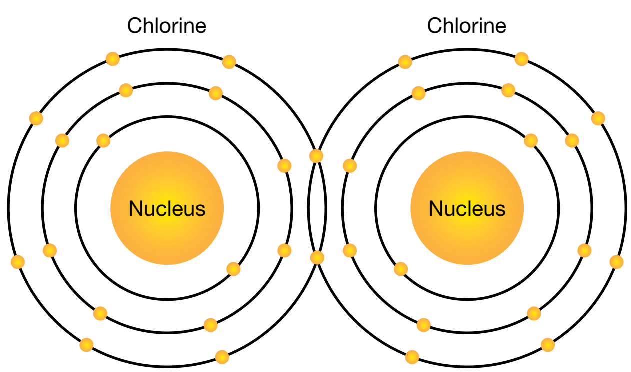
Figure 3.4 Polar and non-polar molecules.

With these non-polar molecules, the charge distribution is even over the surface of the molecules even though polar covalent bonds are present.

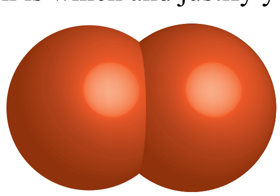
The shape of a molecule helps to determine whether or not polar bonds cancel each other out and thus whether the molecule will be polar or non-polar. You will be learning about shapes of molecules soon.

QUESTIONS

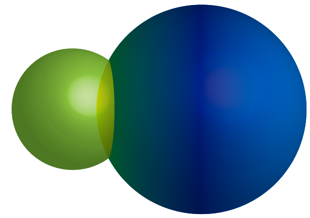
1. A molecule of chlorine is drawn below.
   (a) Identify the shared electrons in this molecule.
   (b) Explain why the chlorine molecule is said to contain a non-polar covalent bond.



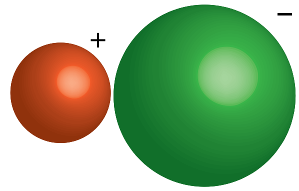
2. The following diagrams are said to illustrate the difference between an ionic bond, a non-polar covalent bond and a polar covalent bond. Identify which is which and justify your decisions.
   (a)



(b)



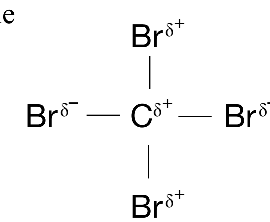
(c)



3. Copy and complete the table to show whether or not each of the substances listed has polar or non-polar bonds within its molecules.

Substance	Formula	Polar/non-polar bonds
Hydrogen		
Ammonia		
Hydrogen bromide		
Water		
Carbon dioxide		

4. The word 'polar' can be applied to a bond, a molecule and a substance. Discuss this statement.
5. Explain the difference in polarity between a hydrogen molecule and a hydrogen fluoride molecule.
6. Why is the tetrabromomethane molecule non-polar, even though it contains polar bonds.



7. Identify each of the following statements as true or false and justify your answer.
   (a) Oxygen molecules are non-polar.
   (b) Sodium chloride contains molecules of NaCl.
   (c) Chlorine contains polar covalent bonds.
   (d) Covalent bonds are strong forces of attraction within molecules.
8. Check your knowledge with this quick quiz.
   (a) A polar bond is an attraction between two atoms which are (the same/different).
   (b) The covalent bond in a bromine molecule is a (polar/non-polar) bond.
   (c) The covalent bond in a hydrogen fluoride molecule is (polar/non-polar).
   (d) Covalent bonds occur when electrons are (shared/donated/received).

Answers

Topic 4 Intermolecular Forces and Gases

1 Molecular Substances

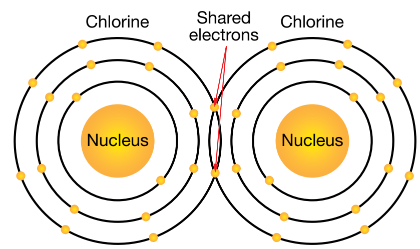
1. (a) A covalent bond is a strong attractive force which is the result of the sharing of electrons between non-metal atoms. It holds the atoms together within a molecule or a lattice.
   (b) A covalent compound is a compound made of non-metal atoms held together by covalent bonds.
   (c) A covalent lattice is a large network of non-metal or semi-metal atoms held together by covalent bonds throughout the lattice.
   (d) A molecule is the smallest amount of a substance that can exist and move independently.
   (e) Intermolecular forces are weak forces of attraction between molecules. They include dispersion forces, also called van der Waals forces.
2. (a) Various, e.g. helium H, krypton Kr.
   (b) Various, e.g. hydrogen H_2, chlorine Cl_2, oxygen O_2.
3. (a) Various, e.g. hydrogen chloride HCl, carbon monoxide CO, hydrogen iodide HI.
   (b) Various, e.g. carbon dioxide CO_2, ammonia NH_3, diphosphorus pentoxide P_2O_5, sulfur dioxide SO_2, methane CH_4.
4. (a) Carbon – covalent lattice.
   (b) Carbon dioxide – small covalent molecules.
   (c) Nitrogen – small covalent molecules.
   (d) Ammonia – small covalent molecules.
   (e) Phosphine (phosphorus trihydride) – small covalent molecules.
   (f) Silicon dioxide – covalent lattice.
5. (a) A molecule of chlorine (Cl_2) showing two identical chlorine atoms, each with original electron configuration 2.8.7, but now sharing an electron from their outer valence shells so that they have a stable configuration of 2.8.8.
   (b) A molecule of methane CH_4, showing just the outermost valence shell of the carbon atom. The carbon atom is sharing one of its valence electrons with each hydrogen atom so that all atoms have a stable configuration. Hydrogen: 2, and carbon: 2.8.
6. (a) Sharing.
   (b) Diatomic.
   (c) Carbon or silicon.
   (d) Various, e.g. polymers such as starch, cellulose, polyethene, polystyrene.

2 Representing Molecular Substances

1. Various.
   For example, you might describe how drawing the structure of ammonia as a two-dimentional image gives no information about the arrangement of the hydrogen atoms around the nitrogen, whereas concrete ball and stick or similar models can show this information including the angles and lengths of bonds.
2. Phosphorus trichloride is a covalent molecular compound composed of two non-metal atoms joined by covalent bonds. Covalent bonds are, by convention, shown as a straight line joining the two atoms that share electrons.
   Sodium chloride is an ionic compound. Its sodium and chloride ions are held together in a lattice by electrostatic attraction between opposite charges. No electrons are shared. Ionic bonds are never represented as a line joining ions.
3. Although these models are useful to allow visualisation of the structures and explain how the valence electrons are bonded, they all have limitations. There is no visualisation provided for the structure of atoms or the dynamic nature of atoms and bonds. They show atoms as either letters or solid spheres with no movement and no indication of energy involved either within atoms or within bonds.

3 Intramolecular Forces

1. (a)



   (b) The bond is the attractive force between the two chlorine atoms and it is formed by the sharing of an electron from each atom. The shared electrons orbit both atoms, holding them together. A bond which involves shared electrons (rather than the electrons being completely donated or taken away) is called a covalent bond. These two chlorine atoms are identical to each other and so they exert the same pull on the two electrons that they share. This means that the two valence electrons are shared equally between the two chorine atoms so the bond is described as non-polar – it does not have a pole (charged end) because the charged particles are distributed evenly throughout the whole molecule.
2. (a) This could be a non-polar covalent bond in a molecule such as Cl_2 or F_2. Electrons are shared equally between the two identical atoms; the electron cloud is symmetrical.
   (b) This could represent a polar bond between atoms which are different to each other, e.g. in HCl or HF. In a polar covalent bond, electrons are shared unequally between two different atoms.
   (c) Diagram (c) could represent the attraction between an anion and a cation, e.g. between sodium and chloride ions in sodium chloride, Na^+Cl^-. In an ionic bond, electrons are not shared, they are transferred from one atom to another – from the sodium to the chlorine. (Later we will see that the difference in electronegativity is big enough for the most electronegative atom (e.g. chlorine) to completely remove the electron from the other atom (e.g. sodium.) The bond is an electrostatic attraction between charged particles (ions). This diagram shows two oppositely charged particles, a cation and an anion.
3.

Substance	Formula	Polar/non-polar bonds
Hydrogen	H_2	Non-polar
Ammonia	NH_3	Polar
Hydrogen bromide	HBr	Polar
Water	H_2O	Polar
Carbon dioxide	CO_2	Non-polar

4. Polar refers to having charged ends.
   A polar bond is an attraction between atoms where one atom is more electronegative and so attracts the shared pair of electrons more strongly. The electrons spend more time near the most electronegative atom so it develops a slight negative charge, e.g. δ^+ H–Cl δ^-
   Polar molecules refer to molecules which have charged areas. Hydrogen chloride only has the one bond – it is polar so the molecule is polar. Larger molecules are polar if they contain polar bonds which do not cancel each other out, e.g. water molecules.
   A substance is polar if it contains polar molecules.