

FHSST Authors

**The Free High School Science Texts:
Textbooks for High School Students
Studying the Sciences
Chemistry
Grades 10 - 12**

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Contents

I	Introduction	1
II	Matter and Materials	3
1	Classification of Matter - Grade 10	5
1.1	Mixtures	5
1.1.1	Heterogeneous mixtures	6
1.1.2	Homogeneous mixtures	6
1.1.3	Separating mixtures	7
1.2	Pure Substances: Elements and Compounds	9
1.2.1	Elements	9
1.2.2	Compounds	9
1.3	Giving names and formulae to substances	10
1.4	Metals, Semi-metals and Non-metals	13
1.4.1	Metals	13
1.4.2	Non-metals	14
1.4.3	Semi-metals	14
1.5	Electrical conductors, semi-conductors and insulators	14
1.6	Thermal Conductors and Insulators	15
1.7	Magnetic and Non-magnetic Materials	17
1.8	Summary	18
2	What are the objects around us made of? - Grade 10	21
2.1	Introduction: The atom as the building block of matter	21
2.2	Molecules	21
2.2.1	Representing molecules	21
2.3	Intramolecular and intermolecular forces	25
2.4	The Kinetic Theory of Matter	26
2.5	The Properties of Matter	28
2.6	Summary	31
3	The Atom - Grade 10	35
3.1	Models of the Atom	35
3.1.1	The Plum Pudding Model	35
3.1.2	Rutherford's model of the atom	36

3.1.3	The Bohr Model	37
3.2	How big is an atom?	38
3.2.1	How heavy is an atom?	38
3.2.2	How big is an atom?	38
3.3	Atomic structure	38
3.3.1	The Electron	39
3.3.2	The Nucleus	39
3.4	Atomic number and atomic mass number	40
3.5	Isotopes	42
3.5.1	What is an isotope?	42
3.5.2	Relative atomic mass	45
3.6	Energy quantisation and electron configuration	46
3.6.1	The energy of electrons	46
3.6.2	Energy quantisation and line emission spectra	47
3.6.3	Electron configuration	47
3.6.4	Core and valence electrons	51
3.6.5	The importance of understanding electron configuration	51
3.7	Ionisation Energy and the Periodic Table	53
3.7.1	Ions	53
3.7.2	Ionisation Energy	55
3.8	The Arrangement of Atoms in the Periodic Table	56
3.8.1	Groups in the periodic table	56
3.8.2	Periods in the periodic table	58
3.9	Summary	59
4	Atomic Combinations - Grade 11	63
4.1	Why do atoms bond?	63
4.2	Energy and bonding	63
4.3	What happens when atoms bond?	65
4.4	Covalent Bonding	65
4.4.1	The nature of the covalent bond	65
4.5	Lewis notation and molecular structure	69
4.6	Electronegativity	72
4.6.1	Non-polar and polar covalent bonds	73
4.6.2	Polar molecules	73
4.7	Ionic Bonding	74
4.7.1	The nature of the ionic bond	74
4.7.2	The crystal lattice structure of ionic compounds	76
4.7.3	Properties of Ionic Compounds	76
4.8	Metallic bonds	76
4.8.1	The nature of the metallic bond	76
4.8.2	The properties of metals	77

4.9	Writing chemical formulae	78
4.9.1	The formulae of covalent compounds	78
4.9.2	The formulae of ionic compounds	80
4.10	The Shape of Molecules	82
4.10.1	Valence Shell Electron Pair Repulsion (VSEPR) theory	82
4.10.2	Determining the shape of a molecule	82
4.11	Oxidation numbers	85
4.12	Summary	88
5	Intermolecular Forces - Grade 11	91
5.1	Types of Intermolecular Forces	91
5.2	Understanding intermolecular forces	94
5.3	Intermolecular forces in liquids	96
5.4	Summary	97
6	Solutions and solubility - Grade 11	101
6.1	Types of solutions	101
6.2	Forces and solutions	102
6.3	Solubility	103
6.4	Summary	106
7	Atomic Nuclei - Grade 11	107
7.1	Nuclear structure and stability	107
7.2	The Discovery of Radiation	107
7.3	Radioactivity and Types of Radiation	108
7.3.1	Alpha (α) particles and alpha decay	109
7.3.2	Beta (β) particles and beta decay	109
7.3.3	Gamma (γ) rays and gamma decay	110
7.4	Sources of radiation	112
7.4.1	Natural background radiation	112
7.4.2	Man-made sources of radiation	113
7.5	The 'half-life' of an element	113
7.6	The Dangers of Radiation	116
7.7	The Uses of Radiation	117
7.8	Nuclear Fission	118
7.8.1	The Atomic bomb - an abuse of nuclear fission	119
7.8.2	Nuclear power - harnessing energy	120
7.9	Nuclear Fusion	120
7.10	Nucleosynthesis	121
7.10.1	Age of Nucleosynthesis ($225 \text{ s} - 10^3 \text{ s}$)	121
7.10.2	Age of Ions ($10^3 \text{ s} - 10^{13} \text{ s}$)	122
7.10.3	Age of Atoms ($10^{13} \text{ s} - 10^{15} \text{ s}$)	122
7.10.4	Age of Stars and Galaxies (the universe today)	122
7.11	Summary	122

8 Thermal Properties and Ideal Gases - Grade 11	125
8.1 A review of the kinetic theory of matter	125
8.2 Boyle's Law: Pressure and volume of an enclosed gas	126
8.3 Charles's Law: Volume and Temperature of an enclosed gas	132
8.4 The relationship between temperature and pressure	136
8.5 The general gas equation	137
8.6 The ideal gas equation	140
8.7 Molar volume of gases	145
8.8 Ideal gases and non-ideal gas behaviour	146
8.9 Summary	147
9 Organic Molecules - Grade 12	151
9.1 What is organic chemistry?	151
9.2 Sources of carbon	151
9.3 Unique properties of carbon	152
9.4 Representing organic compounds	152
9.4.1 Molecular formula	152
9.4.2 Structural formula	153
9.4.3 Condensed structural formula	153
9.5 Isomerism in organic compounds	154
9.6 Functional groups	155
9.7 The Hydrocarbons	155
9.7.1 The Alkanes	158
9.7.2 Naming the alkanes	159
9.7.3 Properties of the alkanes	163
9.7.4 Reactions of the alkanes	163
9.7.5 The alkenes	166
9.7.6 Naming the alkenes	166
9.7.7 The properties of the alkenes	169
9.7.8 Reactions of the alkenes	169
9.7.9 The Alkynes	171
9.7.10 Naming the alkynes	171
9.8 The Alcohols	172
9.8.1 Naming the alcohols	173
9.8.2 Physical and chemical properties of the alcohols	175
9.9 Carboxylic Acids	176
9.9.1 Physical Properties	177
9.9.2 Derivatives of carboxylic acids: The esters	178
9.10 The Amino Group	178
9.11 The Carbonyl Group	178
9.12 Summary	179

10 Organic Macromolecules - Grade 12	185
10.1 Polymers	185
10.2 How do polymers form?	186
10.2.1 Addition polymerisation	186
10.2.2 Condensation polymerisation	188
10.3 The chemical properties of polymers	190
10.4 Types of polymers	191
10.5 Plastics	191
10.5.1 The uses of plastics	192
10.5.2 Thermoplastics and thermosetting plastics	194
10.5.3 Plastics and the environment	195
10.6 Biological Macromolecules	196
10.6.1 Carbohydrates	197
10.6.2 Proteins	199
10.6.3 Nucleic Acids	202
10.7 Summary	204
III Chemical Change	209
11 Physical and Chemical Change - Grade 10	211
11.1 Physical changes in matter	211
11.2 Chemical Changes in Matter	212
11.2.1 Decomposition reactions	213
11.2.2 Synthesis reactions	214
11.3 Energy changes in chemical reactions	217
11.4 Conservation of atoms and mass in reactions	217
11.5 Law of constant composition	219
11.6 Volume relationships in gases	219
11.7 Summary	220
12 Representing Chemical Change - Grade 10	223
12.1 Chemical symbols	223
12.2 Writing chemical formulae	224
12.3 Balancing chemical equations	224
12.3.1 The law of conservation of mass	224
12.3.2 Steps to balance a chemical equation	226
12.4 State symbols and other information	230
12.5 Summary	232
13 Quantitative Aspects of Chemical Change - Grade 11	233
13.1 The Mole	233
13.2 Molar Mass	235
13.3 An equation to calculate moles and mass in chemical reactions	237

13.4 Molecules and compounds	239
13.5 The Composition of Substances	242
13.6 Molar Volumes of Gases	246
13.7 Molar concentrations in liquids	247
13.8 Stoichiometric calculations	249
13.9 Summary	252
14 Energy Changes In Chemical Reactions - Grade 11	255
14.1 What causes the energy changes in chemical reactions?	255
14.2 Exothermic and endothermic reactions	255
14.3 The heat of reaction	257
14.4 Examples of endothermic and exothermic reactions	259
14.5 Spontaneous and non-spontaneous reactions	260
14.6 Activation energy and the activated complex	261
14.7 Summary	264
15 Types of Reactions - Grade 11	267
15.1 Acid-base reactions	267
15.1.1 What are acids and bases?	267
15.1.2 Defining acids and bases	267
15.1.3 Conjugate acid-base pairs	269
15.1.4 Acid-base reactions	270
15.1.5 Acid-carbonate reactions	274
15.2 Redox reactions	276
15.2.1 Oxidation and reduction	277
15.2.2 Redox reactions	278
15.3 Addition, substitution and elimination reactions	280
15.3.1 Addition reactions	280
15.3.2 Elimination reactions	281
15.3.3 Substitution reactions	282
15.4 Summary	283
16 Reaction Rates - Grade 12	287
16.1 Introduction	287
16.2 Factors affecting reaction rates	289
16.3 Reaction rates and collision theory	293
16.4 Measuring Rates of Reaction	295
16.5 Mechanism of reaction and catalysis	297
16.6 Chemical equilibrium	300
16.6.1 Open and closed systems	302
16.6.2 Reversible reactions	302
16.6.3 Chemical equilibrium	303
16.7 The equilibrium constant	304

16.7.1	Calculating the equilibrium constant	305
16.7.2	The meaning of k_c values	306
16.8	Le Chatelier's principle	310
16.8.1	The effect of concentration on equilibrium	310
16.8.2	The effect of temperature on equilibrium	310
16.8.3	The effect of pressure on equilibrium	312
16.9	Industrial applications	315
16.10	Summary	316
17	Electrochemical Reactions - Grade 12	319
17.1	Introduction	319
17.2	The Galvanic Cell	320
17.2.1	Half-cell reactions in the Zn-Cu cell	321
17.2.2	Components of the Zn-Cu cell	322
17.2.3	The Galvanic cell	323
17.2.4	Uses and applications of the galvanic cell	324
17.3	The Electrolytic cell	325
17.3.1	The electrolysis of copper sulphate	326
17.3.2	The electrolysis of water	327
17.3.3	A comparison of galvanic and electrolytic cells	328
17.4	Standard Electrode Potentials	328
17.4.1	The different reactivities of metals	329
17.4.2	Equilibrium reactions in half cells	329
17.4.3	Measuring electrode potential	330
17.4.4	The standard hydrogen electrode	330
17.4.5	Standard electrode potentials	333
17.4.6	Combining half cells	337
17.4.7	Uses of standard electrode potential	338
17.5	Balancing redox reactions	342
17.6	Applications of electrochemistry	347
17.6.1	Electroplating	347
17.6.2	The production of chlorine	348
17.6.3	Extraction of aluminium	349
17.7	Summary	349
IV	Chemical Systems	353
18	The Water Cycle - Grade 10	355
18.1	Introduction	355
18.2	The importance of water	355
18.3	The movement of water through the water cycle	356
18.4	The microscopic structure of water	359

18.4.1	The polar nature of water	359
18.4.2	Hydrogen bonding in water molecules	359
18.5	The unique properties of water	360
18.6	Water conservation	363
18.7	Summary	366
19	Global Cycles: The Nitrogen Cycle - Grade 10	369
19.1	Introduction	369
19.2	Nitrogen fixation	369
19.3	Nitrification	371
19.4	Denitrification	372
19.5	Human Influences on the Nitrogen Cycle	372
19.6	The industrial fixation of nitrogen	373
19.7	Summary	374
20	The Hydrosphere - Grade 10	377
20.1	Introduction	377
20.2	Interactions of the hydrosphere	377
20.3	Exploring the Hydrosphere	378
20.4	The Importance of the Hydrosphere	379
20.5	Ions in aqueous solution	379
20.5.1	Dissociation in water	380
20.5.2	Ions and water hardness	382
20.5.3	The pH scale	382
20.5.4	Acid rain	384
20.6	Electrolytes, ionisation and conductivity	386
20.6.1	Electrolytes	386
20.6.2	Non-electrolytes	387
20.6.3	Factors that affect the conductivity of water	387
20.7	Precipitation reactions	389
20.8	Testing for common anions in solution	391
20.8.1	Test for a chloride	391
20.8.2	Test for a sulphate	391
20.8.3	Test for a carbonate	392
20.8.4	Test for bromides and iodides	392
20.9	Threats to the Hydrosphere	393
20.10	Summary	394
21	The Lithosphere - Grade 11	397
21.1	Introduction	397
21.2	The chemistry of the earth's crust	398
21.3	A brief history of mineral use	399
21.4	Energy resources and their uses	400

21.5 Mining and Mineral Processing: Gold	401
21.5.1 Introduction	401
21.5.2 Mining the Gold	401
21.5.3 Processing the gold ore	401
21.5.4 Characteristics and uses of gold	402
21.5.5 Environmental impacts of gold mining	404
21.6 Mining and mineral processing: Iron	406
21.6.1 Iron mining and iron ore processing	406
21.6.2 Types of iron	407
21.6.3 Iron in South Africa	408
21.7 Mining and mineral processing: Phosphates	409
21.7.1 Mining phosphates	409
21.7.2 Uses of phosphates	409
21.8 Energy resources and their uses: Coal	411
21.8.1 The formation of coal	411
21.8.2 How coal is removed from the ground	411
21.8.3 The uses of coal	412
21.8.4 Coal and the South African economy	412
21.8.5 The environmental impacts of coal mining	413
21.9 Energy resources and their uses: Oil	414
21.9.1 How oil is formed	414
21.9.2 Extracting oil	414
21.9.3 Other oil products	415
21.9.4 The environmental impacts of oil extraction and use	415
21.10 Alternative energy resources	415
21.11 Summary	417
22 The Atmosphere - Grade 11	421
22.1 The composition of the atmosphere	421
22.2 The structure of the atmosphere	422
22.2.1 The troposphere	422
22.2.2 The stratosphere	422
22.2.3 The mesosphere	424
22.2.4 The thermosphere	424
22.3 Greenhouse gases and global warming	426
22.3.1 The heating of the atmosphere	426
22.3.2 The greenhouse gases and global warming	426
22.3.3 The consequences of global warming	429
22.3.4 Taking action to combat global warming	430
22.4 Summary	431

23 The Chemical Industry - Grade 12	435
23.1 Introduction	435
23.2 Sasol	435
23.2.1 Sasol today: Technology and production	436
23.2.2 Sasol and the environment	440
23.3 The Chloralkali Industry	442
23.3.1 The Industrial Production of Chlorine and Sodium Hydroxide	442
23.3.2 Soaps and Detergents	446
23.4 The Fertiliser Industry	450
23.4.1 The value of nutrients	450
23.4.2 The Role of fertilisers	450
23.4.3 The Industrial Production of Fertilisers	451
23.4.4 Fertilisers and the Environment: Eutrophication	454
23.5 Electrochemistry and batteries	456
23.5.1 How batteries work	456
23.5.2 Battery capacity and energy	457
23.5.3 Lead-acid batteries	457
23.5.4 The zinc-carbon dry cell	459
23.5.5 Environmental considerations	460
23.6 Summary	461
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Chapter 5

Intermolecular Forces - Grade 11

In the previous chapter, we discussed the different forces that exist *between atoms* (intramolecular forces). When atoms are joined to one another they form molecules, and these molecules in turn have forces that bind them together. These forces are known as **intermolecular forces**, and we are going to look at them in more detail in this next section.



Definition: Intermolecular forces

Intermolecular forces are forces that act between stable molecules.

You will also remember from the previous chapter, that we can describe molecules as being either **polar** or **non-polar**. A polar molecule is one in which there is a difference in electronegativity between the atoms in the molecule, such that the shared electron pair spends more time close to the atom that attracts it more strongly. The result is that one end of the molecule will have a slightly positive charge (δ^+), and the other end will have a slightly negative charge (δ^-). The molecule is said to be a **dipole**. However, it is important to remember that just because the bonds within a molecule are polar, the molecule itself may not necessarily be polar. The shape of the molecule may also affect its polarity. A few examples are shown in table 5.1 to refresh your memory!

5.1 Types of Intermolecular Forces

It is important to be able to recognise whether the molecules in a substance are polar or non-polar because this will determine what type of intermolecular forces there are. This is important in explaining the properties of the substance.

1. Van der Waals forces

These intermolecular forces are named after a Dutch physicist called Johannes van der Waals (1837 -1923), who recognised that there were weak attractive and repulsive forces between the molecules of a gas, and that these forces caused gases to deviate from 'ideal gas' behaviour. Van der Waals forces are *weak* intermolecular forces, and can be divided into three types:

(a) Dipole-dipole forces

Figure 5.1 shows a simplified dipole molecule, with one end slightly positive and the other slightly negative.

When one dipole molecule comes into contact with another dipole molecule, the positive pole of the one molecule will be attracted to the negative pole of the other, and the molecules will be held together in this way (figure 5.2). Examples of molecules that are held together by dipole-dipole forces are HCl, FeS, KBr, SO₂ and NO₂.

(b) Ion-dipole forces

As the name suggests, this type of intermolecular force exists between an ion and a dipole molecule. You will remember that an *ion* is a charged atom, and this will

Table 5.1: Polarity in molecules with different atomic bonds and molecular shapes

Molecule	Chemical formula	Bond between atoms	Shape of molecule	Polarity of molecule
Hydrogen	H ₂	Covalent	Linear molecule H — H	Non-polar
Hydrogen chloride	HCl	Polar covalent	Linear molecule H ^{δ+} — Cl ^{δ-}	Polar
Carbon tetrafluoromethane	CF ₄	Polar covalent	Tetrahedral molecule $\begin{array}{c} F^{\delta-} \\ \\ F^{\delta-} - C^{\delta+} - F^{\delta-} \\ \\ F^{\delta-} \end{array}$	Non-polar

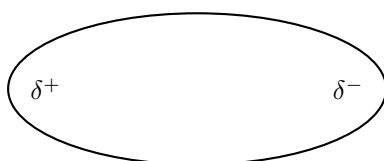


Figure 5.1: A simplified diagram of a dipole molecule

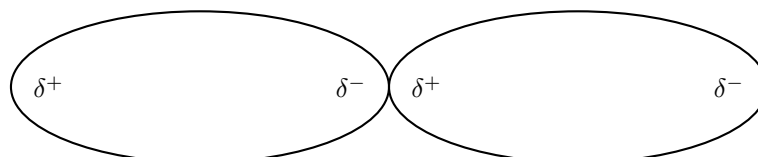


Figure 5.2: Two dipole molecules are held together by the attractive force between their oppositely charged poles

be attracted to one of the charged ends of the polar molecule. A positive ion will be attracted to the negative pole of the polar molecule, while a negative ion will be attracted to the positive pole of the polar molecule. This can be seen when sodium chloride (NaCl) dissolves in water. The positive sodium ion (Na⁺) will be attracted to the slightly negative oxygen atoms in the water molecule, while the negative chloride ion (Cl⁻) is attracted to the slightly positive hydrogen atom. These intermolecular forces weaken the ionic bonds between the sodium and chloride ions so that the sodium chloride dissolves in the water (figure 5.3).

(c) *London forces*

These intermolecular forces are also sometimes called 'dipole-induced dipole' or 'momentary dipole' forces. Not all molecules are polar, and yet we know that there are also intermolecular forces between non-polar molecules such as carbon dioxide. In

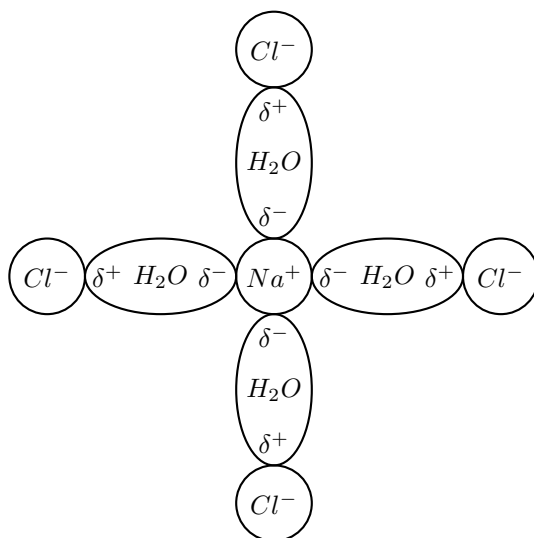


Figure 5.3: Ion-dipole forces in a sodium chloride solution

non-polar molecules the electronic charge is evenly distributed but it is possible that at a particular moment in time, the electrons might not be evenly distributed. The molecule will have a *temporary dipole*. In other words, each end of the molecules has a slight charge, either positive or negative. When this happens, molecules that are next to each other attract each other very weakly. These London forces are found in the halogens (e.g. F_2 and I_2), the noble gases (e.g. Ne and Ar) and in other non-polar molecules such as carbon dioxide and methane.

2. Hydrogen bonds

As the name implies, this type of intermolecular bond involves a hydrogen atom. The hydrogen must be attached to another atom that is strongly electronegative, such as oxygen, nitrogen or fluorine. Water molecules for example, are held together by hydrogen bonds between the hydrogen atom of one molecule and the oxygen atom of another (figure 5.4). Hydrogen bonds are stronger than van der Waals forces. It is important to note however, that both van der Waals forces and hydrogen bonds are weaker than the covalent and ionic bonds that exist between *atoms*.

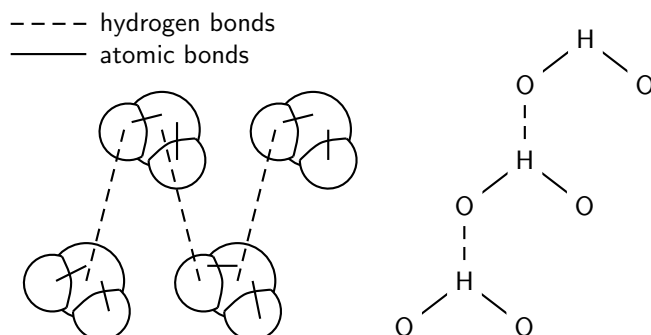


Figure 5.4: Two representations showing the hydrogen bonds between water molecules: space-filling model and structural formula.



Exercise: Types of intermolecular forces

1. Complete the following table by placing a tick to show which type of intermolecular force occurs in each substance:

Formula	Dipole-dipole	Momentary dipole	Ion-dipole	hydrogen bond
HCl				
CO ₂				
I ₂				
H ₂ O				
KI(aq)				
NH ₃				

2. In which of the substances above are the intermolecular forces...

- (a) strongest
(b) weakest

5.2 Understanding intermolecular forces

The types of intermolecular forces that occur in a substance will affect its properties, such as its **phase**, **melting point** and **boiling point**. You should remember, if you think back to the kinetic theory of matter, that the *phase* of a substance is determined by how strong the forces are between its particles. The weaker the forces, the more likely the substance is to exist as a gas because the particles are far apart. If the forces are very strong, the particles are held closely together in a solid structure. Remember also that the *temperature* of a material affects the energy of its particles. The more energy the particles have, the more likely they are to be able to overcome the forces that are holding them together. This can cause a change in phase.



Definition: Boiling point

The temperature at which a material will change from being a liquid to being a gas.



Definition: Melting point

The temperature at which a material will change from being a solid to being a liquid.

Now look at the data in table 5.2.

Formula	Formula mass	Melting point (°C)	Boiling point (°C) at 1 atm
He	4	-270	-269
Ne	20	-249	-246
Ar	40	-189	-186
F ₂	38	-220	-188
Cl ₂	71	-101	-35
Br ₂	160	-7	58
NH ₃	17	-78	-33
H ₂ O	18	0	100
HF	20	-83	20

Table 5.2: Melting point and boiling point of a number of chemical substances

The melting point and boiling point of a substance, give us information about the *phase* of the substance at room temperature, and the *strength of the intermolecular forces*. The examples below will help to explain this.

Example 1: Fluorine (F_2)

Phase at room temperature

Fluorine (F_2) has a melting point of -220°C and a boiling point of -188°C . This means that for any temperature that is greater than -188°C , fluorine will be a gas. At temperatures below -220°C , fluorine would be a solid, and at any temperature inbetween these two, fluorine will be a liquid. So, at room temperature, fluorine exists as a gas.

Strength of intermolecular forces

What does this information tell us about the intermolecular forces in fluorine? In fluorine, these forces must be very weak for it to exist as a gas at room temperature. Only at temperatures below -188°C will the molecules have a low enough energy that they will come close enough to each other for forces of attraction to act between the molecules. The intermolecular forces in fluorine are very weak **van der Waals** forces because the molecules are *non-polar*.

Example 2: Hydrogen fluoride (HF)

Phase at room temperature

For temperatures below -83°C , hydrogen fluoride is a solid. Between -83°C and 20°C , it exists as a liquid, and if the temperature is increased above 20°C , it will become a gas.

Strength of intermolecular forces

What does this tell us about the intermolecular forces in hydrogen fluoride? The forces are stronger than those in fluorine, because more energy is needed for fluorine to change into the gaseous phase. In other words, more energy is needed for the intermolecular forces to be overcome so that the molecules can move further apart. Intermolecular forces will exist between the hydrogen atom of one molecule and the fluorine atom of another. These are **hydrogen bonds**, which are stronger than van der Waals forces.

What do you notice about water? Luckily for us, water behaves quite differently from the rest of the halides. Imagine if water were like ammonia (NH_3), which is a gas above a temperature of -33°C ! There would be no liquid water on the planet, and that would mean that no life would be able to survive here. The hydrogen bonds in water are particularly strong and this gives water unique qualities when compared to other molecules with hydrogen bonds. This will be discussed more in chapter ?? deals with this in more detail. You should also note that the strength of the intermolecular forces increases with an increase in formula mass. This can be seen by the increasing melting and boiling points of substances as formula mass increases.



Exercise: Applying your knowledge of intermolecular forces

Refer to the data in table 5.2 and then use your knowledge of different types of intermolecular forces to explain the following statements:

- The boiling point of F_2 is much lower than the boiling point of NH_3
 - At room temperature, many elements exist naturally as gases
 - The boiling point of HF is higher than the boiling point of Cl_2
 - The boiling point of water is much higher than HF, even though they both contain hydrogen bonds
-

5.3 Intermolecular forces in liquids

Intermolecular forces affect a number of properties in liquids:

- **Surface tension**

You may have noticed how some insects are able to walk across a water surface, and how leaves float in water. This is because of surface tension. In water, each molecule is held to the surrounding molecules by strong hydrogen bonds. Molecules in the centre of the liquid are completely surrounded by other molecules, so these forces are exerted in all directions. However, molecules at the surface do not have any water molecules above them to pull them upwards. Because they are only pulled sideways and downwards, the water molecules at the surface are held more closely together. This is called **surface tension**.

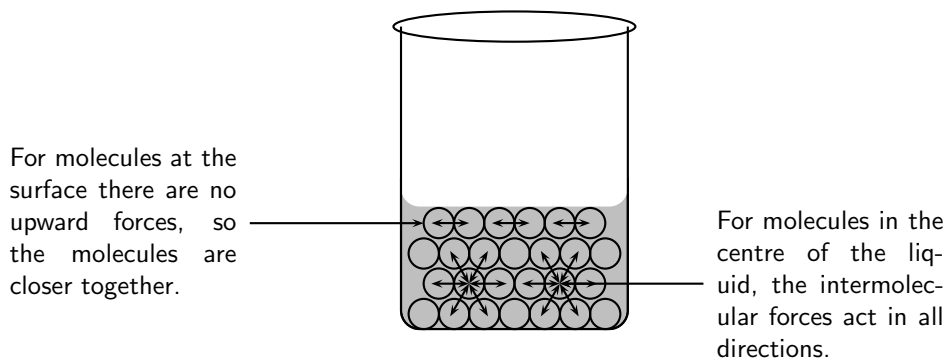
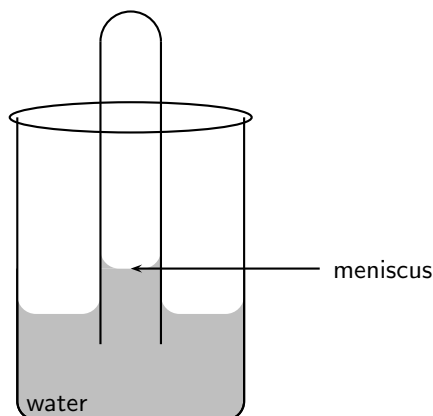


Figure 5.5: Surface tension in a liquid

- **Capillarity**

Activity :: Investigation : Capillarity

Half fill a beaker with water and hold a hollow glass tube in the centre as shown below. Mark the level of the water in the glass tube, and look carefully at the shape of the air-water interface in the tube. What do you notice?



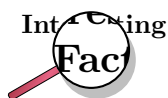
At the air-water interface, you will notice a **meniscus**, where the water appears to dip in the centre. In the glass tube, the attractive forces between the glass and the water are stronger than the intermolecular forces between the water molecules. This causes the water to be held more closely to the glass, and a meniscus forms. The forces between the glass and the water also mean that the water can be 'pulled up' higher when it is in the tube than when it is in the beaker. Capillarity is the surface tension that occurs in liquids that are inside tubes.

- **Evaporation**

In a liquid, each particle has kinetic energy, but some particles will have more energy than others. We therefore refer to the *average* kinetic energy of the molecules when we describe the liquid. When the liquid is heated, those particles which have the highest energy will be able to overcome the intermolecular forces holding them in the liquid phase, and will become a gas. This is called **evaporation**. Evaporation occurs when a liquid changes to a gas. The stronger the intermolecular forces in a liquid, the higher the temperature of the molecules will have to be for it to become a gas. You should note that a liquid doesn't necessarily have to reach boiling point before evaporation can occur. Evaporation takes place all the time. You will see this if you leave a glass of water outside in the sun. Slowly the water level will drop over a period of time.

What happens then to the molecules of water that remain in the liquid? Remember that it was the molecules with the highest energy that left the liquid. This means that the average kinetic energy of the remaining molecules will decrease, and so will the *temperature* of the liquid.

A similar process takes place when a person sweats during exercise. When you exercise, your body temperature increases and you begin to release moisture (sweat) through the pores in your skin. The sweat quickly evaporates and causes the temperature of your skin to drop. This helps to keep your body temperature at a level that is suitable for it to function properly.



Transpiration in plants - Did you know that plants also 'sweat'? In plants, this is called *transpiration*, and a plant will lose water through spaces in the leaf surface called *stomata*. Although this water loss is important in the survival of a plant, if a plant loses too much water, it will die. Plants that live in very hot, dry places such as deserts, must be specially adapted to reduce the amount of water that transpires (evaporates) from their leaf surface. Desert plants have some amazing adaptations to deal with this problem! Some have hairs on their leaves, which reflect sunlight so that the temperature is not as high as it would be, while others have a thin waxy layer covering their leaves, which reduces water loss. Some plants are even able to close their stomata during the day when temperatures (and therefore transpiration) are highest.



Important: In the same way that intermolecular forces affect the properties of liquids, they also affect the properties of solids. For example, the stronger the intermolecular forces between the particles that make up the solid, the *harder* the solid is likely to be, and the higher its *melting point* is likely to be.

5.4 Summary

- **Intermolecular forces** are the forces that act between stable molecules.
- The **type** of intermolecular force in a substance, will depend on the **nature of the molecules**.
- **Polar molecules** have an unequal distribution of charge, meaning that one part of the molecule is slightly positive and the other part is slightly negative. **Non-polar molecules** have an equal distribution of charge.

- There are three types of **Van der Waal's forces**. These are dipole-dipole, ion-dipole and London forces (momentary dipole).
- **Dipole-dipole** forces exist between two **polar molecules**, for example between two molecules of hydrogen chloride.
- **Ion-dipole** forces exist between **ions and dipole molecules**. The ion is attracted to the part of the molecule that has an opposite charge to its own. An example of this is when an ionic solid such as sodium chloride dissolves in water.
- **Momentary dipole** forces occur between two **non-polar molecules**, where at some point there is an unequal distribution of charge in the molecule. For example, there are London forces between two molecules of carbon dioxide.
- **Hydrogen bonds** occur between **hydrogen atoms** and other **atoms that have a high electronegativity** such as oxygen, nitrogen and fluorine. The hydrogen atom in one molecule will be attracted to the nitrogen atom in another molecule, for example. There are hydrogen bonds between water molecules and between ammonia molecules.
- Intermolecular forces affect the **properties** of substances. For example, the stronger the intermolecular forces, the higher the **melting point** of that substance, and the more likely that substance is to exist as a solid or liquid. Its **boiling point** will also be higher.
- In **liquids**, properties such as **surface tension, capillarity** and **evaporation** are the result of intermolecular forces.



Exercise: Summary Exercise

1. Give one word or term for each of the following descriptions:
 - (a) The tendency of an atom in a molecule to attract bonding electrons.
 - (b) A molecule that has an unequal distribution of charge.
 - (c) A charged atom.
2. For each of the following questions, choose the one correct answer from the list provided.
 - (a) The following table gives the melting points of various hydrides:

Hydride	Melting point ($^{\circ}\text{C}$)
HI	-50
NH ₃	-78
H ₂ S	-83
CH ₄	-184

In which of these hydrides does hydrogen bonding occur?

- i. HI only
- ii. NH₃ only
- iii. HI and NH₃ only
- iv. HI, NH₃ and H₂S

(IEB Paper 2, 2003)

- (b) Refer to the list of substances below:

HCl, Cl₂, H₂O, NH₃, N₂, HF

Select the true statement from the list below:

- i. NH₃ is a non-polar molecule
- ii. The melting point of NH₃ will be higher than for Cl₂
- iii. Ion-dipole forces exist between molecules of HF
- iv. At room temperature N₂ is usually a liquid

3. The respective boiling points for four chemical substances are given below:
Hydrogen sulphide -60°C
Ammonia -33°C
Hydrogen fluoride 20°C
Water 100°C
- (a) Which one of the substances exhibits the strongest forces of attraction between its molecules in the liquid state?
- (b) Give the name of the force responsible for the relatively high boiling points of ammonia and water and explain how this force originates.
- (c) The shapes of the molecules of hydrogen sulphide and water are similar, yet their boiling points differ. Explain.
- (IEB Paper 2, 2002)
-

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