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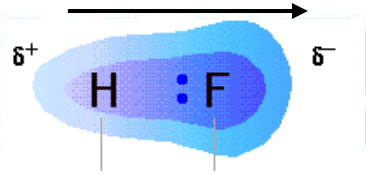
Permanent and Instantaneous/Induced Dipoles

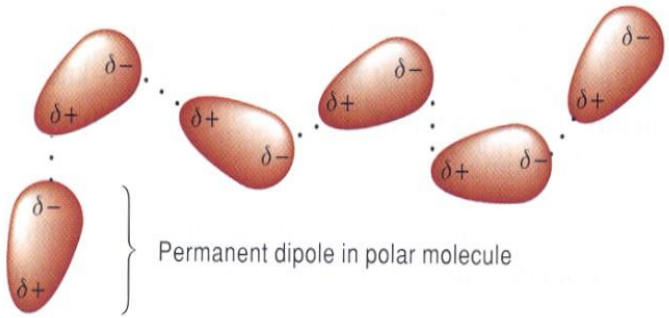
Permanent Dipole

A polar molecule acts as an ***electric dipole*** which can interact with electric fields that are created artificially or that arise from nearby ions or polar molecules.

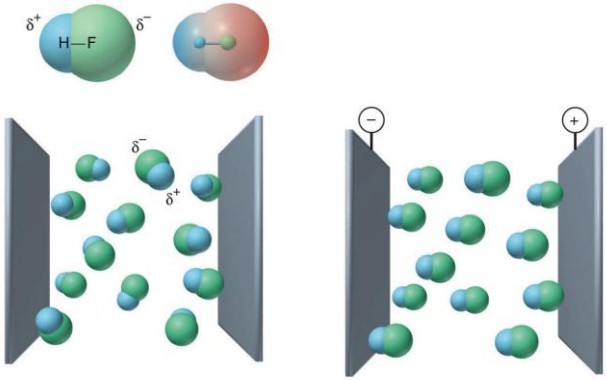
Dipoles are conventionally represented as arrows pointing in the direction of the negative end.



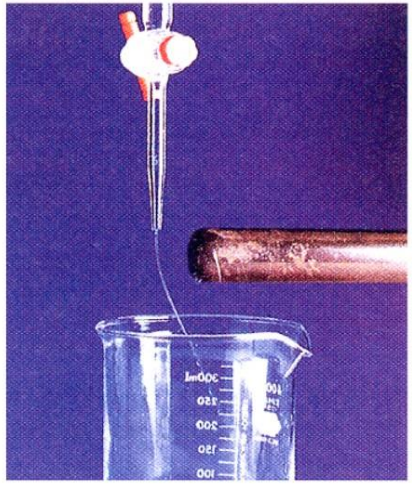
Permanent dipole – permanent dipole attraction forces



Fixed alignments of polar covalent molecule in an electric field

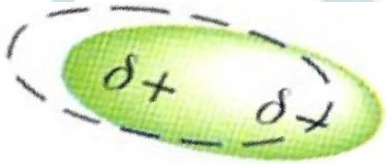


Polar molecules are deflected in presence of charged rod



Instantaneous/*Induced Dipole*

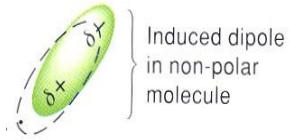
When its electrons which are mobile moves and there will be an instant when the congregation of electrons in a spatial area creates a ***temporal charged region that allows the establishment of temporarily weak intermolecular forces*** *between each other.*



Congregation of electrons that give rise to a partial negative charge denoted by δ-

Instantaneous/Induced dipole – induced dipole attraction forces

instantaneous dipole



Factors for determining polar or non-polar covalent molecules

- Existence of polar covalent bond due to difference in electronegativities of bonding atoms
- Shape of molecules
- Vector summation of dipole moments

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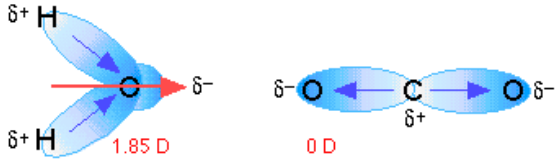
Determining whether covalent molecules are polar or non-polar

a. Diatomic molecule

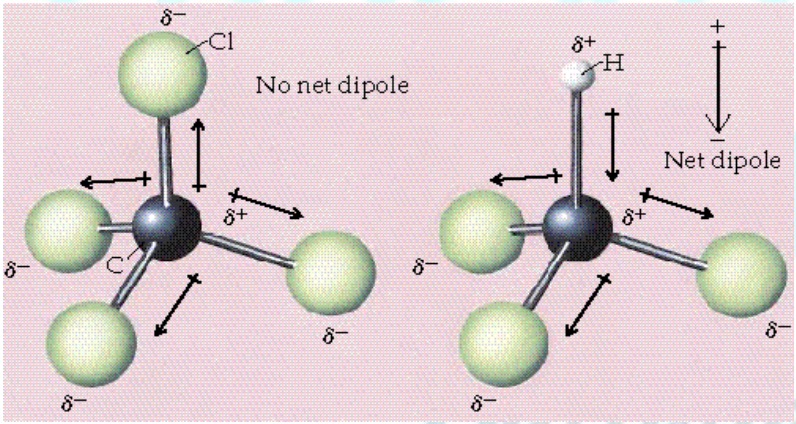
- X-X: molecules are non-polar since there is no polar covalent bond
- X-Y: molecules are polar since there is polar covalent bond and dipole moment



b. Polyatomic molecule

- Determine the shape of molecule
- Mark the dipole moment of each polar covalent bond
- Conduct vector summation of the dipole moments

Example: CCl_4 and $CHCl_3$



- Molecules which have zero lone pairs, and have identical atoms bonded to the central atom are non-polar. Examples: $BeCl_2$, BF_3, $AlCl_3$, CCl_4, CF_4, PCl_5 and SF_6.

c. Acid molecules like HNO_3, HNO_2, H_2SO_4, H_2SO_3, and HClO have to release H^+ in the presence of water and they are polar covalent molecules. The hydrogen atom in an acid molecule is covalently bonded to the most electronegative atom to ensure that the hydrogen is δ+ and susceptible to be attracted and lost to water molecules.

Comparing instantaneous/induced dipole-dipole attraction forces between non-polar covalent molecules

- **Total number of electrons in molecule**

The **greater the number of electrons in the molecule**, the molecule can **better** polarize leading to a stronger **instantaneous/induced dipole to induced dipole attraction forces**

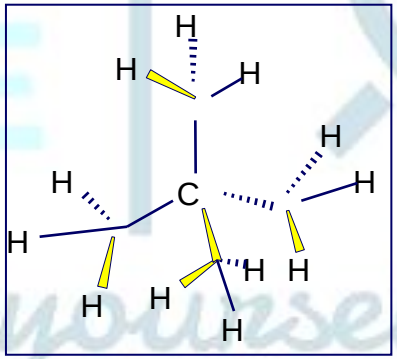
Example 1: Boiling points of Group 14 hydrides

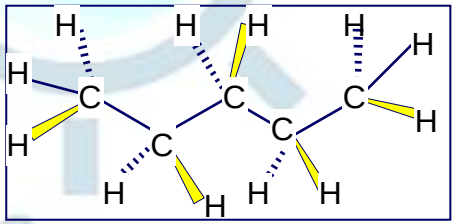
	CH_4	SiH_4	GeH_4	SnH_4
Boiling Point	-162 ºC	-112 ºC	-90 ºC	-52 ºC
Size of molecules Increases down the Group 14 Hydrides				

- **Molecular area to polarize molecule**

Cylindrical-shaped molecule has larger molecular area than spherical shaped and **better** able to polarize the molecule to a stronger **instantaneous/induced dipole to induced dipole attraction forces**

Example: The boiling point of 2,2-dimethylpropane is 9.5ºC, while the boiling point of pentane is 36ºC.





2,2-dimethylpropane pentane

branched	unbranched
More spherical	More cylindrical/elongated
Smaller molecular area	Larger molecular area

Exercise 1A:

Q1. Which of the following compounds: hydrogen or hydrogen chloride has a higher boiling point?

Hydrogen gas is non-polar since hydrogen atoms have the same electronegativity. HCl consists of polar covalent molecules, which establish permanent dipole- permanent dipole attraction forces.

Q2. Which of the following compounds: BrF or ClF has a higher boiling point?

Electronegativity: F>Cl>Br. Difference in electronegativity between F and Br is higher and thus BrF has a stronger permanent dipole than ClF, and hence higher boiling point.

Q3. Which of the following compounds: BrF or Cl_2 has a higher boiling point?

Large difference in electronegativities between Br and F; stronger intermolecular permanent dipole-dipole attraction forces between BrF molecules.

Q4. Polar/Non-Polar SO_3, ICl_3, SF_4?

Q5. Compare which molecules are more polar?

- **H_2O, H_2S, H_2Se**
- **O=C=O, O=C=S, O=C=Se**

Q6. Which of the following statements is true?

- Polar covalent molecule must contain at a least a polar covalent bond.
- Non-polar covalent molecule cannot contain polar covalent bond.
- Molecules with non-polar covalent bonds are non-polar.
- Molecules with polar covalent bonds are polar.

Q7. Polar or non-polar for Carbon Monoxide and label its dipole moment.

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Exercise 1B: Polar / Non Polar Covalent Molecules

Q1. Determine which of the following molecule is polar.

Molecule	Learning Pointer
HCl	Studying diatomic molecule.
HBr	
ClF	
$BeCl_2$	Studying molecules that do not have lone pair electrons and all the bonding atoms to the central atom are identical.
BF_3	
$AlCl_3$	
CCl_4	
CF_4	
PCl_5	
SF_6	
Ethene	Studying molecule that contains a C=C double bond. C=C contains a pi bond resulting in _____ rotation of the C to C atoms.
CH_2=CHCl	
Cl_2C=CCl_2	
CH_3Cl	Studying molecule that contains a methyl group. A methyl is electron _____.
$(CH_3)_3N$	
Ethane	Alkane molecules are saturated hydrocarbon and they are _____.
Benzene	Understanding shape of a molecule.
XeF_4	
PtF_6	
CH_3NH_2	

Q2. Which of the following molecules has no permanent dipole?

A . CCl_2F_2 B . $CHCl_3$ C. C_2Cl_4 D. C_2H_5Cl

Briefly explain your answer.

Q3. Which of the following molecules has the highest boiling point?

A . CCl_4 B . CF_4 C. C_2Cl_4 D. C_2H_6

Briefly explain your answer.

Q4. Which of the following statements about a polar molecule is TRUE?

A. consists of atoms differing widely in electronegativity.

B. Consists of ions.

C. Takes up a preferred orientation when placed in an electric field.

D. Is composed of an odd number of atoms.

E. Consists of polar covalent bond.

Give an example of non-polar molecules for each of the statement that is NOT TRUE about a polar molecule.

Q5. Which of the following statements is NOT CORRECT? You can have more than 1 answer.

A. A molecule, XY_2 is polar when X is a central atom with 1 lone pair of electrons.

B. A molecule, XY_2 is polar when X is a central atom with 2 lone pair of electrons.

C. A molecule, XY_2 is polar when X is a central atom with 3 lone pair of electrons.

D. A molecule, XY_4 is polar when X is a central atom with 1 lone pair of electrons.

E. A molecule, XY_4 is polar when X is a central atom with 2 lone pair of electrons.

Q6. Polar solvent like water are deflected by a charged sphere, like a stream of free flowing water as shown below. Sketch HNO_3, HNO_2, H_2SO_4, H_2SO_3, HCl, HClO, $CHCl_3$, CH_2Cl_2, CCl_4 and BCl_3 molecules and determine whether they are to be deflected by the same charged sphere.

Q7. Sketch the shape of ICl_3 and sketch the orientation of the molecules in the presence of an electric field set up by the charged plates as shown below.

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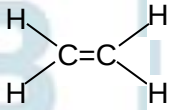
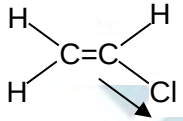
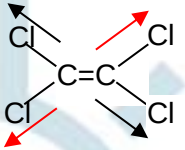
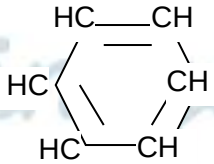
Q1. Determine which of the following molecule is polar.

Molecule	Learning Pointer
HCl	Studying diatomic molecule. X-Y: polar X-X: non-polar
HBr	
ClF	
$BeCl_2$	Studying molecules that do not have lone pair electrons and all the bonding atoms to the central atom are identical.
BF_3	
$AlCl_3$	
CCl_4	
CF_4	
PCl_5	
SF_6	
Ethene	Studying molecule that contains a C=C double bond. C=C contains a pi bond resulting in restricted rotation of the C to C atoms.
CH_2=CHCl	
$Cl_2C=CCl_2$	
CH_3Cl	Studying molecule that contains a methyl group. A methyl/alkyl (C_nH_{2n+1}) group is electron releasing/donating.
$(CH_3)_3N$ trigonal pyramidal	
Ethane	Alkane molecules (C_nH_{2n+2}) are saturated hydrocarbon and they are non polar consisting of C-H bonds which are little polarised.
Benzene	Understanding shape of a molecule.
XeF_4	With respect to Xe, square planar
PtF_6	With respect to Pt, octahedral
CH_3NH_2	With respect to N, trigonal pyramidal









Molecules marked in red are polar covalent molecules.

Q2. Which of the following molecules has no permanent dipole?

A . CCl_2F_2 B . $CHCl_3$ **C. C_2Cl_4** D. C_2H_5Cl

Briefly explain your answer.

$Cl_2C=CCl_2$

Alkyl group: C_nH_{2n+1}-

All alkyl groups are electron releasing

Q3. Which of the following molecules has the highest boiling point?

A . CCl_4 B . CF_4 **C. C_2Cl_4** D. C_2H_6

Briefly explain your answer.

All molecules are non-polar

Larger electron cloud, better able to polarize the molecule,

Stronger id-id/td-td

Q4. Which of the following statements about a polar molecule is TRUE?

A. consists of atoms differing widely in electronegativity. O=C=O

B. Consists of ions.

C. Takes up a preferred orientation when placed in an electric field.

D. Is composed of an odd number of atoms. Cl-Be-Cl

E. Consists of polar covalent bond. CCl_4

Give an example of non-polar molecules for each of the statement that is NOT TRUE about a polar molecule.

Q5. Which of the following statements is NOT CORRECT? You can have more than 1 answer.

Learning pointers:

- 2 atoms per molecule – linear
- 3 atoms per molecule – linear; bent
- 4 atoms per molecule – trigonal planar, trigonal pyramidal, T shaped
- 5 atoms per molecule – tetrahedral, see saw, square planar
- 6 atoms per molecule – trigonal bipyramidal, square pyramidal
- 7 atoms per molecule – octahedral

Examiners are likely to ask those which may have more than 2 shapes.

A. A molecule, XY_2 is polar when X is a central atom with 1 lone pair of electrons. Shape: bent Y-X-Y; dipole moments cannot cancel

B. A molecule, XY_2 is polar when X is a central atom with 2 lone pairs of electrons. Shape: bent Y-X-Y; dipole moments cannot cancel

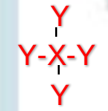
False

C. A molecule, XY_2 is polar when X is a central atom with 3 lone pairs of electrons. Shape: linear Y-X-Y

D. A molecule, XY_4 is polar when X is a central atom with 1 lone pair of electrons. Shape: see saw shaped; dipole moments at the equatorial sites cannot cancel

False

E. A molecule, XY_4 is polar when X is a central atom with 2 lone pairs of electrons. Shape: square planar



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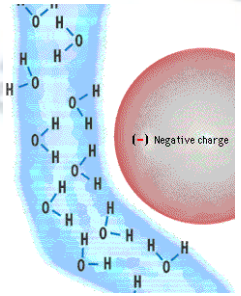


H-O-N=O; deflected; polar

O=N→O; deflected; polar
O-H

Covalent compounds that contain "OH" group would be polar.

O-H
O=S=O; deflected; polar
O-H

O-H; deflected; polar
O=S
O-H

H-Cl; deflected; polar

H-O-Cl; deflected; polar

All weak/strong acids are polar.

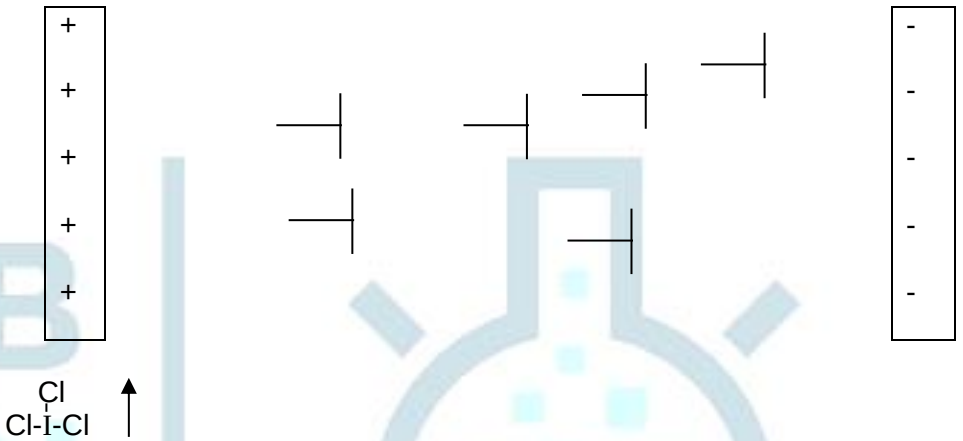
Cl
Cl-C-H; deflected; polar
Cl

Cl
H-C-H; deflected; polar
Cl

Cl
Cl-C-Cl ; not deflected; non-polar
Cl

Cl
Cl-B-Cl ; not deflected; non-polar

Q7. Sketch the shape of ICl_3 and sketch the orientation of the molecules in the presence of an electric field set up by the charged plates as shown below.



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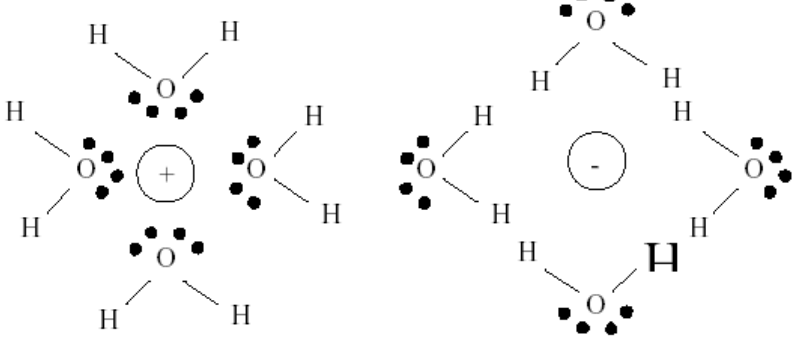
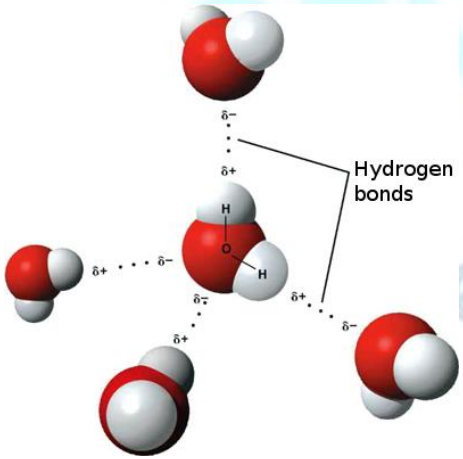
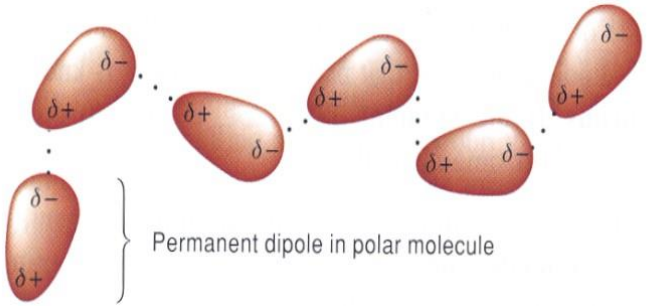
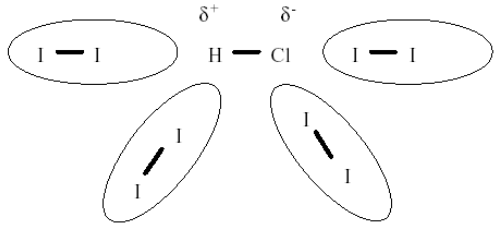
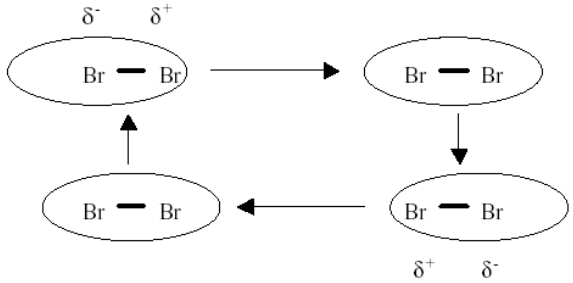
Types of Intermolecular Forces In Simple Covalent Molecules

Intermolecular forces	Forces between	Possible example	Strength of forces
Ion-Dipole attraction forces	Ions and permanent dipole	Na+ / Cl- and water molecules	Strongest
			
Hydrogen bonding	permanent dipoles	Water molecules	Stronger
			
Permanent dipole to dipole attraction forces [Keesom forces]	permanent dipoles	HCl molecules	Strong
			
Permanent dipole to Instantaneous/ induced dipole attraction forces [Debye forces]	permanent dipole and induced dipole	HCl and iodine vapour	Weak
			
Dispersion forces or Instantaneous/ Induced to induced dipole attraction forces [London forces]	induced dipoles	Bromine molecules	weakest
			

van der Waals' forces refer to attraction force between molecules that may consist of pd-pd and/or id-id. E.g. $CH_3CH_2CH_2Cl$

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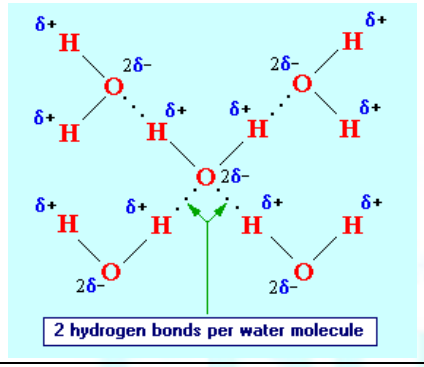
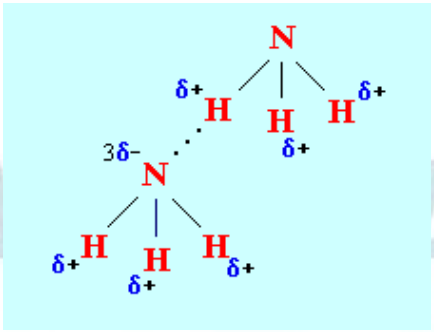
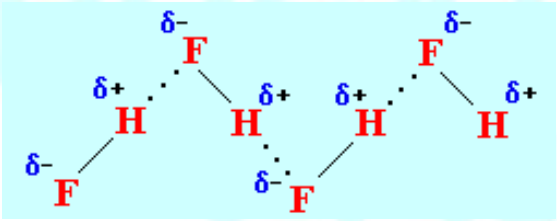
Hydrogen Bonding

- **Hydrogen must be electron deficient/protonic**, i.e. hydrogen has no outer electron shell as it is drawn away by its neighbouring atom which has very large electronegativity, like H-O, H-N and H-F

- **Lone pair electron of the highly electronegative atom** (namely O, N and F) establish bond with the electron deficient hydrogen







Label the bond angle of HOH, HNH and FHF & HFH in the above diagrams. Note: hydrogen bond is equivalent to a bond pair.

Understanding Hydrogen bond

The strength of hydrogen bond is uniquely strong when compared amongst permanent dipole to permanent dipole attractive forces since the occurrence of hydrogen bond takes place when the electron deficient hydrogen provides its partial "empty orbital" while the highly electronegative atom N/O/F provides the lone pair electrons for bonding.

Hence the intermolecular attractive force is best described with the word "bond" and appropriately named after "hydrogen" as an electron deficient hydrogen that is covalently bonded to a highly electronegative atom is required.

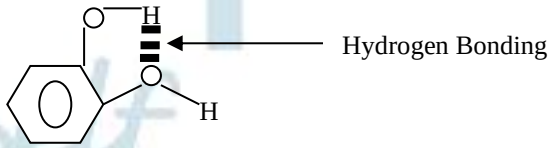
	No. of lone pair electrons	No. of electron deficient H	Average number of hydrogen bond per molecule	Strength of each hydrogen bond	Boiling point
HF	3	1	1	Highest	Higher
H_2O	2	2	2	Higher	Highest
NH_3	1	3	1	High	High

Despite a more electron deficient hydrogen and stronger intermolecular hydrogen bonds in HF, water molecule can form **more extensive intermolecular hydrogen bonds** as compared to HF and thus has a higher boiling point than HF.

- **Electronegativity of F > O > N; H in H-F should be most electron deficient/protonic followed by H_2O and then NH_3**

- **Extensiveness of hydrogen bonds**

Intramolecular hydrogen bonding occurs within the covalent molecule like in the case of 1,2-dihydroxybenzene as shown below. In such cases the intermolecular forces between the molecules will be lower than expected while the reactivity expected of the compound would also have changed.

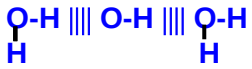


Presence of **intramolecular hydrogen bonds** would mean **less electron deficient/protonic hydrogen available for intermolecular hydrogen bonds**.

Thus molecules that form intramolecular hydrogen bonds would have **less extensive intermolecular hydrogen bonds**.

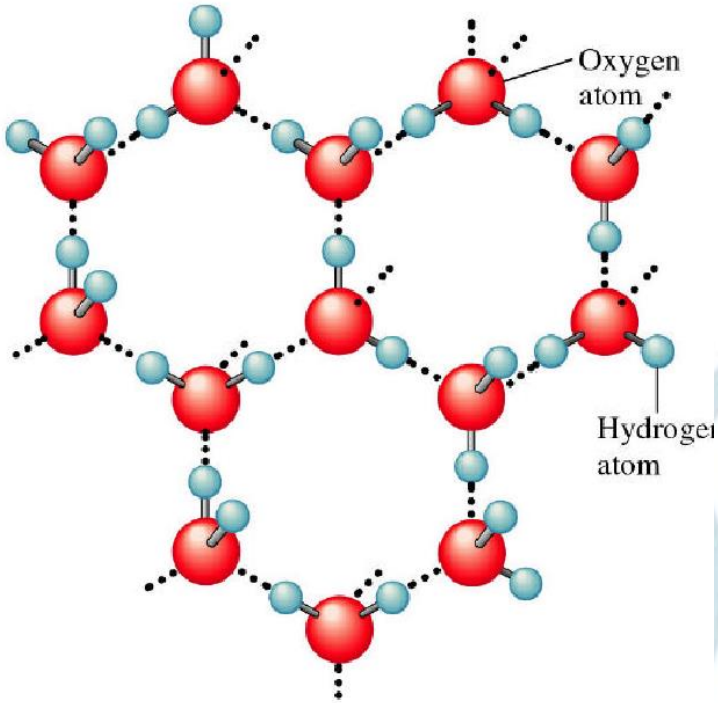
Why water has high surface tension? Why a pond insect can stand on water surface?

- **Per H_2O molecule would have 2 lone pairs of electrons and 2 protonic/electron deficient hydrogen atoms for establishment of intermolecular hydrogen bonds with different H_2O molecules**



- **Forming a film of network of water molecules held by strong intermolecular hydrogen bonds on the water surface**

Why ice has a low density? What is the bond angle of H-O-H in ice?



Ice

- **Each H_2O molecule would have 2 lone pairs of electrons and 2 protonic/electron deficient hydrogen atoms for establishment of 4 intermolecular hydrogen bonds with 4 different H_2O molecules when freezing**
- **Open cage structure in ice resulting in molecules being more spaced out than in water.**
- **109.5° (4 bp)/hydrogen bond considered as a bond pair**

Exercise 2: Types of Intermolecular Forces

Q1. Determine the type of intermolecular forces that exists in the following compounds or elements:

Hydrogen
Oxygen
Argon
HF
HCl
HBr
ClF
$BeCl_2$
Ethene
CH_2=CHCl
Cl_2C=CCl_2
CH_3Cl
SO_2
SO_3
SF_6
ammonia
CCl_4
Ethane
Benzene
XeF_4
Hydrogen peroxide
Carbon monoxide
NO
NO_2
N_2O

Q2. Rank the following in ascending order of bond strength?

(1) Ion-dipole interaction forces
(2) Permanent Dipole-Dipole Forces
(3) Dispersion Forces/instantaneous dipole-induced dipole
(4) Hydrogen Bond

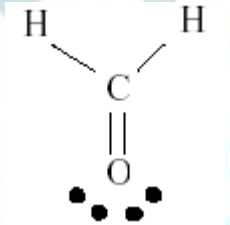
Q3. Solid carbon dioxide, CO_2(s), is used as a refrigerating agent because it readily changes directly from the solid into the vapour state at a low temperature. What does this indicate about the main intermolecular bonding in CO_2(s)?

A Covalent bonding
B hydrogen bonding
C ionic bonding
D permanent dipole to dipole attractive forces

Q4.

a. Comment on and explain the main type of intermolecular forces that exist in the following compounds:

(1) formaldehyde (structure as show below)



(2) hydrogen cyanide (HCN)

b. State the main type of interaction forces that exists in between formaldehyde and hydrogen cyanide molecules.

Q5.

a. Draw the shape of ethanal (CH_3CHO) molecule.
b. What are the approximate values for the following bond angles in the structure?
c. Comment on the main type of intermolecular forces that exist between ethanal molecules.

Exercise 2: Types of Intermolecular Forces

Q1. Determine the type of intermolecular forces that exists in the following compounds or elements:

Hydrogen Oxygen Argon	Instantaneous dipole-induced dipole attraction forces Non-polar; common element – same electronegativity
HF	Hydrogen bonding
HCl	Pd-pd
HBr	Pd-pd
ClF	Pd-pd
$BeCl_2$	Non-polar; Instantaneous dipole-induced dipole attraction forces; linear
Ethene; $H_2C=CH_2$	Non-polar; dipole moments cancel away
$CH_2=CHCl$	Pd-pd
$Cl_2C=CCl_2$	Instantaneous dipole-induced dipole attraction forces Non-polar; dipole moments cancel away
CH_3Cl	Pd-pd
SO_2	Pd-pd
SO_3 SF_6	Instantaneous dipole-induced dipole attraction forces Non-polar; dipole moments cancel away
ammonia	Hydrogen bonding
CCl_4 Ethane Benzene	Instantaneous dipole-induced dipole attraction forces Non-polar; dipole moments cancel away
XeF_4	Instantaneous dipole-induced dipole attraction forces Non-polar; dipole moments cancel away Shape: square planar
Hydrogen peroxide	Hydrogen bonding
Carbon monoxide NO	Pd-pd; diatomic molecules which have atoms with different electronegativities would be polar
NO_2	Pd-pd; bent since there is 1 lone electron and 2 bond pairs
N_2O	Pd-pd
	Shape: linear N ⟵ N = O

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Q2. Rank the following in ascending order of bond strength?

(3) , (2) , (4) , (1)

(1) Ion-dipole interaction forces (2) Permanent Dipole-Dipole Forces (3) Dispersion Forces/instantaneous dipole-induced dipole (4) Hydrogen Bond

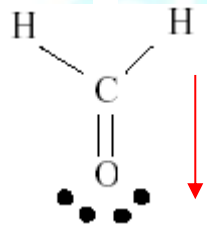
Q3. Solid carbon dioxide, $CO_2(s)$, is used as a refrigerating agent because it readily changes directly from the solid into the vapour state at a low temperature. What does this indicate about the main intermolecular bonding in CO_2(**S**)?

A Covalent bonding
B hydrogen bonding
C ionic bonding
D permanent dipole to dipole attractive forces

Q4.

a. Comment on and explain the main type of intermolecular forces that exist in the following compounds:

(1) formaldehyde (structure as show below)



(2) hydrogen cyanide (H-C≡N)

b. State the main type of interaction forces that exists in between formaldehyde and hydrogen cyanide molecules.

Q5.

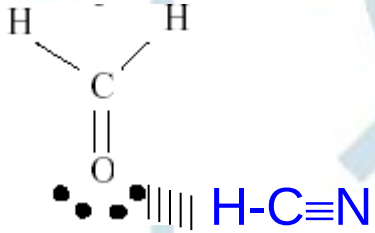
a. Draw the shape of ethanal (CH_3CHO) molecule.
b. What are the approximate values for the following bond angles in the structure?
c. Comment on the main type of intermolecular forces that exist between ethanal molecules.

Special Case –
Non-polar covalent compounds which have polar covalent bonds
As a solid, the molecules would arrange itself such that the they estab pd-pd

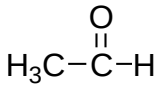
$^{-\delta}O=^{+\delta}C^{\delta+}=O^{\delta-}$
$^{-\delta}O=^{+\delta}C^{\delta+}=O^{\delta-}$
$^{-\delta}O=^{+\delta}C^{\delta+}=O^{\delta-}$

arrangement and stacking of molecules during freezing is to have positively induced C atom to establish pd-pd with negatively induced oxygen atom
Ans: D

(1) & (2) - Intermolecular pd-pd attraction forces



Intermolecular pd-pd attraction forces



a. & b.
With respect to C in methyl group: tetrahedral/109.5°;
With respect to C in CHO group: trigonal planar/120°

c. Intermolecular pd-pd attraction forces

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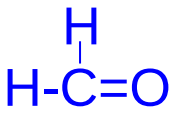
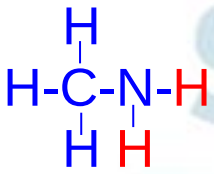
Exercise 3: Hydrogen Bonding & Others

Q1. Which of the following molecules will not form hydrogen bonds with another of its own molecules?

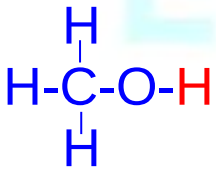
A HCHO



B. CH_3NH_2

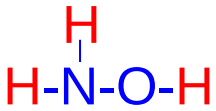


C. CH_3OH



D. NH_3

E. NH_2OH / hydroxylamine



a. Explain which of the compounds above has the highest boiling point.
b. Which of the molecules above is planar?

Q2. Account for the boiling points as shown below.

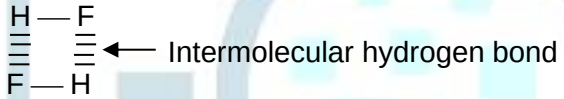
Compound	Mr	Boiling Point / ^oC
NH_3	17	-33.3
HF	20	19.7
H_2O	18	100
NH_2OH	33	110

Q3.

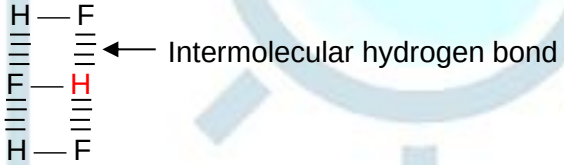
a. Aluminium chloride forms a dimer by ____ bonds to produce a larger molecule with relative molecular mass of 267. State the molecular formula of the larger molecule and fill in the blank.

b. It is found using the mass spectrometer that HF has a larger apparent relative molecular mass than expected. The relative molecular mass collected is 40 or 60. Which of the structures below explain the formation of dimer and trimer? If the structure were wrong, draw the correct structure, and suggest an explanation. Suggest the angle of H-F-H in the dimer and trimer.

Dimer



Trimer



c. Using the same deduction in (b), explain why the apparent relative molecular mass of ethanoic acid (CH_3COOH) is not 60, but 120.

d. Suggest a possible relative molecular mass of a sample of pure methanoic acid (HCOOH).

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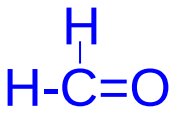
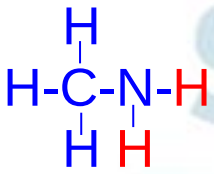
Exercise 3

Q1. Which of the following molecules will not form hydrogen bonds with another of its own molecules?

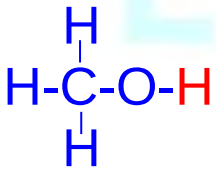
A HCHO



B. CH_3NH_2

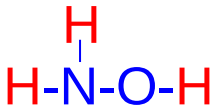


C. CH_3OH



D. NH_3

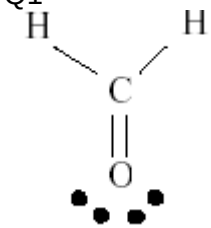
E. NH_2OH / hydroxylamine



c. Explain which of the compounds above has the highest boiling point.

d. Which of the molecules above is planar?

Q1



absence of electron deficient hydrogen
Ans: A

Learning pointers: any compound that contains the hydroxyl group/OH or amine group: NH would form intermolecular hydrogen bonds

a) Option E - hydroxylamine / NH_2OH

- More electronegative oxygen/more electron deficient hydrogen/ Stronger intermolecular hydrogen
- Presence of larger number of electron deficient/protonic hydrogen atoms and lone pair electrons of N/O per molecule to form hydrogen bond; more extensive intermolecular hydrogen bonds

b) Option A - HCHO

- Trigonal planar

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Q2. Account for the boiling points as shown below.

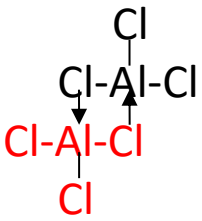
Compound	Mr	Boiling Point / °C
NH_3	17	-33.3
HF	20	19.7
H_2O	18	100
NH_2OH	33	110

- Bp of H_2O > HF > NH_3
- More electronegative F/more electron deficient hydrogen/ Stronger intermolecular hydrogen in HF relative to ammonia
- Despite a more electron deficient hydrogen and stronger intermolecular hydrogen bonds in HF, water molecule can form **more extensive intermolecular hydrogen bonds** as compared to HF and thus has a higher boiling point than HF.

- Hydroxylamine – highest bp
- More electronegative oxygen/more electron deficient hydrogen/ Stronger intermolecular hydrogen
- Presence of larger number of electron deficient/protonic hydrogen (**3 such atoms per molecule as compared to water which has 2, and the rest which has 1**) and greater availability of lone pair electrons of N and O per molecule; more extensive intermolecular hydrogen bonds

Learning Pointers
(1) En of F > O > N; H in H-F should be most electron deficient/protonic followed by H_2O and then NH_3
(2) Extensiveness of hydrogen bonds

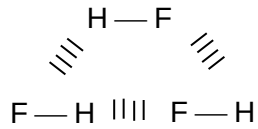
Q3.
a.



- Dative/coordinate bonds
- With respect to Al in $AlCl_3$, shape is trigonal planar
- With respect to Al in Al_2Cl_6 (dimer), shape is tetrahedral

b. Trimer structure is incorrect

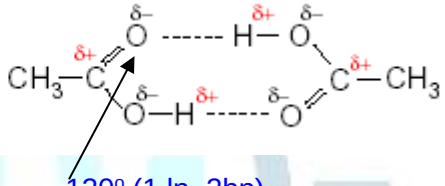
H at most can take a dative bond since it has a maximum of 1 orbital in its valence electron shell



With respect to F, 2 bond pairs, 2 lone pairs
(hydrogen bond considered as a bond pair)
Bond angle of HFH = 104.5^0

c. Dimer to be formed

In non-polar solvents, molecules dimerize due to intermolecular hydrogen bonding.



~120° (1 lp, 2bp)

d.
Dimer to be formed
46 x 2 = 92

$2HCOOH \Leftrightarrow (HCOOH)_2$

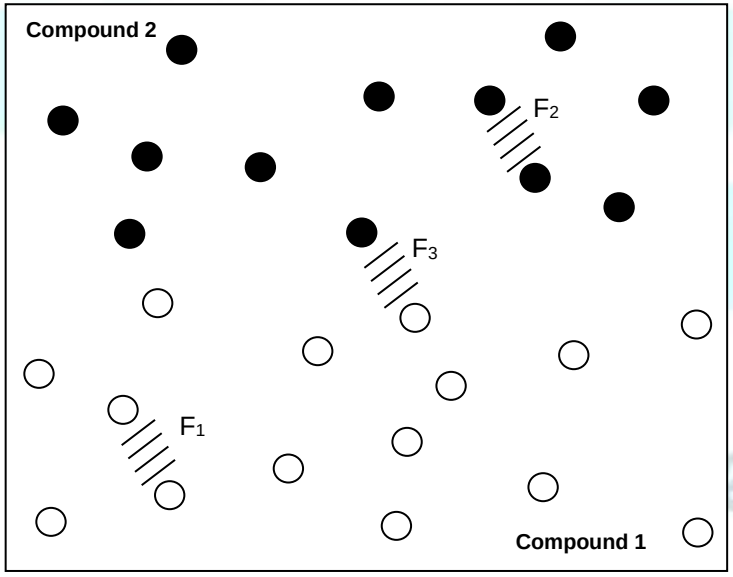
HCOOH, Mr = 46
$(HCOOH)_2$, Mr = 92

Apparent Mr of the gas mixture is 60.

46x + 92(1-x) = 60; x is the fraction of HCOOH in the mixture

Understanding Solubility

Solute is insoluble in solvent	Solute is soluble in solvent
Interaction forces between solute and solvent is **weaker than** intermolecular forces amongst solute or amongst solvent molecules.	Interaction forces between solute and solvent is **stronger than or comparable to** intermolecular forces amongst solute or amongst solvent molecules.



When F_1 or $F_2 > F_3$, compound 1 and 2 are immiscible.

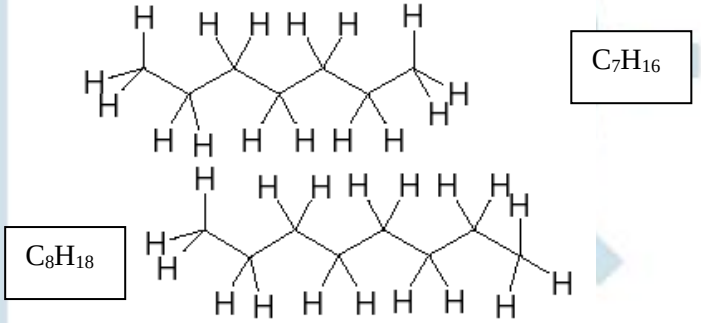
- **Black dot – alkane/hexane (non-polar);** F_2 – weak Instantaneous dipole-induced dipole attraction forces
- **White dot – water (polar);** F_1 – intermolecular hydrogen bonding
- **Interaction force between water and hexane; F_3 – pd-id < F_1 – hydrogen bonding**

When $F_3 \geq F_1$ **AND** $F_3 \geq F_2$, compound 1 and 2 are miscible.

- **Black dot – ethanoic acid, CH_3COOH (polar);** F_2 – intermolecular hydrogen bonding
- **White dot – water (polar);** F_1 – intermolecular hydrogen bonding
- **Interaction force between ethanoic acid and water; F_3 – intermolecular hydrogen bond which is comparable in strength to F_1 & F_2**

Non Polar Solvent

- Examples of non-polar solvents include fat, benzene, methylbenzene, carbon tetrachloride, C_7H_{16}, and C_8H_{18}.
- Only interaction forces present when non-polar solvent dissolves a chemical substance physically is **instantaneous dipole to induced dipole attraction forces** since these interaction forces are comparable to interaction forces between the non-polar solvent and between the non-polar solute. Example: Iodine dissolves in carbon tetrachloride and C_7H_{16} in C_8H_{18}



- Non-polar solvent does not dissolve polar covalent compounds well because the interaction forces between the non-polar solvent molecules and polar covalent compounds (**permanent dipole to induced dipole attraction forces / induced dipole to dipole attraction forces**) is weaker than the **permanent dipole to dipole attraction forces** amongst the polar molecules.
- Non-polar solvent does not dissolve ionic compounds well because the interaction forces between the non-polar solvent molecules and **ions in ionic compound** (**induced dipole to ion attraction forces**) is weaker than the **ionic bond** between the cations and anions in the ionic compound.

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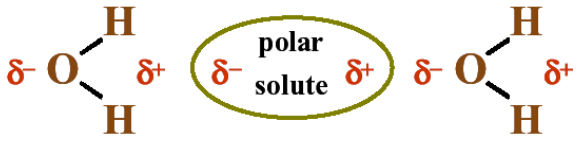
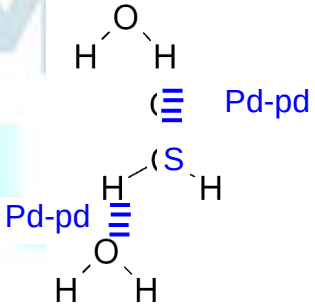
Polar Solvent; example: water molecules

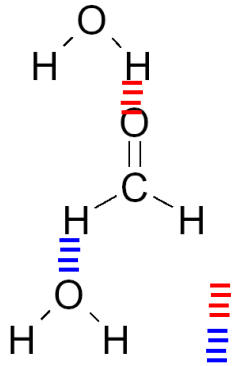
- **Permanent Dipole-dipole interaction forces** occurring between covalent molecules



Example: Permanent dipole to dipole interaction forces between H_2S and water is comparable in strength to the hydrogen bonds formed amongst water molecules and the permanent dipole to dipole interaction forces amongst H_2S molecules



- **Hydrogen bonding** between solute and polar solvent

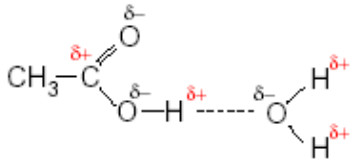


Water and formaldehyde can form hydrogen bonds between water and formaldehyde which is comparable to the hydrogen bonds amongst water molecules and the permanent dipole to dipole interaction forces amongst formaldehyde molecules.

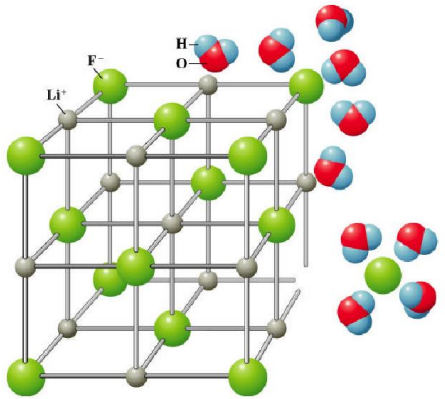
Intermolecular hydrogen bond

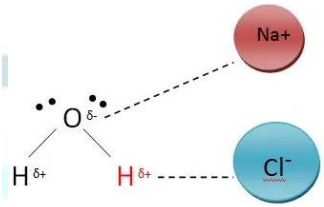
Intermolecular pd-pd

Intermolecular hydrogen bonding between ethanoic acid and water



- **Ion – dipole attractive forces** between cations/anions in ionic compound and polar solvent results in its solubility.





Comment which is more soluble in water: NaCl, **HCHO, H_2S or HCOOH.**

- **NaCl – most soluble / formation of ion-dipole attraction forces** between ions and water molecules that compensate for the energy required to overcome intermolecular hydrogen bonds btw water molecules and ionic attraction forces btw the cations and anions
- **HCOOH/Carboxylic acid – 2nd most soluble / presence of polar/hydrophilic C=O and OH groups that can form extensive hydrogen bonds with water molecules**
- **HCHO – next most soluble / presence of polar/hydrophilic C=O can form hydrogen bonds & pd-pd attraction forces with water molecules**
- **Hydrogen Sulfide – least soluble / presence of less polar/hydrophilic H-S bond forming pd-pd attraction forces with water molecules** that less able to compensate for the energy required to overcome intermolecular hydrogen bonds btw water molecules

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Types of compounds

Giant ionic — Ionic Compound

- Strong electrostatic attractive forces between anions and cations

Strength of ionic bond:
Lattice energy depends on
(1) charge and size of cation
(2) charge and size of anion

Magnitude of Lattice Energy $\propto \left| \frac{Q^+ Q^-}{r^+ + r^-} \right|$

One metal elt and One non-metal elt except $AlCl_3$, $AlBr_3$ $BeCl_2$,$BeBr_2$ which are simple molecular

Covalent Compound

Simple molecular — Polar Molecule

Examples: -OH, -NH, HF

Intermolecular Hydrogen bond

- Attraction force between lone pair electron of highly electronegative N/O/F & electron deficient or protonic hydrogen

Strength of H-bond:
(1) F≈H > O≈H > N≈H
(2) extensiveness of H bond
(3) intramolecular H-bond

Polar simple covalent molecule

- Permanent dipole to dipole (pd-pd) attractive forces between molecules

Strength of pd-pd:
magnitude of permanent dipole of polar covalent molecule

Simple molecular — Non-polar Molecule

Non-polar simple covalent molecule

- Instantaneous dipole to induced dipole (id-id) attractive forces between molecules

Strength of id-id:
(1) no. of electrons per molecule
(2) shape / molecular area: cylindrical > spherical

Giant metallic — Metal

- Strong electrostatic attractive forces between delocalised electrons and cations

Strength of metallic bond
(1) number of delocalised electron (mp Al>Mg>Na)
(2) charge density of cation (mp Li>Na>K)

Giant molecular — Macromolecule

Examples: Si, SiO_2, diamond, graphite, SiC, BN

Covalent bonds between atoms

- Strong covalent bonds between bonding atoms

Strength of covalent bond:
(1) Bond length
(2) Bond energy
(a) Atomic Size
(b) sigma & pi bonds
(c) polarity of bond

	Polar solute	Non-polar solute
Polar solvent	**Dissolves well**	**Poorly dissolves**
Non-polar solvent	**Poorly dissolves**	**Dissolves well**

Exercise 4: Solubility

Q1.

a. Sketch the formation of hydrogen bonds for the following which explains why they are very soluble in water.

Ammonia dissolves in water
Ethanol dissolves in water
Ethanoic Acid dissolves in water

_____ and water molecules interact to form

_____ which is comparable in strength to the intermolecular hydrogen bonds amongst _____ and amongst water molecules.

_____ group is hydrophobic and has poor interaction forces (permanent–instantaneous/induced dipole) with water molecules.

_____ is hydrophilic and has strong interaction forces (permanent dipole – dipole or hydrogen bonds) with water molecules.

b. "The formation of hydrogen bonds enhances the solubility of covalent compounds, like in the case of ammonia, amine (R-NH_2), carboxylic acid (RCOOH) and alcohol (ROH), where R is an alkyl group". State whether the statement is correct. Explain your answer.

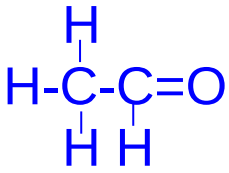
Q2. Explain the solubility of alcohol in water as summarized in table below.

Name	Formula	Solubility in H_2O (g/100 g H_2O at 20°C)
Methanol	CH_3OH	Miscible
Ethanol	CH_3CH_2OH	Miscible
1-Propanol	$CH_3CH_2CH_2OH$	Miscible
1-Butanol	$CH_3CH_2CH_2CH_2OH$	7.9
1-Pentanol	$CH_3CH_2CH_2CH_2CH_2OH$	2.7
1-Hexanol	$CH_3CH_2CH_2CH_2CH_2CH_2OH$	0.6

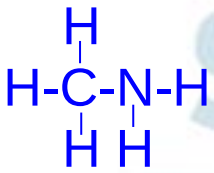
Q3. Suggest whether ethanamide (CH_3CONH_2) is soluble in water. Explain your answer.

Q4. Suggest which of the following is expected to be the least soluble in water. Briefly explain your answer.

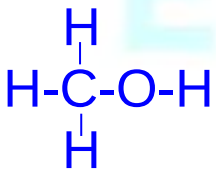
A CH_3HO



B. CH_3NH_2

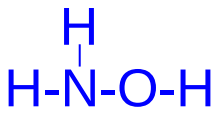


C. CH_3OH



D. NH_3

E. NH_2OH



Q5. Suggest an explanation that “Titanium chloride is insoluble in water as compared to sodium bromide in water”.

[2]

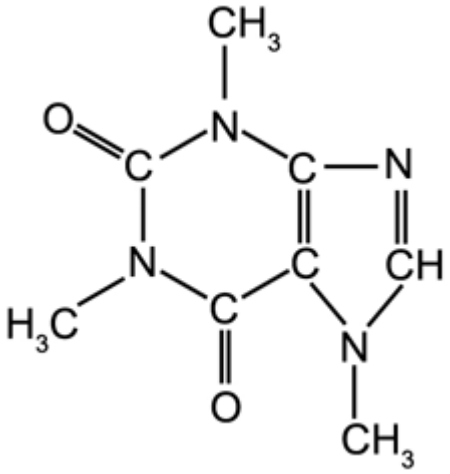
Q6. Suggest an explanation that “Magnesium chloride has a lower solubility than sodium chloride in water, while aluminium oxide is completely insoluble in water”.

[2]

Q7. Which has a higher solubility: hydrogen chloride or ammonia in water. Explain your answer.

[5]

Q8. Enclosed below is a caffeine molecule.



a. Is the molecule planar? [**Planar molecules are linear, bent, trigonal planar, square planar and T-shaped**]
b. Circle one of the carbon atoms which has a bond angle of 120º.
c. Circle one of the carbon atoms which has a bond angle of 109º.
d. With respect to nitrogen, what is the bond angle?
e. Suggest 2 reasons which of the following solvent can best dissolve caffeine and extract caffeine from the coffee to produce decaffeinated coffee.

Cyclohexane, Benzene, Carbon Dioxide

f. Calculate the concentration of caffeine in $moldm^{-3}$ in a $250cm^3$ cup of coffee which typically contains 39mg of caffeine (Mr = 194). [0.000804 $moldm^{-3}$]

[2]

Q9. Is hydrogen peroxide molecule planar and polar? Explain.
State the intermolecular forces amongst hydrogen peroxide molecules.

[5]

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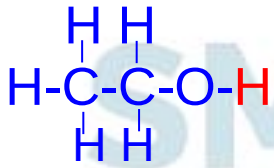
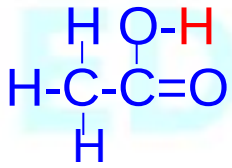
Exercise 4: Solubility

Q1.

a. Sketch the formation of hydrogen bonds for the following, which explains why they are very soluble in water.

Ammonia dissolves in water NH_3
Ethanol dissolves in water 
Ethanoic Acid dissolves in water 

X and water molecules interact to form

Hydrogen bonds which is comparable in strength to the

intermolecular hydrogen bonds amongst X and amongst

water molecules.

b. "The formation of hydrogen bonds enhances the solubility of covalent compounds, like in the case of ammonia, amine (R-NH_2), carboxylic acid (RCOOH) and alcohol (ROH), where R is an alkyl group". State whether the statement is correct. Explain your answer.

Non-polar alkyl (R/ C_nH_{2n+1}-) group is hydrophobic and has poor interaction forces (**permanent dipole**–instantaneous/induced dipole) with water molecules.

Polar NH/OH/CO is hydrophilic and has strong interaction forces (permanent dipole – permanent dipole or hydrogen bonds) with water molecules.

Q2. Explain the solubility of alcohol in water as summarized in table below.

Name	Formula	Solubility in H_2O (g/100 g H_2O at 20°C)
Methanol	CH_3OH	Miscible
Ethanol	CH_3CH_2OH	Miscible
1-Propanol	$CH_3CH_2CH_2OH$	Miscible
1-Butanol	$CH_3CH_2CH_2CH_2OH$	7.9
1-Pentanol	$CH_3CH_2CH_2CH_2CH_2OH$	2.7
1-Hexanol	$CH_3CH_2CH_2CH_2CH_2CH_2OH$	0.6

Short/small non-polar alkyl group is hydrophobic and has poor interaction forces (**permanent dipole**–instantaneous/induced dipole) with water molecules.

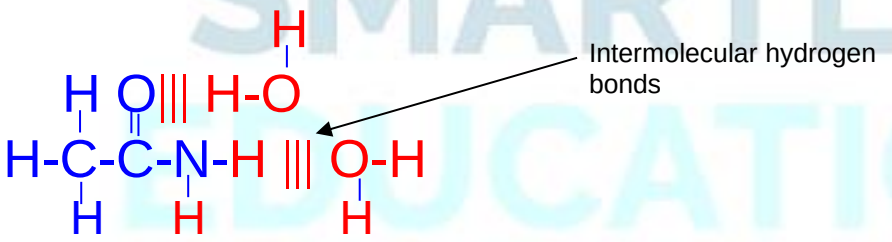
NH is hydrophilic and has strong hydrogen bonds with water molecules

CO is hydrophilic and forms permanent dipole – permanent dipole with water molecules

OH is hydrophilic/polar and has strong hydrogen bonds with water molecules. Hence first 3 members of alcohol in table are miscible in water.

As non-polar alkyl group becomes larger and more dominant, entire molecule becomes more hydrophobic and has poor interaction forces (**permanent dipole**–instantaneous/induced dipole) with water molecules, **which formed relatively stronger intermolecular hydrogen bonds amongst water molecules**.

Q3. Suggest whether ethanamide (CH_3CONH_2) is soluble in water. Explain your answer.



- **Soluble compound**
- **Able to form extensive intermolecular hydrogen bonds with numerous water molecules as illustrated in the diagram above**
- **which is comparable in strength to the intermolecular hydrogen bonds amongst ethanamide and amongst water molecules.**

Q4. Suggest which of the following is expected to be the least soluble in water. Briefly explain your answer.

A CH_3CHO
B. CH_3NH_2
C. CH_3OH
D. NH_3
E. NH_2OH

Option A; absence of electron deficient/protonic hydrogen to form hydrogen bonds with water molecules

Less extensive hydrogen bonds formed with water molecules

Q5.
$TiCl_4$ - Non-polar / simple covalent molecules
hydrophobic / poor interaction forces (permanent dipole–instantaneous/induced dipole) with water molecules.

NaBr – ionic / relatively stronger ion-dipole attractive forces

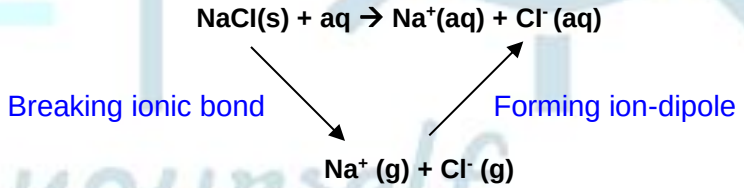
Al_2O_3 – insoluble / predominantly ionic / extremely high magnitude of lattice energy relative to magnitude of hydration energies

Q6.

$$\textbf{Magnitude of Lattice Energy} \propto \frac{Q^+ Q^-}{r^+ + r^-}$$

$MgCl_2$ < NaCl
Highly charged Mg^{2+} & smaller internuclear distance results in stronger ionic bonds relative to ions-dipole attraction forces with water molecules.
"extremely high magnitude of lattice energy relative to magnitude of hydration energies"

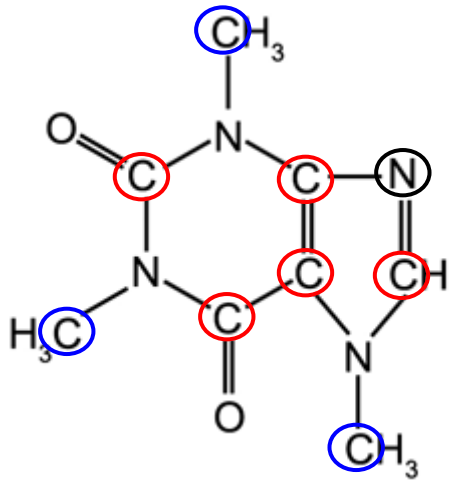
Al_2O_3 - insoluble
Highly charged Al^{3+} and O^{2-} results in stronger ionic bonds relative to Weaker ions-dipole attraction forces with water molecules.



Q7.
- HCl is more soluble; $HCl + H_2O \rightarrow H_3O^+ + Cl^-$
- Strong acid; completely ionises to form H_3O^+ and Cl^- which
- Forms strong ion-dipole attraction forces with water molecules
- NH_3 is a weak base; partially dissociates/mainly as molecules which
- Forms relatively weaker hydrogen bonds with water molecules

Note: HCl completely ionized as a strong acid!

Q8. Enclosed below is a caffeine molecule.



a. Is the molecule planar?
b. Circle one of the carbon atoms which has a bond angle of 120°.
c. Circle one of the carbon atoms which has a bond angle of 109°.
d. With respect to nitrogen, what is the bond angle? **Black circled N ~ 110-120° [1 lone pair and 2 bond pairs], rest – 107°, trigonal pyramidal**
e. Suggest 2 reasons which of the following solvent can best dissolve caffeine and extract caffeine from the coffee to produce decaffeinated coffee.

Cyclohexane, Benzene, Carbon Dioxide

f. Calculate the concentration of caffeine in moldm^{-3} in a 250cm^3 cup of coffee which typically contains 39mg of caffeine (Mr = 194).
[0.000804 moldm^{-3}]

a.
- Non planar

d.
- nitrogen atom in black circle – bent / ~120 ° (slightly less than)
- N is sp2 hybridised
- Rest of nitrogen – trigonal pyramidal / 107.3°
- N is sp3 hybridised

e. carbon dioxide [**has polar covalent bonds unlike cyclohexane and Benzene**]
- polar C=O group in carbon dioxide can form relatively stronger pd-pd interaction forces with caffeine molecules (relative to the weaker id-id/td-id/td-td interaction forces between caffeine and benzene/cyclohexane molecules)
- **carbon dioxide easily vapourises as a gas at rtp leaving the extracted caffeine (cyclohexane and benzene are liquids)**

Note:
Non-polar covalent molecules with polar covalent bonds, e.g CO_2
- capable of forming pd-pd when solidified
- capable of forming pd-pd when acting as a solvent to interact with polar covalent molecules

f.
- number of moles = 39 x 10^{-3} ÷ 194 (Mr) moles
- concentration = $\frac{(39 \times 10^{-3} \div 194) \text{ moles}}{0.25 \text{ dm}^3}$

Q9. Is hydrogen peroxide and water molecules planar and polar? Explain. State the intermolecular forces amongst hydrogen peroxide molecules.

[5]

- Non-planar for hydrogen peroxide molecule despite with respect to O atom, it is bent/V-shaped; since O-O single bond can be rotated such that both hydrogen atoms rest on different planes. Water molecule is planar.
- Both molecules are polar, since the dipole moments of O-H do not cancel.
- Both molecules have intermolecular hydrogen bonds.