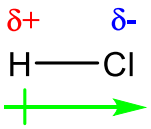
3.6 INTERMOLECULAR FORCES, ELECTRONEGATIVITY AND BOND PROPERTIES

Learning outcomes
Candidates should be able to:

1. (a) describe hydrogen bonding, limited to molecules containing N–H and O–H groups, including ammonia and water as simple examples
   (b) use the concept of hydrogen bonding to explain the anomalous properties of H_2O (ice and water):
   • its relatively high melting and boiling points
   • its relatively high surface tension
   • the density of the solid ice compared with the liquid water
2. use the concept of electronegativity to explain bond polarity and dipole moments of molecules
3. (a) describe van der Waals' forces as the intermolecular forces between molecular entities other than those due to bond formation, and use the term van der Waals' forces as a generic term to describe all intermolecular forces
   (b) describe the types of van der Waals' force:
   • instantaneous dipole – induced dipole (id-id) force, also called London dispersion forces
   • permanent dipole – permanent dipole (pd-pd) force, including hydrogen bonding
   (c) describe hydrogen bonding and understand that hydrogen bonding is a special case of permanent dipole – permanent dipole force between molecules where hydrogen is bonded to a highly electronegative atom
4. state that, in general, ionic, covalent and metallic bonding are stronger than intermolecular forces

Bond polarity and dipole moments

When the electronegativity values of the two atoms forming a covalent bond are the same, the pair of electrons is equally shared. We say that the covalent bond is **non-polar**. For example, hydrogen (H_2), chlorine (Cl_2) and bromine (Br_2) are non-polar molecules.
When a covalent bond is formed between two atoms having different electronegativity values, the more electronegative atom attracts the pair of electrons in the bond towards it.
As a result: the centre of positive charge does not coincide with the centre of negative charge
we say that the electron distribution is asymmetric, the two atoms are partially charged



Not all molecules with polar bonds are polar molecules. Sometimes the polar bonds cancel each other out because the same types of bonds have dipoles 'pulling' in opposite directions.

1. Explain the meaning of the term **bond polarity.** **[1]**

2. Are the following molecules polar or non-polar? In each case give a reason for your answer.
   (Electronegativity values: F = 4.0, Cl = 3.0, Br = 2.8, S = 2.5, C = 2.5, H = 2.1)
   chlorine, Cl_2

   hydrogen fluoride, HF

the V-shaped molecule, sulfur dichloride, SCl_2

the tetrahedral molecule, chloromethane, CH_3Cl

the tetrahedral molecule, tetrabromomethane, CBr_4

1. Which of the following dipole labels is not correct?

a. $\overset{\delta+}{C}\text{-}\overset{\delta-}{O}$ in propanol

b. $\overset{\delta+}{C}=\overset{\delta-}{O}$ in propanal

c. $\overset{\delta+}{C}\text{-}\overset{\delta-}{H}$ in propane

d. $\overset{\delta+}{C}\text{-}\overset{\delta-}{Cl}$ in chloropropane

3. A bond between nitrogen and hydrogen can be represented as $\overset{\delta-}{N}\text{——}\overset{\delta+}{H}$

i. In this representation, state the meaning of δ+. 1

ii. From this bond representation, state what can be deduced about the electronegativity of hydrogen relative to that of nitrogen.

1

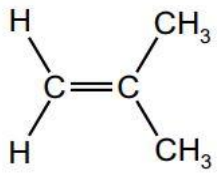
4. Complete Table 1.2 by placing a tick (✓) to show which of the compounds have molecules with an overall dipole moment.

compound	O=C=O	O=S=O	S=C=S	S=C=O
overall dipole moment				

5. Suggest why the bond in a molecule of CO contains a dipole moment. [1]

2. Which molecule has the largest overall dipole moment?

A



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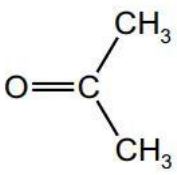

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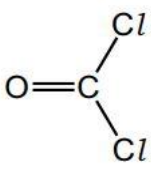

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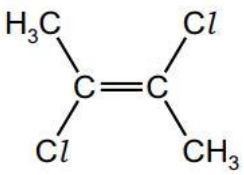
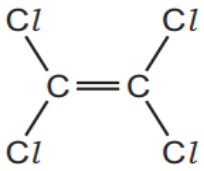


3. Which molecule has the largest overall dipole?

A



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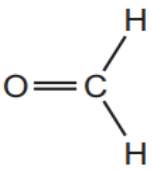

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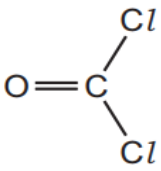

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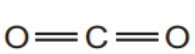


4. For which molecule is the dipole moment zero?

A CH_3Cl **B** CH_2Cl_2 **C** $CHCl_3$ **D** CCl_4

van der Waals' forces

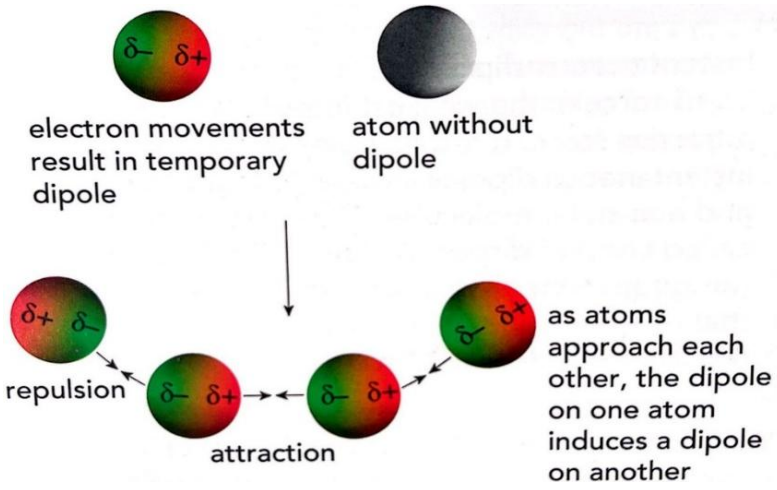
The forces within molecules due to covalent bonding are strong. However, the forces between molecules are much weaker. We call these forces van der Waals' forces (intermolecular forces).
There are two types of van der Waals' (intermolecular) force:

- instantaneous (temporary) dipole–induced dipole forces (id–id) forces. These are also called London dispersion forces.
- permanent dipole–permanent dipole (pd–pd) forces (including hydrogen bonding).

A special case of permanent dipole–permanent dipole forces is hydrogen bonding.

Instantaneous dipole–induced dipole (id–id) forces London dispersion forces

The electron charge clouds in a non-polar molecule (or atom) are constantly moving. It often happens that more of the charge cloud is on one side of the molecule than the other. This means that one end of the molecule has, for a short time, more negative charge than the other. A temporary dipole is set up. This dipole can set up (induce) a dipole on neighbouring molecules. As a result of this, there are forces of attraction between the δ+ end of the dipole in one molecule and the δ– end of the dipole in a neighbouring molecule (Figure 4.34). These dipoles are always temporary because the electron clouds are always moving. **Instantaneous dipole–induced dipole forces** are sometimes called **temporary dipole–induced dipole forces**.



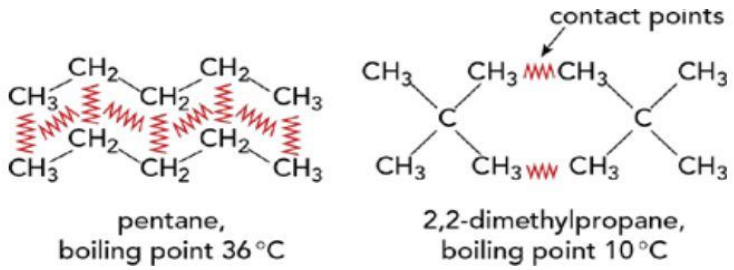
Instantaneous dipole–induced dipole forces increase with:

- increasing number of electrons (and protons) in the molecule
- increasing the number of contact points between the molecules: contact points are places where the molecules come close together.

The table lists the formulae and boiling points of some alkanes. Explain the trend in terms of instantaneous dipole–induced dipole forces.

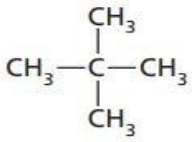
Alkane	methane	ethane	propane	butane
Structural formula	CH_4	CH_3CH_3	$CH_3CH_2CH_3$	$CH_3CH_2CH_2CH_3$
Boiling point	–164**°C**	–88**°C**	–42**°C**	0°C

The effect of increasing the number of contact points can be seen by comparing the boiling points of pentane (boiling point 36 °C) and 2,2-dimethylpropane (boiling point 10 °C). These compounds have equal numbers of electrons in their molecules.



The molecules in pentane can line up beside each other so there is a large number of contact points. The id–id forces are higher, so the boiling point is higher. The molecules of 2,2-dimethylpropane are more compact. The surface area available for coming into contact with neighbouring molecules is smaller. The id–id forces are relatively lower, so the boiling point is lower.

The id–id forces between individual atoms are very small. However, the total id–id forces between very long non-polar molecules such as poly(ethene) molecules can be much larger. That is why poly(ethene) is a solid at room temperature.

Molecule	Boiling point/°C
CH_4	–162
SiH_4	–112
F_2	–188
Cl_2	–34
Br_2	+58
CH_4	–161
C_2H_6	–89
C_3H_8	–42
C_4H_{10}	0
	+10
$CH_3CH_2CH_2CH_2CH_2CH_3$	+36

6. The boiling points of the halogens are:
fluorine –188°C chlorine –35°C bromine +59°C iodine +184°C
Describe the trend in these boiling points going down Group 17.

5. Chlorine and bromine have different volatilities.
Which row identifies the more volatile of the two elements, and gives the correct explanation?

	identity of the more volatile element	explanation for the difference in volatility
A	bromine	intermolecular forces are greater in bromine than they are in chlorine
B	bromine	intermolecular forces are greater in chlorine than they are in bromine
C	chlorine	intermolecular forces are greater in bromine than they are in chlorine
D	chlorine	intermolecular forces are greater in chlorine than they are in bromine

7. The elements in Group 17 are known as the halogens.
Between the molecules of Group 17 elements van der Waals' forces exist.
State the trend in the relative strength of van der Waals' forces down Group 17. [1]

6. The boiling points of methane, ethane, propane and butane are given.

compound	CH_4	CH_3CH_3	$CH_3CH_2CH_3$	$CH_3CH_2CH_2CH_3$
boiling point / K	112	185	231	273

Which statement explains the increase in boiling point from methane to butane?

A Closer packing of molecules results in stronger van der Waals' forces.
B More covalent bonds are present, and therefore, more energy is required to break the bonds.
C More electrons in the molecules result in stronger van der Waals' forces.
D More hydrogen atoms in the molecules result in stronger hydrogen bonding.

8. Sulfides are compounds that contain sulfur but not oxygen.
Carbon disulfide, CS_2, is a volatile liquid at room temperature and pressure.
State the meaning of volatile. [1]

9. CS_2 is a liquid under room conditions, while CO_2 is a gas.
Explain what causes the difference in the physical properties between CS_2 and CO_2. [2]

7. Silver and iodine are both shiny crystalline solids.
Which force exists between neighboring iodine molecules in solid iodine and particles in solid silver?

	Iodine	Silver
A	Metallic bonds	Covalent bonds
B	Ionic bonds	Metallic
C	Covalent bonds	Covalent bonds
D	Van der Waals' forces	Metallic

Permanent dipole–permanent dipole (pd–pd) forces

10. The table states the electronegativity values of carbon, nitrogen and oxygen atoms.

	C	N	O
electronegativity	2.5	3.0	3.5

Use the electronegativity values and relevant details from the **Data Booklet** to complete the table below. [2]

	CO	N_2
number of electrons per molecule		
type(s) of intermolecular (van der Waals') force		

11. Complete the table by naming **all** the types of intermolecular forces (van der Waals') in separate samples of $N_2(g)$ and CO(g). [2]

	$N_2(g)$	CO(g)
number of electrons per molecule	14	14
presence of a dipole moment	x	√
boiling point/°C	–195.8	–191.5
intermolecular forces (van der Waals')		

12. Gallium is a metal in Group 13 of the Periodic Table.
Gallium and its compounds show similar properties to aluminium and its compounds.
Gallium reacts with excess chlorine to form gallium trichloride.
(i) At 500° C, gallium trichloride is a gas.
Suggest the type of attraction that exists at 500 ° C
●● between atoms within a gallium trichloride molecule

……
●● between gallium trichloride molecules.

…… [2]

13. The reaction of ethene, C_2H_4, with a 1:1 mixture of CO and H_2 is shown in equation 1.
equation 1 $C_2H_4(g) + CO(g) + H_2(g) \rightarrow CH_3CH_2CHO(g)$
The reaction mixture is cooled to collect CH_3CH_2CHO as a liquid. Identify all types of van der Waals' forces that are present between molecules of CH_3CH_2CHO. [1]

8. In which substance are the only intermolecular forces temporary dipole-induced dipole attractions?

A hydrogen chloride **B** methanol **C** octane **D** water

14. SCl_2 has $M_r = 103.1$ and is a liquid at room temperature. SBr_2 has $M_r = 191.9$ and is a gas at room temperature. Explain the difference in the physical state of SCl_2 and SBr_2. Give your answer in terms of intermolecular forces. [2]

15. Methanal, CH_2O is a liquid at –30 °C but carbon dioxide is a gas at this temperature. Explain why.

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..... [2]

1. Nitrogen, N_2, and carbon monoxide, CO, both have Mr = 28.
The boiling point of N_2 is 77 K.
The boiling point of CO is 82 K.
What could be responsible for this difference in boiling points?

A CO molecules have a permanent dipole; the N_2 molecules are not polar.
B N_2 has covalent bonding only; CO has covalent and coordinatebonding .
C N_2 has a strong N≡N bond; CO has a C=O bond.
D The CO molecule has more electrons than the N_2 molecule.

2. The boiling points of some hydrogen halides are shown.

hydrogen halide	boiling point / K
H–C**l**	188
H–Br	206
H–I	238

What is the explanation for the trend in boiling point for the hydrogen halides from HCl to HI?

A The bond energies of the hydrogen halides increase from HC**l** to HI.
B There is an increase in the strength of the intermolecular forces of attraction from HC**l** to HI.
C The intermolecular hydrogen bonds become stronger from HC**l** to HI.
D There is an increase in the bond polarity from HC**l** to HI.

3. The boiling points of Br_2, ICl and IBr are given in the table.

	Br_2	IC*l*	IBr
boiling point / °C	59	97	116

Which row explains:
why the boiling point of ICl is greater than Br_2?
why the boiling point of IBr is greater than ICl ?

	boiling point of IBr is greater than ICl	boiling point of IC*l* is greater than Br_2
A	IBr has stronger instantaneous dipole-induced dipoles	IC*l* has stronger instantaneous dipole-induced dipoles
B	IBr has stronger instantaneous dipole-induced dipoles	IC*l* has permanent dipoles
C	IBr has stronger permanent dipoles	IC*l* has stronger instantaneous dipole-induced dipoles
D	IBr has stronger permanent dipoles	IC**l** has permanent dipoles

4. Why does ICl have a higher boiling point than Br2?

A because of the difference in the bond energies of the covalent bonds within ICl and Br2
B because of the difference in the polar nature of ICl and Br2
C because of the difference in the number of electrons contained within ICl and Br2
D because of the difference in the relative molecular mass of ICl and Br2

5. Elements X, Y, and Z are all in the first two periods of the Periodic Table.
Their Pauling electronegativity values, E_N, are shown.

Element	*E*N
X	1.0
Y	2.1
Z	4.0

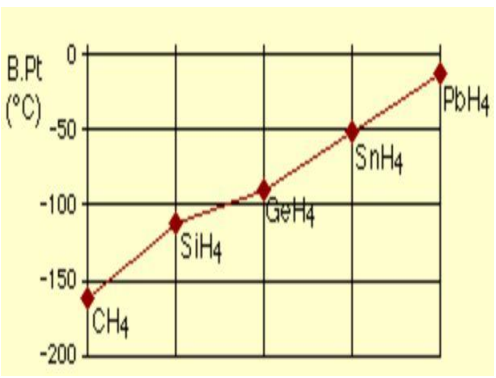
Substances exist with formulae XZ, YZ, and Z_2.
Which row puts these substances in order of increasing melting point?

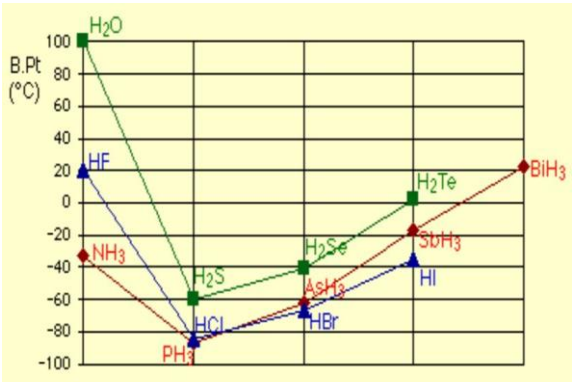
	Lowest melting point →		highest melting point
A	XZ	YZ	Z_2
B	XZ	Z_2	YZ
C	Z_2	YZ	XZ
D	Z_2	XZ	YZ

16. **C1** has melting point –94°C and boiling point +49°C.
Explain these properties by referring to the type of van der Waals' forces between molecules. [2]

C1

Hydrogen bonding





Ammonia has an average of 1 hydrogen bond per molecule.

17. State the strongest type of intermolecular force in **a** water and **b** hydrogen sulfide (H_2S).

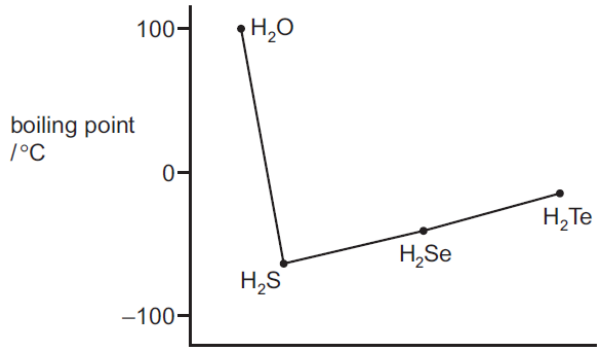
6. In a sample of pure water, what is the maximum number of hydrogen bonds that one molecule of water can be involved in?

A 1 **B** 2 **C** 3 **D** 4

7. At room temperature and pressure, H_2O is a liquid and H_2S is a gas.
What is the reason for this difference of state?

A O has higher first and second ionisation energies than S.
B The covalent bond between O and H is stronger than the covalent bond between S and H.
C There is significant hydrogen bonding between H_2O molecules but **not** between H_2S molecules.
D The instantaneous dipole-induced dipole forces between H_2O molecules are stronger than the instantaneous dipole-induced dipole forces between H_2S molecules.

8. The graph shows the boiling points of the hydrogen compounds of Group 16 elements.



Which statement correctly explains why water does **not** fit the trend of the other compounds?

A There are fewer electrons in the oxygen atoms so there is less shielding of the nuclear charge.
B There are strong hydrogen bonds in water but not in the other compounds.
C The covalent bonds in water are much stronger than in the other compounds.
D The water molecules are smaller and so have stronger van der Waals' forces.

18. The table lists the boiling points of some Group 15 hydrides.

Hydride	**Boiling point / °C**
ammonia, NH_3	–33
phosphine, PH_3	–88
arsine, AsH_3	–55
stibine, SbH_3	–17

Table 4.5: Information table for Question 17.

i. Explain the trend in the boiling points from phosphine to stibine.

iii. Explain why the boiling point of ammonia does not follow this trend.

19. Hydrogen halides are compounds formed when halogens (Group 17 elements) react with hydrogen. The bond polarity of the hydrogen halides decreases from HF to HI.
Some relevant data are shown in the table.

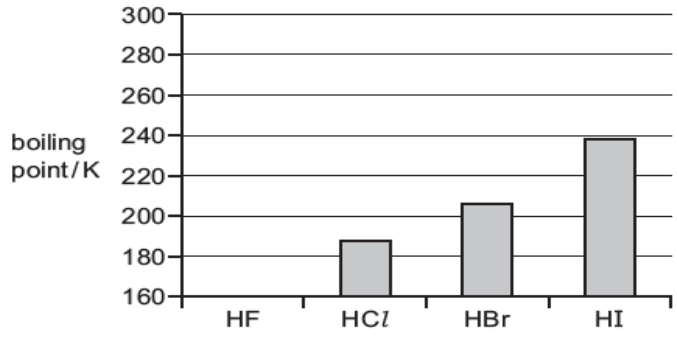
hydrogen halide	HF	HC*l*	HBr	HI
boiling point/°C	19	–85	–67	–35
H–X bond energy/KJ mol^{-1}	562	431	366	299

Suggest why the boiling point of HF is much higher than the boiling points of the other hydrogen halides. [2]

9. For which pair is the boiling point of the first compound **higher** than the boiling point of the second compound?

A CH_3CH_2OH and CH_3CH_2SH
B $CH_3CO_2CH_3$ and $CH_3CH_2CO_2H$
C CH_3OCH_3 and CH_3CH_2OH
D CH_3CH_2CHO and $CH_3CH_2CO_2H$

20. The bar chart shows the boiling points of HC*l*, HBr and HI. The boiling point of HF is not shown.



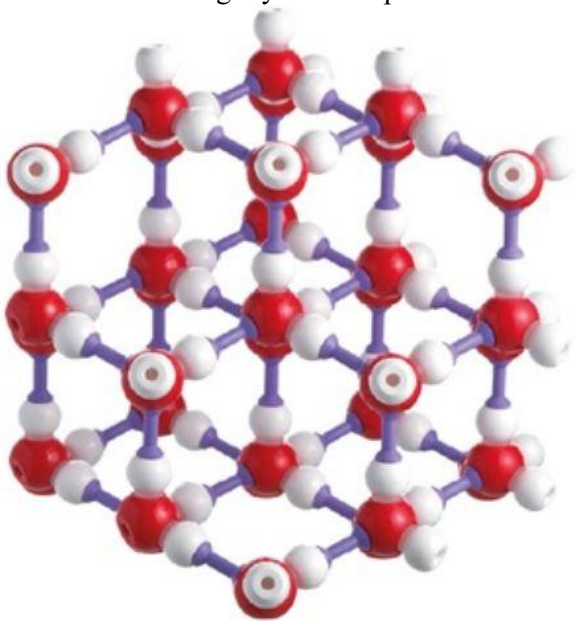
Hydrogen bonds form between HF molecules.
Draw a bar on the bar chart to predict the boiling point of HF.
Explain your answer. [1]

ANOMALOUS PROPERTIES OF H_2O

It has relatively high melting and boiling points.
Due to extensive hydrogen bonding
In average a water molecule has 2 hydrogen bonds

It has relatively high surface tension.
The hydrogen bonds in water also exert a significant downward force at the surface of the liquid. This causes the surface tension of water to be higher than for most liquids. Hydrogen bonding reduces the ability of water molecules to slide over each other, so the viscosity of water is high.

The density of the solid ice is less compared with the liquid water.
Most solids are denser than their liquids. This is because the molecules are more closely packed in the solid state. But this is not true of water. In ice, there is a three-dimensional hydrogen-bonded network of water molecules. This produces a rigid lattice in which each oxygen atom is surrounded by a tetrahedron of hydrogen atoms. This 'more open' arrangement, due to the relatively long bond lengths of the hydrogen bonds, allows the water molecules to be slightly further apart than in the liquid. So the density of ice is less than that of liquid water.



10. The strength of hydrogen bonding increases as the electronegativity of the element bonded to hydrogen increases.
Some information for a range of hydrides is given.

hydride	boiling point/ K
PH_3	185
HCl	188
HF	293
H_2O	373

Which statement and reason about these hydrides is correct?

1. The boiling point of PH_3 is much lower than the boiling point of H_2O because PH_3 does not form hydrogen bonds or instantaneous dipole-induced dipole forces between its molecules.
2. The boiling point of HF is higher than the boiling point of HCl because the bond energy of H–F is greater than the bond energy of H–Cl.
3. The boiling point of H_2O is higher than the boiling point of HF because each hydrogen bond between the H2O molecules is stronger than each hydrogen bond between HF molecules.
4. The boiling points of PH_3 and HCl are similar because the molecules of PH_3 and HCl have the same number of electrons and similar intermolecular forces.

21. (i) Name the strongest type of intermolecular force in ice. [1]

(ii) Draw a fully labelled diagram of two water molecules in ice, showing the force in **(i)** and how it forms. [3]

22. Methanol, CH_3OH, is soluble in water because it forms hydrogen bonds with water molecules.
Draw a fully labelled diagram to show how a hydrogen bond forms between a water molecule and a methanol molecule. [3]

23. (i) Name the strongest intermolecular force that exists between $NH_3(l)$ molecules. [1]

(ii) Draw a diagram to show the formation of the strongest intermolecular force between **two** molecules of $NH_3(l)$.
Include any relevant lone pairs of electrons and dipoles. [2]

(iii) The melting points of ice and ammonia are shown in Table 1.2.

solid	melting point/K
ice	273
ammonia	195

(ii) Suggest **two** reasons for the difference in the melting points of ice and ammonia. [2]

11. Descriptions of the bonding in three substances are given.

substance 1 strong covalent bonds between atoms, permanent dipole-dipole attractions between molecules
substance 2 strong covalent bonds between atoms, weak forces between molecules
substance 3 strong covalent bonds between atoms, hydrogen bonding between molecules

Which compounds could be substances 1, 2 and 3?

	substance 1	substance 2	substance 3
A	CH_3OH	Al_2Cl_6	CH_2Cl_2
B	Al_2Cl_6	CH_2Cl_2	CH_4
C	CH_2Cl_2	CH_4	CH_3OH
D	CH_4	CH_3OH	H_2O

24. Lactic acid forms hydrogen bonds with water.
Complete Fig. 4.2 to show the formation of a hydrogen bond between one molecule of lactic acid and one molecule of water.
Label the hydrogen bond. Show any relevant dipoles and lone pairs of electrons. [3]

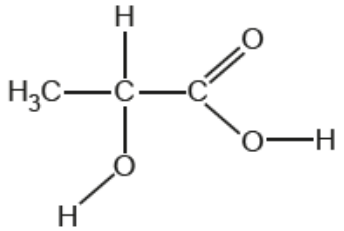


Fig. 4.2

12. In which of the following, when in liquid form, are there only intermolecular forces based on temporary dipoles between the particles?

A bromine B ethanol C hydrogen chloride D water

Common properties of compounds having different kind of bonds

Physical state at room temperature and pressure

Ionic compounds- mostly solid

Metals- solids (except mercury) with high melting and boiling points
Covalent compounds- usually gas and liquids due to weak intermolecular forces- some are solids if have relatively stronger intermolecular forces.

Solubility

Ionic compounds – soluble in water- due to ion-dipole interactions
Metals – insoluble in water
Covalent compounds
    Non-polar compounds insoluble in water
    Polar compounds slightly soluble in water- compounds that can form hydrogen bond- soluble in water

Electrical conductivity

Ionic compounds- conductor in liquid or solution; non-conductor in solid(Crystal) state
Metals- conductor in both solid and liquid
Covalent compounds- non-conductor

13. The compound $(CH_3)_3NAlCl_3$ has a simple molecular structure.
Which statement about $(CH_3)_3NAlCl_3$ is correct?

A $(CH_3)_3NAlCl_3$ molecules attract each other by hydrogen bonds.
B The Al atom in $(CH_3)_3NAlCl_3$ has an incomplete valence shell of electrons.
C The bonds around the Al atom are planar.
D The molecules contain coordinate bonding.

14. The table shows bond energies for some diatomic molecules. Deuterium, D, is an isotope of hydrogen.

energy / kJ mol^{-1}	bond
158	F–F
242	Cl–Cl
193	Br–Br
151	**I–I**
436	H–H
442	D–D

Which statements are correct?

1 Diatomic molecules have exact values for their bond energies, which are always positive.

2 The trend in Group 7 bond energies can be explained by the variation in instantaneous dipole–induced dipole (id–id) forces.

3 A value for the enthalpy change for the reaction between deuterium and chlorine can be calculated using these data alone.

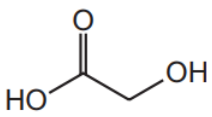
A 1 only **B** 1 and 2 only **C** 1 and 3 only **D** 2 and 3 only

15. Phosphine, PH_3, can react with hydrogen ion H^+, to from phosphonium ion.
Which type of bond is formed in this reaction?

a. Dipole-dipole forces
b. Ionic bond
c. Dative covalent bond
d. Hydrogen bond

25. Explain why **C** is very soluble in water

C



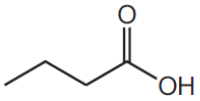
[1]

16. Which type of interaction exists between water molecules and metal cations in aqueous solution?

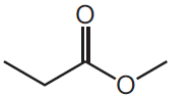
A dipole-dipole interactions
B hydrogen bonds
C ion-dipole interactions
D ionic bonds

17. The structures represent three compounds, each with four carbon atoms per molecule.

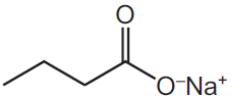
X



Y



Z



Which row is correct?

	lowest boiling point	→	highest boiling point
A	X	Y	Z
B	Y	X	Z
C	Z	X	Y
D	Z	Y	X

18. The boiling point of water, H_2O, is higher than that of hydrogen sulfide, H_2S.
Which statement explains this difference in boiling points?

A The bond energy of O–H is greater than the bond energy of S–H.
B The intermolecular forces in H_2O are weaker than the intermolecular forces in H_2S.
C The S–H bond in H_2S is longer than the O–H bond in H_2O.
D There is significant intermolecular hydrogen bonding in H_2O but not in H_2S.

*****This is not a complete note. It is to guide you. It is recommended to study the prescribed textbooks along with this material. *****