CAPS

Mind the Gap!

Physical Science Part 2 Chemistry

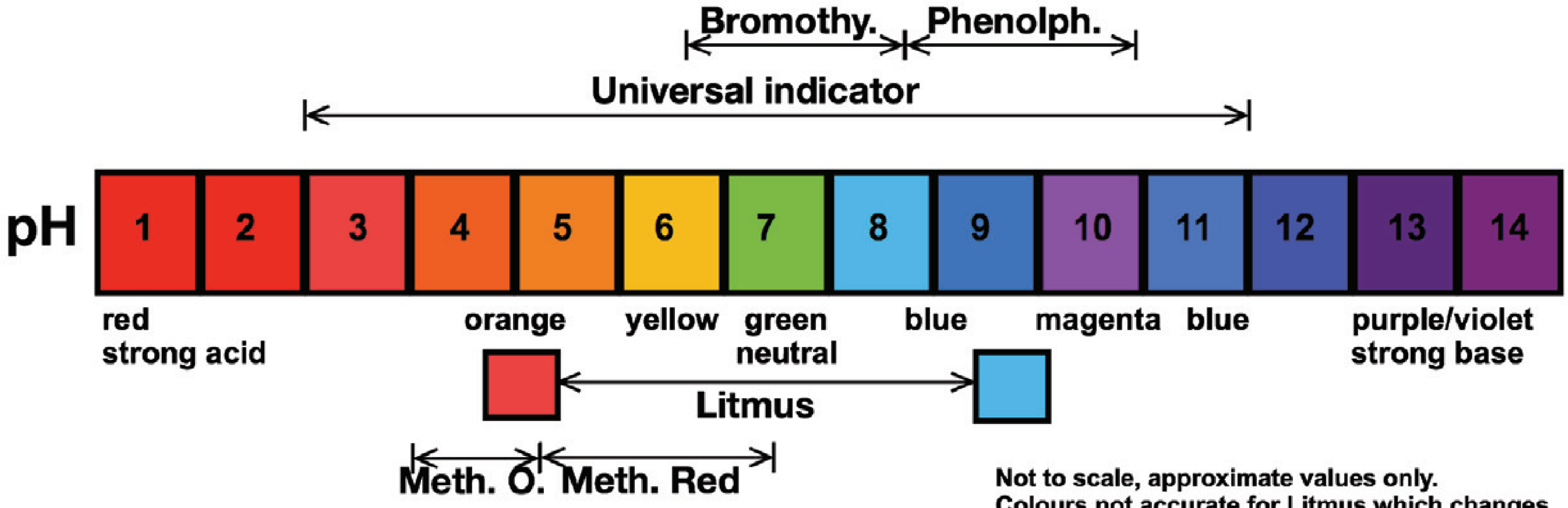
Study Guide

Grade 12

basic education

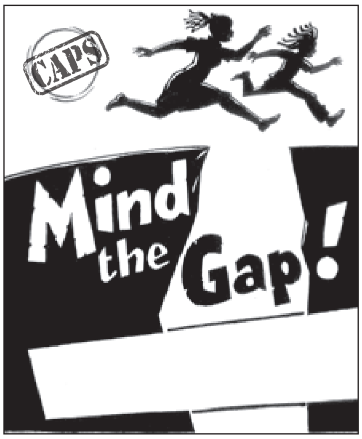
Department:
Basic Education
REPUBLIC OF SOUTH AFRICA

Colour Diagrams: Acid-base Indicators*



Not to scale, approximate values only.
Colours not accurate for Litmus which changes from pinkish-red to blue.

* Refer to page 136



Curriculum and Assessment Policy Statement (CAPS) Grade 12
Mind the Gap study guide for Physical Science Part 2: Chemistry
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The first edition, published in 2012, for the Revised National Curriculum Statement (RNCS) Grade 12 Mind the Gap study guides for Accounting, Economics, Geography and Life Sciences; the second edition, published in 2014 , aligned these titles to the Curriculum and Assessment Policy Statement (CAPS) and added more titles to the series in 2015, including the CAPS Grade 12 **Mind the Gap study guide for Physical Science Part 2: Chemistry**
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Ministerial foreword

Matsie Angelina Motshekga, MP
Minister of Basic Education

The Department of Basic Education (DBE) has pleasure in releasing the second edition of the *Mind the Gap* study guides for Grade 12 learners. These study guides continue the innovative and committed attempt by the DBE to improve the academic performance of Grade 12 candidates in the National Senior Certificate (NSC) examination.

The study guides have been written by teams of exerts comprising teachers, examiners, moderators, subject advisors and coordinators. Research, which began in 2012, has shown that the *Mind the Gap* series has, without doubt, had a positive impact on grades. It is my fervent wish that the *Mind the Gap* study guides take us all closer to ensuring that no learner is left behind, especially as we celebrate 20 years of democracy.

The second edition of *Mind the Gap* is aligned to the 2014 Curriculum and Assessment Policy Statement (CAPS). This means that the writers have considered the National Policy pertaining to the programme, promotion requirements and protocols for assessment of the National Curriculum Statement for Grade 12 in 2014.

The CAPS aligned *Mind the Gap* study guides take their brief in part from the 2013 National Diagnostic report on learner performance and draw on the Grade 12 Examination Guidelines. Each of the *Mind the Gap* study guides defines key terminology and offers simple explanations and examples of the types of questions learners can expect to be asked in an exam. Marking memoranda are included to assist learners to build their understanding. Learners are also referred to specific questions from past national exam papers and examination memos that are available on the Department's website – www.education.gov.za.

The CAPS editions include Accounting, Economics, Geography, Life Sciences, Mathematics, Mathematical Literacy and Physical Sciences Part 1: Physics and Part 2: Chemistry. The series is produced in both English and Afrikaans. There are also nine English First Additional Language (EFAL) study guides. These include EFAL Paper 1 (Language in Context); EFAL Paper 3 (Writing) and a guide for each of the Grade 12 prescribed literature set works included in Paper 2. These are Short Stories, Poetry, *To Kill a Mockingbird, A Grain of Wheat, Lord of the Flies, Nothing but the Truth* and *Romeo and Juliet*. (Please remember when preparing for EFAL Paper 2 that you need only study the set works you did in your EFAL class at school.)

The study guides have been designed to assist those learners who have been underperforming due to a lack of exposure to the content requirements of the curriculum and aim to mind-the-gap between failing and passing, by bridging the gap in learners' understanding of commonly tested concepts, thus helping candidates to pass.

All that is now required is for our Grade 12 learners to put in the hours required to prepare for the examinations. Learners, make us proud – study hard. We wish each and every one of you good luck for your Grade 12 examinations.

Matsie Angelina Motshekga
MP Minister of Basic Education
2015

Table of contents

Dear Grade 12 learner

This *Mind the Gap* study guide helps you to prepare for the end-of-year CAPS Grade 12 exam.

The study guide does NOT cover the entire curriculum, but it does focus on core content of each knowledge area and points out where you can earn easy marks.

You must work your way through this study guide to improve your understanding, identify your areas of weakness and correct your own mistakes.

To ensure a good pass, you should also cover the remaining sections of the curriculum using other textbooks and your class notes.

Overview of the Grade 12 exam

The following topics make up each of the TWO exam papers that you write at the end of the year:

Cognitive level	Description	Paper 2 (Chemistry)
1	Remembering/Recall	15%
2	Understanding/Comprehension	40%
3	Applying and analysing	35%
4	Evaluating and creating (synthesis)	10%

Paper	Type of questions	Duration	Total	Date	Marking
2	**Chemistry** 10 multiple-choice questions – 20 marks Structured questions – 130 marks	3 hours	150	October/November	External

Paper 2: Chemistry Focus							
Content	Marks	Total	Duration	Weighting of cognitive levels			
Chemical change	84	150 marks	3 hours	15	40	35	10

How to use this study guide

This study guide covers selected parts of the different topics of the CAPS Grade 12 curriculum in the order they are usually taught during the year. The selected parts of each topic are presented in the following way:

- An explanation of terms and concepts;
- Worked examples to explain and demonstrate;
- Activities with questions for you to answer; and
- Answers for you to use to check your own work.

NB	Pay special attention	hint	Hints to help you remember a concept or guide you in solving problems	e.g.	Worked examples
	Step-by-step instructions	exams	Refers you to the exemplar paper		Activities with questions for you to answer

- The activities are based on exam-type questions. Cover the answers provided and do each activity on your own. Then check your answers. Reward yourself for things you get right. If you get any incorrect answers, make sure you understand where you went wrong before moving on to the next section.
- In these introduction pages, we will go through the mathematics that you need to know, in particular, algebra and graphs. These are crucial skills that you will need for any subject that makes use of mathematics. Make sure you understand these pages before you go any further.
- Go to www.education.gov.za to download past exam papers for you to practice.

Top 10 study tips

1. Have all your materials ready before you begin studying – pencils, pens, highlighters, paper, etc.

2. Be positive. Make sure your brain holds on to the information you are learning by reminding yourself how important it is to remember the work and get the marks.

3. Take a walk outside. A change of scenery will stimulate your learning. You'll be surprised at how much more you take in after being outside in the fresh air.

4. Break up your learning sections into manageable parts. Trying to learn too much at one time will only result in a tired, unfocused and anxious brain.

5. Keep your study sessions short but effective and reward yourself with short, constructive breaks.

6. Teach your concepts to anyone who will listen. It might feel strange at first, but it is definitely worth reading your revision notes aloud.

7. Your brain learns well with colours and pictures. Try to use them whenever you can.

8. Be confident with the learning areas you know well and focus your brain energy on the sections that you find more difficult to take in.

9. Repetition is the key to retaining information you have to learn. Keep going – don't give up!

10. Sleeping at least 8 hours every night, eating properly and drinking plenty of water are all important things you need to do for your brain. Studying for exams is like strenuous exercise, so you must be physically prepared.

> *If you can't explain it simply, you don't understand it well enough.*
>
> **Albert Einstein**

Mnemonics

A mnemonic code is a useful technique for learning information that is difficult to remember.

Here's the most useful mnemonic for Mathematics, Mathematical Literacy, and Physical Science:

BODMAS:

B – **B**rackets

O – **O**f or Orders: powers, roots, etc.

D – **D**ivision

M – **M**ultiplication

A – **A**ddition

S – **S**ubtraction

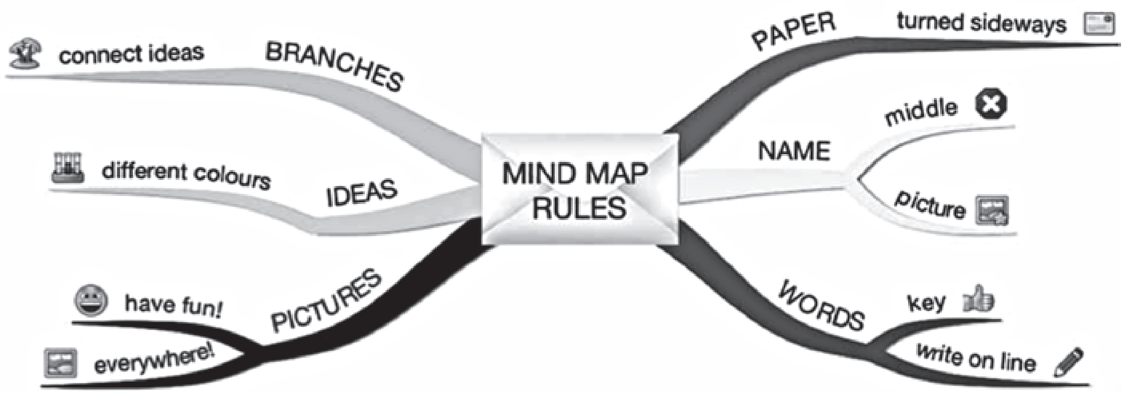
Throughout the book you will be given other mnemonics to help you remember information.

The more creative you are and the more you link your 'codes' to familiar things, the more helpful your mnemonics will be.

> *Education helps one cease being intimidated by strange situations.*
>
> **Maya Angelou**

Mind maps

There are several mind maps included in the Mind the Gaps guides, summarising some of the sections.



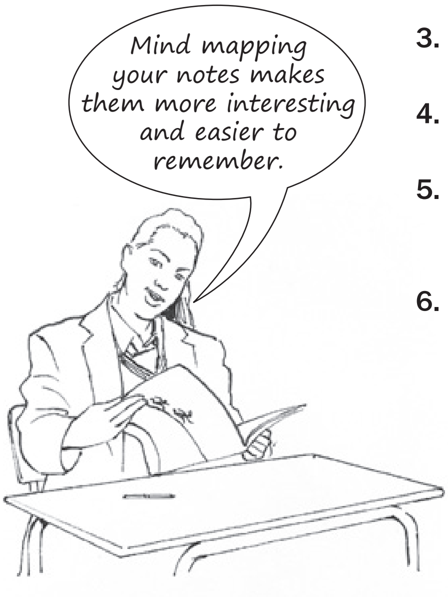
Mind maps work because they show information that we have to learn in the same way that our brains 'see' information.

As you study the mind maps in the guide, add pictures to each of the branches to help you remember the content.

You can make your own mind maps as you finish each section.

How to make your own mind maps:

1. Turn your paper sideways so your brain has space to spread out in all directions.
2. Decide on a name for your mind map that summarises the information you are going to put on it.
3. Write the name in the middle and draw a circle, bubble or picture around it.
4. Write only key words on your branches, not whole sentences. Keep it short and simple.
5. Each branch should show a different idea. Use a different colour for each idea. Connect the information that belongs together. This will help build your understanding of the learning areas.
6. Have fun adding pictures wherever you can. It does not matter if you can't draw well.



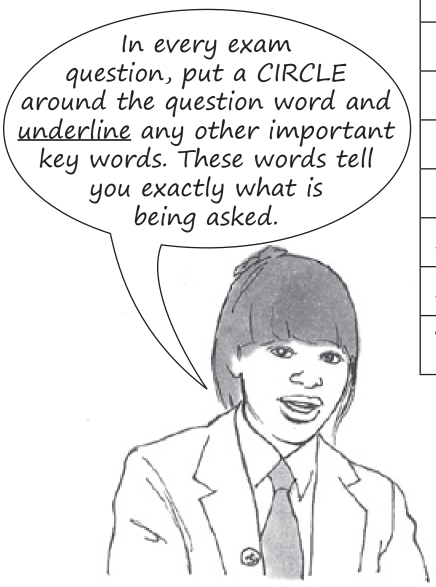
On the day of the exam

1. Make sure you have all the necessary stationery for your exam, i.e. pens, pencils, eraser, protractor, compass, calculator (with new batteries). Make sure you bring your ID document and examination admission letter.
2. Arrive on time, at least one hour before the start of the exam.
3. Go to the toilet before entering the exam room. You don't want to waste valuable time going to the toilet during the exam.
4. Use the 10 minutes reading time to read the instructions carefully. This helps to 'open' the information in your brain. Start with the question you think is the easiest to get the flow going.
5. Break the questions down to make sure you understand what is being asked. If you don't answer the question properly you won't get any marks for it. Look for the key words in the question to know how to answer it. Lists of difficult words (vocabulary) is given a bit later on in this introduction.
6. Try all the questions. Each question has some easy marks in it so make sure that you do all the questions in the exam.
7. Never panic, even if the question seems difficult at first. It will be linked with something you have covered. Find the connection.
8. Manage your time properly. Don't waste time on questions you are unsure of. Move on and come back if time allows. Do the question that you know the answers for, first.
9. Write big and bold and clearly. You will get more marks if the marker can read your answer clearly.
10. Check weighting – how many marks have been allocated for your answer? Take note of the ticks in this study guide as examples of marks allocated. Do not give more or less information than is required.

Question words to help you answer questions

It is important to look for the question words (the words that tell you what to do) to correctly understand what the examiner is asking. Use the words in the table below as a guide when answering questions.

Question word	What is required of you
Analyse	Separate, examine and interpret
Calculate	This means a numerical answer is required – in general, you should show your working, especially where two or more steps are involved
Classify	Group things based on common characteristics
Compare	Point out or show both similarities and differences between things, concepts or phenomena
Define	Give a clear meaning
Describe	State in words (using diagrams where appropriate) the main points of a structure/process/phenomenon/ investigation
Determine	To calculate something, or to discover the answer by examining evidence
Differentiate	Use differences to qualify categories
Discuss	Consider all information and reach a conclusion
Explain	Make clear; interpret and spell out
Identify	Name the essential characteristics PAY SPECIAL ATTENTION
Label	Identify on a diagram or drawing
List	Write a list of items, with no additional detail
Mention	Refer to relevant points
Name	Give the name (proper noun) of something
State	Write down information without discussion
Suggest	Offer an explanation or a solution
Tabulate	Draw a table and indicate the answers as direct pairs



Vocabulary

The following vocabulary consists of all the difficult words used in Mind the Gap Mathematics, Mathematical Literacy, and Physical Science. We suggest that you read over the list below a few times and make sure that you understand each term. Tick next to each term once you understand it so you can see easily where the gaps are in your knowledge.

KEY	
Abbreviation	**Meaning**
(v)	verb: doing-word or action word, such as "walk"
(n)	noun: naming word, such as "person"
(adj)	adjective: describing word such as "big"
(adv)	adverb: describing word for verbs, such as "fast"
(prep)	preposition: a word describing a position, such as "on", "at"
(sing)	singular: one of
(pl)	plural: more than one of
(abbr)	abbreviation

General terms

Term	Meaning
A	
abbreviate	(v). Make shorter.
abundant	(adj). Having plenty of something.
accept	(v). Agree to receive something; say yes to; believe; tolerate something.
account for	(v). Explain why.
adjacent	(adj). Next to something.
affect	(v). Make a difference to; touch the feelings of. Do not confuse with effect. See effect.
analyse	(v). Examine something in detail.
ante-	(prep). Before (e.g., ante-natal – before birth)
anti-	(prep). Against (e.g., anti-apartheid – against apartheid).
apparent	(adj). Clearly visible; the way something seems to be or the way it appears.
appear	(v). Come into sight; seem to be.
approximate	(v. & adj.). Come close to (v); roughly, almost, not perfectly accurate, close but not exact. The verb is pronounced "approxi-mayt" and the adjective is pronounced "approxi-mitt".
aquatic	(adj). Growing or living near or in water.
arbitrary	(adj). Based on random choice; unrestrained and autocratic.
C	
category	(n). Class or group of things.
cause	(v). Make something happen.
cause	(n). The person or thing that makes something happen; an aim or movement to which a person is committed.
causality	(n). Someone or something responsible for a result.
collide	(v). To crash into; to hit.
complex	(adj). Consisting of many different parts; not easy to understand (n) a group or system of things connected in a complicated way.
component	(n). A part.
compose	(v). To make up from parts.
composite	(n). Something made up of parts; (adj) made up of several parts.
condition	(n). The state something is in; the situation that must exist before something else is possible.
conjunction	(n). When two or more things come together at the same point; in grammar, a part of speech that connects words, sentences, phrases or clauses, e.g.: "and"
consider	(v). Think about.
contrast	(v). Show the difference between; (n). something that is very different from what it is being compared with.
conversely	(adv). The opposite of.
counteract	(v). Act against something in order to stop it.
D	
data (pl), **datum (sing)**	(n). Information given or found.
deduce	(v). To work something out by reasoning.

deduction	(n). Conclusion or idea that someone has worked out.
define	(v). Give the meaning of a word or words.
definition	(n). The meaning of a word or words.
deliver	(v). To bring and hand over.
denote	(v). To refer to or mean something.
determine	(v). Work out, usually by experiment or calculation.
discreet	(adj). Careful, polite.
discrete	(adj). Single, separate, distinct, a part.
E	
effect	(n). Result.
effect	(v). Carry out, do, enact.
eject	(v). Force or throw something or someone out violently or suddenly.
elapse	(v). Pass by or finish, e.g., time.
establish	(v). Show or prove, set up or create.
exceed	(v). Go beyond.
excess	(n). More than necessary.
excluding	(prep). Not including.
exclusive	(adj). Excluding or not admitting other things; reserved for one particular group or person.
exemplar	(n). A good or typical example.
exempt	(v). To free from a duty.
exempt	(adj). Be freed from a duty.
exemption	(n). Being freed from an obligation.
exhibit	(v). To show or display.
exhibit	(n). A part of an exhibition.
expel	(v). Force someone or something to leave a place. Eject.
extent	(n). The area covered by something.

F	
factor	(n). A circumstance, fact or influence that contributes to a result; a component or part.
factory	(n). A place where goods are made or put together from parts.

find	(v). Discover or locate.
find	(n). Results of a search or discovery.
finding	(n). Information discovered as the result of an inquiry.
fixed	(adj). Not able to move, attached; or repaired, not broken.
format	(n). Layout or pattern; the way something is laid out.
G	
global	(adj). Found all over the world (globe).
H	
hazard	(n). Something dangerous.
heterogeneous	(adj). Made up of many different parts.
homogeneous	(adj). Uniform, made up of the same types of parts.
hypothesis	(n). A theory or proposed explanation.
hypothetical	(adj). Theoretical or tentative; waiting for further evidence.
I	
identify	(v). Recognise or point out.
illustrate	(v). Give an example to show what is meant; draw.
impair	(v). Weaken or damage.
imply	(v). Suggest without directly saying what is meant.
indicate	(v). Point out or show.
initial	(n). First.
initiation	(n). The action of beginning something; the action of admitting somebody into a group or organisation.
insufficient	(adj). Not enough.
interchangeable	(adj). Can be swapped or exchanged for each other.
investigate	(v). Carry out research or a study.
issues	(v). Comes out of.
issues	(n). An important problem or a topic for debate.

M	
macroscopic	(adj). Visible without being made bigger.
manipulate	(v). Handle or control (a thing or a person).
microscopic	(adj). Very small, not visible without being made bigger.
motivate	(v). Give someone a reason for doing something.
multiple	(adj). Many.
N	
negligible	(adj). Small and insignificant; can be ignored. From “neglect” (ignore).
numerical	(adj). Relating to or expressed as a number or numbers.
numerous	(adj). Many.
O	
observe	(v). Look at; watch carefully.
obtain	(v). Get.
occur	(v). Happen.
operate	(v). Work; drive; control.
optimal	(adj). Best; most favourable.
optimum	(adj). Best; (n) the most favourable situation for growth or success.
overabundance	(n). More than enough; too much.
P	
phenomenon	(n). A fact or situation that is seen to exist or happen.
phenomena	(n). Plural of phenomenon.
prefix	(n). Part of a word that is attached to the beginning of many different words, changing their meaning, e.g., prehistoric – before written records were kept.
prepare	(v). Make ready before an event; set things up.
principal	(n). Head of a school.
principal	(adj). Main or most important.
principle	(n). A basic truth that guides the way a person behaves.
provide	(v). Make available for use; supply.

Q	
quality	(n). The standard of something compared to other similar things; a characteristic of someone or something.
R	
reciprocal	(adj). Given or done in return.
record	(v). Make a note of something in order to refer to it later (pronounced ree-cord).
record	(n). A note made in order to refer to it later; evidence of something; a copy of something (pronounced rec-cord.
relative	(adj). Considered in relation to something else; compared to.
relative	(n). A family member.
represent	(v). Be appointed to act or speak for someone; amount to.
resolve	(v). Finalise something or make it clear; bring something to a conclusion.
respect	(v). Admire something or someone; consider the needs or feelings of another person.
respectively	(adj). In regards to each other, in relation to items listed in the same order.
S	
simultaneously	(adv). At the same time.
site	(n). Place.
suffice	(v). Be enough.
surplus	(adj). More than is needed.
survey	(n). A general view, examination, or description of someone or something.
survey	(v). Look closely at or examine; consider a wide range of opinions or options.
T	
tendency	(n). An inclination to do something in a particular way; a habit.
tertiary	(adj). Third level.

U	
uniform	(n). Standardised clothing.
uniform	(adj). Remaining all the same at all times; unchanging.
V	
verify	(v). Show to be true; check for truth; confirm.
vice versa	(adv). The other way round.
versus	(prep). Against. Abbreviated "vs" and sometimes "v".

Technical terms

A	
absorption	(n). To take into; the process of taking something in.
account	(n. & v.). Finance: A record of income and expenditure. To explain (v), e.g. "Account for why the sky is blue".
acetic	(adj). Pertaining to vinegar; an organic molecule containing two carbons. See organic, eth- for more.
acetone	(n). Propanone. CH_3COCH_3; the ketone of acetic acid. See ketone for more.
acetylene	(n). Ethyne, C_2H_2. Used in welding torches (blowtorches). See also alkene.
acid	(n). A proton donor or substance that ionises into H^+ or H_3O^+ when dissolved in water; sour-tasting substance; corrosive; pH below 7. See also base and alkali.
acidified	(adj). To have been made acidic.
acidity	(n). How acid something is.
activated	(adj). Made to function. Chemistry: something moved into an unstable higher-energy level or state. Usually "activated complex", the combination of reactants just before they turn into products. See also reactant, reagent, product.
activation	(n). The process of activating something. "Activation energy", the required energy to create an activated complex.
aerosol	(n). A solution of substances in air or other gas, e.g. as in an aerosol can.
affinity	(n). A liking for something; an attraction to something; a tendency to react with something (chemistry). See also paraffin.
alcohol	(n). In common usage, ethanol C_2H_5OH. Technically, any organic substance or molecule containing an -OH group. See organic.
aldehyde	(n). Any organic molecule containing -CHO, formed by oxidising alcohols. See alcohol and organic.
algae	(n). Adjective: algal (pertaining to algae); an aquatic plant (lives in water), which lacks leaves, stems, roots.
algebra	(n). A mathematical system where unknown quantities are represented by letters, which can be used to perform complex calculations through certain rules.
alkali	(n). See base.
alkane	(n). An organic molecule or compound or substance which contains only single bonds between carbons. See organic.
alkene	(n). An unsaturated organic molecule, compound or substance, which contains at least one double bond between carbons. See organic and unsaturated.
alkyl	(n). A prefix (word part) which shows that the word after it has an alkane group attached to it, by removing one hydrogen from the alkane.
alkyne	(n). An unsaturated organic molecule, compound or substance, which contains at least one triple bond between carbons. See organic and unsaturated.
amalgam	(n). General use: a mixture. In chemistry, specifically a mercury alloy.
amide	(n). An organic compound containing the group $-C(O)NH_2$; an inorganic compound containing the group NH_2^-.
amine	(n). The same as an amide except the $-NH_2$ can be attached to anything, and does not have the CO group shown above.
ammonia	(n). NH_3.
ammonium	(adj). NH_4^+, found as a cation or as part of a salt. See salt and cation.
amphiprotic	(n). See ampholyte.
ampholyte	(n). A substance that can act as an acid or base. See acid, base.

anions	(n). A negative ion. See cation, ion.
anode	(n). The negative electrode of a cell or current supplier; the positive electrode of an electrolytic system; attracts negative ions. See electrode, cathode.
antacid	(n). A substance used to neutralise (react with) acid. E.g. chalk. See acid, neutralise.
apparatus	(n). Equipment; parts of a scientific experiment.
aqueous	(n). Dissolved in water.
Arrhenius	(n). Arrhenius' theory of acids and bases: That acids produce H^+ or H_3O^+ in water, and bases produce OH^-. See Brønsted-Lowry.
asbestos	(n). A fireproof fibrous substance containing silicon used for fireproofing.
asbestosis	(n). A lung disease caused by inhaling asbestos fibres, can lead to cancer.
atm	(n). Abbreviation: atmospheres of pressure (1 atm = 101,3 kPa). The pressure of the air at sea level. Same as "bar" (barometric pressure).
ATM	(n). Abbreviation: automatic teller machine.
atmosphere	(n). The air or the gases surrounding a planet; the sky; as a unit of measurement, see atm.
atmospheric	(adj). To do with the atmosphere.
atom	(n). The smallest unit of a chemical element, which, if broken down further, no longer behaves in the same way chemically. Consists of a nucleus or centre part which is positively charged, and an electron cloud (negatively charged) which surrounds the nucleus. See nuclear.
attract	(v). To bring something closer.
average	(n). Mathematics: The sum of parts divided by the quantity of parts. In common use: neither very good, strong, etc., but also neither very weak, bad, etc; the middle. In Physical Science and Mathematics: if you are asked to find the average, you always have to calculate it using the information you have. For example, the average of (1;2;3) is 2, because (1+2+3)/3 = 2. See also mean, median and mode.
avogadro (constant or number)	(n). $6,023 \times 10^{23}$ particles; one mole. See mole and mol.

axis (sing), axes (pl, pronounced "akseez")	(n). A line along which points can be plotted (placed), showing how far they are from a central point, called the origin. See origin. "Vertical axis" or "y-axis" refers to how high up a point is above the origin (or how far below). "Horizontal axis" or "x-axis" refers to how far left or right a point is away from the origin.
B	
bakelite	(n). A type of hard, brittle plastic that can't melt once it has set or taken shape (thermosetting), made from phenol C_6H_5OH, and formaldehyde (methanal), CH_2O.
balance	(v. & n.). To make two things equal (v); a scale to weigh objects (n). Chemistry: to compare two sides of a chemical equation and make sure that there are the same numbers of atoms on both sides.
base	(n). A proton acceptor, or substance that ionises into OH^- when dissolved in water; a bitter-tasting substance, corrosive, pH above 7. See also acid. Do not confuse with common everyday use, meaning "the bottom" or "low".
basic	(n). Bitter or made of a base. Do not confuse with popular use, meaning "low" or "simple" or "crude".
battery	(n). A collection of cells connected in series (end-to-end). See cell. In common use, "battery" is used to mean the same as "cell" (e.g. a penlight or AA cell), but this use is incorrect except for a car battery, which consists of a series of cells.
benzoic	(adj). Contains benzene or a benzene ring.
bi-	(prefix). Two.
bicarbonate	(n). Any salt containing the ion -HCO_3^-. So called because the carbonate (CO_3^{2-}) attaches to another ion and the hydrogen (two bonds). The name "hydrogen carbonate" is now preferred.
biodegradable	(adj). Can be broken down by natural processes e.g. involving bacteria, moulds, fungus, etc.
biodiesel	(n). Diesel (a type of petrol) made from plants rather than fossil fuels (coal, oil).

BODMAS	(abbr). Brackets, of/orders (powers, squares, etc), division, multiplication, addition, subtraction. A mnemonic (reminder) of the correct order in which to do mathematical operations.
boil	(v). Physics: to cause a liquid's vapour pressure to exceed the pressure of the gas in the container, usually by heating it, but it can be done by lowering the pressure of the gas in the container, too. See vapour pressure. In common usage, to make a liquid hot until it bubbles.
bond	(n). A connection. In physics and chemistry, between atoms and molecules.
breadth	(n). How wide something is. From the word "broad".
brine	(n). A saturated salt solution (a mixture of water and salt which can't dissolve any more salt).
bromide	(n). Something containing bromine, usually one ion. See ion.
bromo-	(prefix). Something containing bromine.
bromothymol (blue)	(n). A type of acid-base indicator used to tell whether something is an acid or base. Turns blue (in base) or yellow (in acid).
Brønsted-Lowry	(n). A theory of acids and bases which says that acids are proton donors (they give away protons), and bases are proton acceptors (they take protons). Since H^+ is just a proton, this does not mean something different from the Arrhenius theory that an acid is a substance that dissolves into H^+ in water. See proton, Arrhenius.
but-	(prefix). Four carbons. Pronounced "beaut". E.g. butane is a four-carbon alkane.
C	
calibrate	(v). To adjust a measuring tool or measurement against a known accurate measurement to ensure that the measuring tool or measurement is accurate; to check a measurement or measuring tool's accuracy; to mark with accurate measurements using a standard scale like cm, mm, mℓ, etc. Common use: to assess or evaluate carefully.

carbohydrate	(n). Organic compounds containing carbon and hydrogen, occurring in foods and living tissues and including sugars, starch, and cellulose. They contain hydrogen and oxygen in the same ratio as water (2:1). Not the same as hydrocarbons, which are any substances containing mostly hydrogen and carbon.
carbonate	(n). $-CO_3^{2-}$
carbonic	(adj). Anything containing carbon, or more specifically, CO_2
carbonyl	(adj). Containing double bonded carbon and oxygen: $=C=O$.
carboxyl	(adj). Containing $-COOH$.
carboxylic	(adj). Carboxyl-containing.
Cartesian	(adj). Anything believed or proposed by Rene Descartes. In particular, the x-and-y axis coordinate system.
catalyst	(n). A substance that alters the rate of a chemical reaction without itself being consumed in the reaction. Without qualification, or as "positive catalyst", something that starts or speeds up a reaction. A "negative" catalyst slows down a reaction.
catalytic	(n). Containing or using a catalyst.
cathode	(n). The positive electrode of a cell or current supplier; the negative electrode of an electrolytic system; attracts positive ions. See electrode, anode, ion.
cathodic	(adj). Involving a cathode. Cathodic protection: To use a more reactive metal to protect a less reactive metal from oxidation. See anode, cathode, oxidise.
cation	(n). A positively charged ion. See anion, ion.
caustic	(adj). Basic; a base.
cell	(n). An apparatus that generates electricity using electrochemistry. An AA or Penlight battery, as it is commonly called, is a cell. A car battery consists of a number of cells inside a single container.
CFC	(n). A chlorofluorocarbon. A substance containing carbon, chlorine and fluorine. Responsible for breaking down ozone (O_3) which protects us from too much UV radiation from the sun.

chain	(n). Chemistry: a long series of atoms bonded together, usually carbon.
charge	(n). Chemistry: having too many or too few electrons (most commonly), resulting in a substance ionising. A positive charge results from too few electrons, and a negative charge from too many electrons. Physics: a basic feature of all physical electromagnetic particles, except, e.g. neutrons and photons, which have zero charge. All protons have a positive charge, all electrons have a negative charge.
chart	(v). To draw a diagram comparing values on Cartesian axes.
Le Châtelier's Principle	(n). That in reversible reactions, chemical systems will favour the forward or reverse reaction to minimise the change imposed on the system. If a chemical equilibrium is disturbed by changing the conditions, the position of equilibrium moves to counteract the change.
chloro-	(prefix). Containing chlorine.
chlorofluorocarbons	See CFC.
chloroform	(n). $CHC\ell_2$. A liquid formerly used as an anaesthetic.
chlorophyll	(n). A green substance found in plants which enables photosynthesis (broadly, generating food from CO_2). See photosynthesis.
coefficient	(n). A constant value placed next to an algebraic symbol as a multiplier. Same as constant (see below). Or: a multiplier or factor that measures a property, e.g. coefficient of friction.
combustion	(n). The process of burning, usually in oxygen. Rapid oxidation.
completion	(n). Chemistry: when a reaction no longer proceeds (continues) because it has run out of one or more of the reactants. See reactant, reaction.
complex (activated)	(n). See activated.
compound	(n). A substance made up of molecules consisting of more than one different type of atom, chemically bonded in a constant ratio. E.g. Water (H_2O) is a compound, but Sulphur powder (S) is not. In a compound, the original chemicals (reactants) have reacted or merged to form a new substance. Compare to mixture.
compressed	(adj). Subjected to pressure, squashed.
concentration	(n). The number of moles of substance per unit volume. See mol, moles. How "strong" a solution is. See solution.
condensation	(n). When a vapour or gas cools down and starts to collect into larger droplets; changing phase from vapour or gas to liquid. Condensation reaction: to produce a larger molecule from two smaller ones.
conditions (STP)	(n). Physics and Chemistry: how the environment is: temperature and pressure. STP (Standard Temperature and Pressure is 25°C and 1 atm).
conjugate	(n). To join together. Chemistry: two things that belong together, e.g. conjugate acid-base pairs.
conservation	(n). A law which describes something that does not change. E.g. the conservation of matter-energy says that matter-energy cannot be created or destroyed, only transformed from one form into another. There are a number of other conservations, e.g. momentum and torque.
constant	(n). See coefficient. Means "unchanging".
contaminate	(v). Chemistry: to introduce impurities or other substances which are not meant to be part of a reaction.
control	(n. and v.). To ensure something does not change without being allowed to do so (v); an experimental situation to which nothing is done, in order to compare to a separate experimental situation, called the 'experiment', in which a change is attempted. The control is then compared to the experiment to see if a change happened.

control variable	(n). A variable that is held constant in order to discover the relationship between two other variables. “Control variable” must not be confused with “controlled variable” (see independent variable).
coordinate	(n). The x or y location of a point on a Cartesian graph, given as an x or y value. Coordinates (pl) are given as an ordered pair (x, y).
correlate	(v). To see or observe a relationship between two things, without showing that one causes the other.
correlation	(n). That there is a relationship between two things, without showing that one causes the other.
correspond	(v). To pair things off in a correlational relationship. For two things to agree or match. E.g. A corresponds to 1, B corresponds to 2, C corresponds to 3, etc.
corrode	(v). Chemistry: to destroy by gradual chemical action. Usually refers to acidic action. Compare to erode. General use: to destroy gradually.
corroding	(adj). A process or substance that corrodes; to be subject to corrosion.
corrosion	(n). To corrode.
corrosive	(adj). To be capable of corroding something.
counteract	(v). Oppose or resist.
covalent	(adj). Chemistry: a bond which results from sharing electrons between atoms. Compare ionic bond.
cracking	(n). A process of breaking a complex organic molecule into simpler parts using heat and pressure.
cubed	(adj). The power of three; multiplied by itself three times.
cubic	(adj). Shaped like a cube; having been multiplied by itself three times.
current	(n). Flowing electrons.
D	
decompose	(v). To break down into components.
degradable	(adj). Capable of breaking down or being broken down.
dehydrating (agent)	(adj). To remove water from. A “dehydrating agent” is a substance which can remove water from another substance. E.g. H_2SO_4, ethanol.
dehydration	(n). The process of removing water from a substance.
dehydrogenation	(n). The process of removing hydrogen from a substance.
dehydrohalogenation	(n). To remove hydrogen and a halogen from a substance. See halogen.
denominator	(n). See divisor. In popular speech: a common factor.
depend	(v). To be controlled or determined by something; to require something to happen or exist first.
dependent (variable)	(adj/n). A variable whose value depends on another; the thing that comes out of an experiment, the effect; the results. See also independent variable and control variable. The dependent variable has values that depend on the independent variable, and we plot it on the vertical axis.
depleted	(adj). Having been used up; run out of.
deposit	(n). Finance: to place money into an account. Physical Science: to cover a surface of one substance with another substance, e.g. metal plating on an electrode.
determine(s) (causation)	(v). To cause; to ensure that; to set up so that; to find out the cause of.
di-	(prefix). Two.
diamine	(n). A substance containing two amine groups. See amine.
diammonium	(n). Having two ammonium (NH_4) groups. See ammonium.
diaphragm	(n). A thin sheet of any substance covering a gap. Biology: the muscle below the lungs which moves to cause breathing. Electrochemistry: a thin sheet inside a cell which separates the electrodes. It is porous and allows solutions containing ions through, but serves to separate gas products.
difference	(n). Mathematics: subtraction. Informally: a dissimilarity. How things are not the same.

dilute	(adj. & v). To lower the concentration of a solution. See solution and concentration (v): a solution which has had its concentration lowered (adj).
dilution	(n). The opposite of concentration; how low a concentration is, measured in mol/dm^3; the process of diluting.
dimer	(n). A molecule made of two identical parts. See also polymer.
diode	(n). A semiconductor device with two terminals (electrodes), usually allowing current to flow in one direction only.
diol	(n). A molecule with two alcohol/hydroxyl (OH) groups.
dipole	(n). A polarised molecule with a distinctly positive and distinctly negatively-charged end.
diprotic	(n). Having two protons.
displace	(v). To move or relocate something.
dissipate	(v). To disperse or scatter (e.g. gas). Thermodynamics (Energy): to cause energy to be lost as heat. Popular use: to disappear.
dissociate	(v). To break apart; to no longer be associated with.
dissolve	(v). To break up into ions within a solution (usually water); to mix a solid (usually powder) into a liquid, to form a solution. See solution, ion. Alternative popular use: to bring to an end.
distil(l)	(v). To purify through repeated heating of a liquid and collection of condensation. The heating process causes the liquid to form gas or vapour, which condenses on the side of the heating vessel (container) or an exit tube, leaving impurities behind in the heating vessel.
distribution	(n). How something is spread out. Mathematics: the range and variety of numbers as shown on a graph.
disturb	(v). Chemistry: to mix or stir a liquid or solution; to shake it up.
divisor	(n). The number below the line in a fraction; the number that is dividing the other number above the fraction line. See numerator, denominator.

domain	(n). The possible range of x-values for a graph of a function. See range.
durable	(adj). Tough; something that can endure.
dynamic	(adj). Changing often. Relating to forces that produce motion. Opposite of static. See static and electrostatic.
E	
ecosystem	(n). An integrated, complex, interacting, mutually dependent living system or environment.
electric	(adj). Containing electricity (electrons).
electro-chemical	(adj). Where chemical reactions cause the release of electrons, usually into a circuit. General use: anything relating to electrical and chemical phenomena.
electrode	(n). General use: the point where electrons enter or exit a power source or a circuit. Specifically (Electrochemistry): Part of a circuit dipped into a solution to receive or release electrons. See anode and cathode.
electrolysis	(n). The splitting of a chemical into ions. (The chemical is usually dissolved in water or another solution.) It is done by means of electricity. See electrochemical.
electrolyte	(n). A substance (usually liquid or gel solution) which contains a compound that will be split by electricity. Ionisable solutions or components.
electromotive	(adj). Usually electromotive force or emf. The potential difference caused by electromagnetism, which causes current to flow. Producing a current with electromagnetism. See emf.
electron	(n). A fundamental physical particle bearing a negative charge, weighing approximately 9×10^{-28}g, which is found around atomic nuclei in areas called 'orbitals'. Responsible for electricity and chemical reactions. Symbol e^-. See proton, nucleus.

electroplate	(v). To cover a surface of a less valuable substance with a more valuable metal, using electrolysis.
element	(n). Mathematics: part of a set of numbers. Physics: a pure substance made only of atoms of one type, with the same number of protons in each nucleus. An element cannot be broken down further without losing its chemical properties. Each element has a unique atomic number which is the number of protons in the nucleus. See nucleus, atom, isotope. Popular use: part of.
eliminate	(v). To remove or get rid of. Mathematics: to cancel a factor out of one side of an equation by dividing by that factor throughout, or by substituting in another formula or value that is equal. Chemistry: to produce a smaller substance as a by-product from reacting more complex substances, usually water or CO_2; in the sense of: to remove those molecules from the reaction.
emf	(abbr). Same as electromotive force. Always written in lowercase (small letters).
emission	(n). Something released, e.g. gas, light, heat.
emit	(v). To release.
empirical	(adj). Relating to the senses or to things that you can see, touch, taste, etc. Chemistry: empirical formula: a formula giving the proportions of the elements present in a compound but not the actual numbers or arrangement of atoms; the lowest ratio of elements without giving structure or quantities.
emulsion	(n). Small particles or droplets of a substance or liquid which do not dissolve in a different liquid; suspended or floating within that liquid, e.g. to mix oil and water by shaking them up.
endothermic	(adj). Taking in heat, $\Delta H > 0$. See enthalpy, exothermic.
energetic	(adj). Having a lot of energy; performing a lot of work.

energy	(n). Work or the ability to do work. There are various forms of energy: motion (E_k), light energy (photons), electrical energy, heat, etc. Energy can neither be created nor destroyed, but only converted from one form to another. See conservation.
enthalpy	(n). The total heat content of a system, H, including the chemical energy.
equilibria (pl), equilibrium (sing)	(n). The state of being in balance. Chemistry: when the forward reaction rate is equal to the reverse reaction rate. See Le Châtelier's Principle.
erode	(v). To wear away by means of friction (rubbing).
ester	(n). An organic compound produced by bonding an alcohol to a carboxylic (organic) acid, by means of dehydration. See carboxylic, organic, alcohol, dehydration. Responsible for fruit flavours and many pleasant odours (smells).
esterfication	(n). The production of esters.
estimate	(n., v.). To give an approximate value close to an actual value; an imprecise calculation.
eth-	(prefix). Containing two carbons.
eutrophication	(n). Excess nutrients in water causing excessive plant growth and strangulation of a waterway.
evaporate	(v). To change phase of matter from liquid to gas. Compare sublimate and boil.
excited	(n). The state of being in a higher energy level (higher than ground state).
exo-	(prefix). Outside of.
exothermic	(adj). Giving off heat, $\Delta H < 0$. See enthalpy, endothermic.
exponent	(n). When a number is raised to a power, i.e. multiplied by itself as many times as shown in the power (the small number up above the base number). So, 2^3 means $2 \times 2 \times 2$. See also cubed.
exponential	(adj). To multiply something many times; a curve representing an exponent.

extrapolation	(n). To extend the line of a graph further, into values not empirically documented, to project a future event or result. In plain language: to say what is going to happen based on past results which were obtained (gotten) by experiment and measurement. If you have a graph and have documented certain results (e.g. change vs time), and you draw the line further in the same curve, to say what future results you will get, that is called 'extrapolation'. See predict.
extrude, extrusion	(v., n.). To push something through a mould or shape, usually a liquid or gel through a hole, to create a new shape.
F	
fahrenheit	(n). A temperature scale based on human body temperature. Water freezes at 32 °F and boils at 212 °F under standard conditions. The conversion formula to centigrade/celcius is: $(^\circ F - 32) \times {}^5/_9 = {}^\circ C$
favoured	(adj). Preferred. Chemistry: in a chemical reaction, the direction of the reaction after the equilibrium is broken.
fermentation	(n). The conversion of a sugar or carbohydrate to an alcohol, usually by yeast or bacteria.
fertilisation	(n). The process of adding nutrients to soil. Biology: the fusion of male and female gametes (sex cells) into a zygote (group of cells that will become a foetus or other living organism).
fertiliser	(n). A substance added to soil for nutritional reasons.
fixation	(n). The process of fixing on something or someone.
fixed (chemistry)	(n). The process of attaching one chemical or compound to another. E.g. nitrogen fixing is the bonding of free N_2 to organic chemicals.
fluid	(n). Any substance that can flow and take the shape of a container; liquid, some gels, and gas.
fluorescent	(n). Bright, colourful, due to changes in energy levels of electrons, as seen in fluorescent tubes, ink, etc. See reflective.
formic	(prefix). Same as meth-. Contains one carbon. From Latin "formica": ant, referring to formic acid, which is found in an ant's sting.
fraction	(n). Mathematics: Not a whole number; a representation of a division. A part. E.g. the third fraction of two is 0,666 or ⅔. meaning two divided into three parts. Chemistry: a part of a solution or mixture separated out by distillation. See distil.
function	(n). Mathematics: when two attributes or quantities correlate. If y changes as x changes, then $y = f(x)$. See correlate, graph, Cartesian, axis, coordinate. Also: a relation with more than one variable (mathematics). Chemistry: functional group: part of a molecule that gives the substance its chemical properties in common with other similar chemicals.
G	
galvanic	(adj). Relating to currents caused by a chemical reaction. See electrochemistry.
galvanising	(n). To electroplate so as to protect, e.g. cover iron with zinc to prevent rust.
gas	(n). The third phase of matter. When a solid is heated it turns into liquid, and when a liquid is heated it turns into gas.
gaseous	(adj). In a gas form.
gradient	(n). A slope. An increase or decrease in a property or measurement. Also the rate of such a change. In the formula for a line graph, $y = mx + c$, m is the gradient.
gradually	(adv). To change or move slowly.
graph	(n). A diagram representing experimental or mathematical values or results. See Cartesian.
graphic	(n., adj.). A diagram or graph (n). Popular use: vivid or clear or remarkable (adj.).
graphically	(adv). Using a diagram or graph. Popular use: to explain very clearly.
groundwater	(n). Water held in the earth (underground).
gypsum	(n). Calcium sulphate.

H	
Haber (process)	(n). An industrial process to produce ammonia from nitrogen and hydrogen, using an iron catalyst at high temperature and pressure.
haemoglobin	(n). A compound containing iron, found in red blood cells, responsible for carrying oxygen.
half-cell	(n). One of the sides of an electrochemical cell; one of the electrodes and the chemical solution around it.
half-reaction	(n). The equation for the chemical reaction occurring in a half-cell.
halide	(n). A compound containing a single halogen, e.g. $NaC\ell$. See halogen.
halo-	(prefix). Containing a halogen. See halogen.
haloalkane	(n). An alkane bonded to a halogen. See halogen.
halogen	(n). Any of the elements fluorine (F), chlorine ($C\ell$), bromine (Br), iodine (I), and astatine (At), in group VIIA (17) of the periodic table. They combine with metals to produce salts. See salt.
halogenation	(n). Adding a halogen.
hardness	(n). (Water). Containing salts, usually calcium carbonate. If water contains too many such salts, soap does not function properly and doesn't produce bubbles or foam. "Water's hardness is determined by the concentration of multivalent cations in the water. Multivalent cations are cations (positively charged metal complexes) with a charge greater than 1+. Usually, the cations have the charge of 2+. Common cations found in hard water include Ca^{2+} and Mg^{2+}." (Wikipedia).
heat	(n). Physics: a measure of the average kinetic energy of the molecules or atoms in a substance; enthalpy; the energy of an object as molecular motion. Alternatively, infra-red radiation (heat radiation) coming off a body. See body.
homologous	(n). Belonging to the same group of things; analogous. Biology: a flipper is homologous with a leg or arm. Chemistry (organic): belonging to the same series of molecules, e.g. alkanes: methane, ethane, propane; having the same functional group.
hydrate	(n). To add water to.
hydration	(n). Having had water added. Some salts are hydrated, meaning that they have a number of water molecules bonded to them, which can be removed by heat. Heating a hydrated salt changes its colour but not the chemical reactions it will undergo. See salt.
hydrocarbon	(n). Any compound consisting mainly of hydrogen and carbon. Compare carbohydrate.
hydrochloric	(adj). Any chemical containing $HC\ell$.
hydrohalogenation	(n). Adding a hydrogen and halogen atom to a molecule.
hydrolysis	(n). Splitting by reacting with water. Applies to salts and organic chemicals. E.g. A haloalkane plus water or a dilute NaOH gives an alcohol and either a hydrohalide or sodium salt. Dissolving a salt in water can be considered hydrolysis.
hydronium	(n). H_3O^+ ion.
hydroxide	(n). OH^- ion. This usage applies specifically to bases (see acid, base). In organic molecules, OH^- is an alcohol functional group called the hydroxyl group. See alcohol, hydroxyl, diol.
hydroxyl	(n). See hydroxide.
hydroxylamine	(n). An amine with a hydroxyl group.
I	
ideal	(adj). Not as seen in real life; theoretical. Ideal gas: a hypothetical gas whose molecules occupy negligible space and have no interactions, and which consequently obeys the gas laws ($PV = nRT$) exactly.
ignition	(n). The start of a combustion reaction. Common use: to start a car (which has an internal combustion engine). See engine, combustion.
illuminate	(v). To explain or light up.
immerse	(v). To cover in liquid.
impair	(v). Prevent; hinder; slow down.
impure	(adj). Containing a variety of additional chemicals in smaller amounts in addition to the main chemical.

incandescent	(adj). Giving off light as a result of being heated.
independent (variable)	(n). The things that act as input to the experiment, the potential causes. Also called the controlled variable. The independent variable is not changed by other factors, and we plot it on the horizontal axis. See control, dependent variable.
indicator	(n). Chemistry: a substance used to check for pH levels, which changes colour according to pH. See acid, base, pH.
indigo	(n). The colour between violet and blue; purplish-blue.
inert	(adj). Chemistry: a chemical or element which does not react or is difficult to cause to react, e.g. Ne, Xe, He. N_2 is sometimes described as inert but it's not in the group of Noble Gases. Common use: lazy, unwilling to move.
inflammable	(adj). Same as flammable; easily set on fire (combustion).
inhibitor	(n). Something that slows down or prevents.
inorganic	(adj). Not containing carbon; mineral. Exceptions are C, CO, CO_2, which, whilst they contain carbon, are not considered organic as they can be produced during inorganic chemical reactions.
insoluble	(adj). Not able to dissolve.
insufficient	(adj). Not enough.
interact	(v). To affect each other, to be directly involved with or act on each other.
intermediate	(adj). A state in between.
intermolecular	(adj). Between molecules. See molecule, intramolecular.
intramolecular	(adj). Within or inside a molecule. See molecule, intermolecular.
inversion	(n). Chemistry: turning something upside down.
ion	(n). An atom or molecule or part of a molecule which has an electrical charge due to gaining or losing one or more electrons.
ionic (bond)	(adj.). A bond in which electrons have been transferred from one side of the molecule to another resulting in a cation and anion, which then attract. E.g. $NaC\ell$.
ionisation	(n). The process of ionising. See ionise.
ionise	(v). To turn into an ion. See ion.
irreversible	(adj). Cannot be reversed. Said of certain chemical reactions, in which case it specifically means that the reaction does not spontaneously reverse (not an equilibrium reaction). The reaction only proceeds in one direction. Example: combustion.
isolate	(v). To separate from. Usual use in Physical Science means to separate one chemical from another. Compare insulate, distil.
isomer	(n). A substance with the same empirical formula but a different structural formula. See empirical, structural.
isotope	(n). An element which has a different number of neutrons from the usual number of neutrons in the element. E.g. ^{12}C has 6 protons and 6 neutrons, but ^{14}C has 8 neutrons and 6 protons, and is radioactive.
IUPAC	(abbr). International Union of Pure and Applied Chemistry. Standardised naming conventions for chemicals.
J	
joule	(n). Unit of energy.
K	
kelvin	(n). Unit of temperature, with absolute zero being the point where no molecular motion occurs, at -273,15˚C. Hence, the freezing point of water is 273,15 K. Note that there is no degree sign before K.
ketone	(n). An organic compound with the carbonyl group = C = O. Made by oxidising secondary alcohols. E.g. acetone.
L	
law	(n). In Physical Science, a formula or statement, deduced (discovered) from observation (watching). The formula or statement will then predict that under the same conditions the same thing will always happen. E.g. the first law of thermodynamics says that matter and energy cannot be destroyed, but only changed from one form to another.

leach	(v). When a substance drains out of soil, e.g. into rivers. Similar to “leak”.
litmus	(n). A type of acid/base indicator. See indicator. It is red when exposed to acid and blue when exposed to a base.
M	
macromolecule	(n). A large molecule, usually a polymer or protein.
macroscopic	(adj). Large enough to be visible to the unaided human eye; big enough to be seen.
magenta	(n). A bright purple/pink colour.
manipulate	(v). To change, or rearrange something. Usually in Mathematics it means to rearrange a formula to solve for (to get) an answer.
material	(n). Any substance, not just cloth.
matter	(n). Substance; stuff. Opposite of vacuum (nothing).
mean	(n). See average.
median	(n). Mathematics: the number in the middle of a range of numbers written out in a line or sequence.
metal	(n). A substance which is malleable (can be hammered flat), is ductile (can be drawn into a wire), which conducts electricity and heat well and which is reflective (most light striking it is emitted again). Most elements are metals except the few on the right hand side of the periodic table starting at Boron (B) and running diagonally down to Astatine (At).
meth-	(prefix). Having one carbon. See formic.
methylated	(adj). Having had a single carbon or methyl group added.
metric	(adj). A measurement system, using a base of 10 (i.e. all the units are divisible by 10). The USA uses something known as the Imperial system, which is not used in science. The Imperial system is based on 12. Examples: 2,54 cm (metric) = 1 inch (imperial). 1 foot = 12 inches = approx. 30 cm; 1 metre = 100 cm. 1 Fl.Oz (fluid ounce) = approx 30 mℓ.
microscopic	(adj). Too small to be seen by the unaided human eye.
minimum	(n). The smallest amount possible.
mixture	(n). When you mix or combine substances without them undergoing a chemical reaction. In other words, the substances mixed stay separate (chemically) and do not bond. Different to compound. See compound, reaction.
modal	(adj). Pertaining to the mode, or method. Can mean: about the mathematical mode or about the method used. See mode.
mode	(n). Mathematics: the most common number in a series of numbers. See also mean, median.
mol	(abbr). Mole.
molar	(adj). About a mole. See mole.
mole	(n). A unit describing an amount of substance. $6{,}023 \times 10^{23}$ molecules or atoms of the substance. E.g. 18 g of water is 1 mol of water (H = 1, O = 16, H_2O = 18).
molecular	(adj). About molecules. See molecule.
molecule	(n). The smallest amount of a compound; a single particle composed of the elements that make up the compound. E.g. in water, a single particle consisting of two hydrogen atoms and one oxygen atom.
mono-	(prefix). One.
monomer	(n). Part of a macromolecule; the simplest repeating unit. Monomers bond to form polymers. See polymer, isomer.
monoprotic	(adj). Having one proton.
N	
neutral	(adj). Chemistry: pH 7,0. Neither acid nor base. E.g. water. In common use: not biased. See bias.
neutralise	(v). To make something neutral; to complete an acid/base titration.
neutron	(n). A subatomic particle with no charge, mass approximately the same as a proton, found in the nucleus of an atom. Symbol n^0. If there are too many protons in a nucleus, the substance will be radioactive as it releases alpha particles (helium nuclei, $2p^+ + 2n^0$).

nitrate	(n). Containing NO_3^-.
nitrite	(n). Containing NO_2^-.
nomenclature	(n). A system of describing things; a naming system, designed to make a name unambiguous or unique.
nonmetal	(n). Any of the elements that are not metals, e.g. Boron (B), Silicon (Si), Sulphur (S), Oxygen (O), etc.
nucleus (sing), **nuclei (pl),** **nuclear (adj)**	(n).The centre of something (generally), specifically the centre of an atom, consisting of at least one proton (hydrogen), or two protons and two neutrons (helium). Plural nuclei is pronounced “noo-klee-eye”.
numerator	(n). The opposite of a denominator; the number on top in a fraction.
O	
-oate	(suffix). An ester.
odour	(n). A smell.
optimal	(adj). Best, most.
organic	(adj). Containing carbon, except C, CO, CO_2.
origin	(n). Mathematics: the centre of a Cartesian coordinate system. General use: the source of anything, where it comes from.
outlier	(n). Statistics: a data point which lies well outside the range of related or nearby data points.
oxalic (acid)	(n). Ethanedioic acid; chem. formula: $(COOH)_2$.
oxidation	(n). Specifically, adding an oxygen atom to a molecule, but more general use: losing electrons from any substance in a redox reaction. See redox.
oxide	(n). A compound containing an oxygen atom, especially if it previously did not contain one, e.g. iron (metal), vs iron oxide (rust).
oxidise	(v). To add an oxygen or remove electrons from a substance.
P	
paraffin	(n). Any waxy organic substance, previously the general name for alkanes. Formula ranges from $C_{20}H_{42}$ to $C_{40}H_{82}$.
parallel	(adj). Keeping an equal distance along a length to another item (line, object, figure). Mathematics: two lines running alongside each other which always keep an equal distance between them.
particle	(n). Any small part, e.g. a proton, an atom, a molecule.
pascal	(n). The unit of pressure, abbreviated Pa, units: N/m^2
pent-	(prefix). Five.
per	(prep). For every, in accordance with. Chemistry: the maximum amount of an element possible for the number of bonds available. See e.g. peroxide.
peroxide	(n). H_2O_2.
perpendicular	(adj). Normal; at right angles to (90˚).
phase	(n). Time, period; a state of matter (solid, liquid, gas); the relationship in time between the cycles of a system (such as an alternating electric current or a light or sound wave) and either a fixed reference point or the states or cycles of another system with which it may or may not be synchronised (simultaneous). I.e. if two systems vibrate at the same time at the same rate, they’re “in phase”.
photosynthesis	(n). The process of converting CO_2 into carbohydrates using atmospheric CO_2, chlorophyll, and light.
pi	(n). π, the Greek letter p, the ratio of the circumference of a circle to its diameter. A constant without units, value approximately 3,14159.
plastic	(n., adj.). An artificial substance made from hydrocarbon polymers which is often flexible and able to be moulded and is often a poor electrical conductor (n); flexible (adj).
plot	(v). To place points on a Cartesian coordinate system; to draw a graph.
poly-	(prefix). Many.
polyester	(n). A polymer made from esters.
polymer	(n). A synthetic substance made from many monomers (repeating units). See monomer.
polymerisation	(n). Making a polymer.
polyprotic	(adj). Having many protons.

porous	(adj). Having many holes that allow fluids through.
positive	(adj). Having many protons not paired with electrons; a lack of electrons.
potential	(n). Having the ability to do work, in particular, E_p (potential energy, the tendency to fall or start moving, as in a spring), or emf (voltage). General use: potential exists when there is an energy difference between two points, e.g. due to gravity or electrical charge. In the context of electricity, read it as "voltage".
precipitate	(n). Chemistry: A product of a reaction that cannot dissolve in the solution and settles at the bottom of the reaction vessel (container).
predict	(v). General use: to foresee. Physical Science: to state what will happen, based on a law. See law.
pressure	(n). A continuous force exerted on an object over a certain area, in pascals, Pa. N/m^2. See pascal.
product	(n). Chemistry: the substance or compound made as a result of a chemical reaction. See reaction. Mathematics: the result of multiplying two numbers.
project	(n. & v.). A project (n., pronounced PRODJ-ekt) is a plan of action or long-term activity intended to produce something or reach a goal. To project (v., pronounced prodj-EKT), is to throw something, or to guess or predict (a projection). To project a result means to predict a result. See extrapolate.
prop-	(prefix). Three carbons. Pronounced "prope" (rhymes with "rope").
proportion	(n). To relate to something else in a regular way, to be a part of something in relation to its volume, size, etc; to change as something else changes. See correlate and respectively.
protein	(n). A large, complex organic molecule containing nitrogen, usually making up structural elements of living things (building blocks of cells, antibodies, etc).
protolytic	(adj). Capable of removing a proton; proton transfer. Compare acid.
proton	(n). The positively-charged particle that forms the centre of an atomic nucleus, weighing 1 836 times as much as an electron, but having the same and opposite charge. Symbol p^+. See also nucleus, neutron, electron.
pump	(n). A machine that uses energy to transfer a fluid from one place to another. In Biology one finds cellular pumps, which are biological machines for transferring ions and nutrients.
pure	(adj). Containing only the compound or element in question, without any other compounds or elements mixed in. See impure.
purification	(n). The process of removing impurities. See distil.
Q	
qualitative	(adj). Relating to the quality or properties of something. A qualitative analysis looks at changes in properties like colour, that can't be put into numbers. Often contrasted with quantitative.
quantitative	(adj). Relating to, or by comparison to, quantities. Often contrasted with qualitative. A quantitative analysis is one in which you compare numbers, values and measurements.
quantity	(n). Amount; how much.
R	
rancid	(n). Having an unpleasant smell due to having started to ferment or rot, usually said of meat, oil or butter.
random	(n). Unpredictable, having no cause or no known cause. Done without planning.
range	(n). Mathematics: the set of values that can be supplied to a function. The set of possible y-values in a graph. See domain.
rate	(n). How often per second (or per any other time period). Physics: number of events per second; see frequency.

ratio	(n). A fraction; how one number relates to another number; exact proportion. If there are five women for every four men, the ratio of women to men is 5:4, written with a colon (:). This ratio can be represented as the fraction $^5/_4$ or 1¼ or 1,25; or we can say that there are 25% more women than men.
react	(v). Chemistry: when two or more elements or compounds are brought into a mixture and form chemical bonds, creating new compounds.
reactant	(n). A chemical before it bonds with another chemical. See reagent.
reaction	(n). Chemistry: The process of reacting; a state in which chemicals react. See endothermic and exothermic. Physics (nuclear): When a nucleus of an atom breaks down and subsequently releases energy and/or bonds with another nucleus. In the first case, it is a fission (splitting) reaction, in the second case a fusion (joining) reaction.
reactive	(adj). Tending to react easily.
reactivity	(n). How reactive a substance is (unreactive or reactive).
reagent	(n). A reactant when it is still in its bottle or container, before being mixed.
redox	(abbr). Chemistry: reduction-oxidation reaction; a chemical reaction in which one substance is reduced (gains electrons), and another is oxidised (loses electrons). See reduce, oxidise, anode, cathode, electrode, electrochemistry.
reduce	(v). To make smaller. Chemistry: to gain electrons (negative charges).
reflux	(n., v.). A substance that flows back into its container after coming out. Chemistry: the process of boiling a liquid so that any vapour is liquefied and returned to the stock (source).
refraction	(n). Bending light when it travels from one medium (e.g. air) into another medium (e.g. water or glass). Changing the direction of propagation of any wave as a result of its travelling at different speeds at different points along the wave front. See Huygens' principle, diffraction.

S	
salt	(n). In common usage, $NaC\ell$. Chemistry: any compound formed from the reaction of an acid with a base, with the hydrogen of the acid replaced by a metal or other cation. A non-metal ion bonded to a metal ion.
saturated	(adj). Organic chemistry: Having no available bonds or only single bonds. Common use: cannot take any more, usually said of a cloth and liquid.
SI	(abbr). Système International. The international system of metric units used by scientists. See metric, IUPAC.
simplify	(v). To make simpler. Mathematics: to divide throughout by a common factor (number or algebraic letter) that will make the equation easier to read and calculate.
slaked (lime)	(n). Calcium Hydroxide, $Ca(OH)_2$.
solubility	(n). How easily something dissolves (mixes into a liquid).
soluble	(adj). See solubility.
solute	(n). The substance that you place in a liquid (the solvent) so as to dissolve it. E.g. salt. See solvent.
solution	(n). A mixture of a solute and a solvent. A liquid which has had something dissolved in it (mixed). Mathematics: the step-by-step displaying of calculations to arrive at answers. Common use: the answer to a problem, in the sense of dissolving (removing) a problem.
solvent	(n). The liquid that dissolves the substance placed into it. E.g. water.
spectator	(n). Chemistry: a compound or chemical which does not get involved in a chemical reaction.
spontaneous	(adj). Randomly, without provocation or cause or prior planning.
stable	(adj). Chemistry and Nuclear Physics: not likely to break down or react further.
standardised	(adj). Chemistry: a solution of known concentration, e.g. 1 molar (1 mol/dm^3).

steam	(n). Water vapour, microscopic droplets of water. Not a gas, a suspension of water droplets in air. See suspension, gas, liquid, phase, aerosol.
STP	(abbr). Standard temperature and pressure; 101,3 kPa and 25 ˚C.
structural (isomer)	(adj.). Pertaining to structure; a series of molecules whose structures are different but their chemical or empirical formulae are the same.
sublimate	(v). To change phase of matter from solid straight to gas without the intermediate phase of liquid. See the case of dry ice (CO_2).
subscript	(n). A number placed below the rest of the line, e.g. CO_2.
substance	(n). Matter. Physical things.
substituent	(n). Chemistry: an ion or functional group or group of atoms that replaces a hydrogen on an organic molecule.
substitute	(v). To replace.
substitutents	(n). Something that gets replaced.
substitution	(n). The process of substituting. Mathematics: to replace an algebraic symbol in a formula with a known value or another formula, so as to simplify the calculation. See simplify. Chemistry: to cause a substituent to bond to a substance.
superscript	(n). A number placed above the rest of the line, e.g. πr^2.
synthesis	(n). The process of manufacturing (making) something. Chemistry: to bond smaller molecules together to create a larger molecule, e.g. methanol from CO and H_2. Synthesis gas: a gas mixture (e.g. CO, H_2), which when heated produces a new compound, e.g. methanol.
synthetic	(adj). Artificial, man-made.
system	(n). Any closely associated and inter-related or inter-dependent group of things; a set of things working together. Chemistry: a vessel (container) which contains a chemical reaction.

T	
terminal	(n). Final; end point.
termination	(n). Coming to an end.
tetra-	(prefix). Four.
theory	(n). A usually mathematical representation of an explanation for something in the sciences, which does not depend on the thing being explained. A theory differs from a law in that theories are prone to empirical (visible or measurable) refutation (rejection); meaning that they can be discarded if evidence comes in that they are wrong. See law.
thermoplastic	(n). Chemistry: will melt if heated.
thermoset	(n). Once set into a shape it cannot melt again.
thiosulphate	(n). A salt containing the anion $S_2O_3^{2-}$.
threshold	(n). Physical Science: the magnitude or limit of something, which, if exceeded, will cause something else, e.g. release of radiation, a chemical reaction, etc; the minimum amount of energy required to cause something. Medicine: the maximum safety level of a dose.
titrate	(v). To measure off a reagent precisely drop by drop into a vessel (container) containing another reagent, so as to work out the concentration of the reagent in the vessel.
toxic, toxin	(adj., n.). Poisonous, poison.
transfer	(n). To move from one place to another. Chemistry: usually refers to moving an electron from one compound to another. Finance: usually refers to a payment or credit. See credit, debit, transaction.
trends	(n). Mathematics: regular patterns within data.
tri-	(prefix). Three.
trial	(n). Chemistry: to repeat an experiment, an iteration, or particular attempt at an experiment. (From "try", to try once).

triprotic	(n). Having three protons.
turbidity	(n). How muddy, muddled or opaque or disturbed a liquid is.
U	
unit	(n). A subdivision of a scale. See scale.
universal (indicator)	(n). A chemical which can indicate how acid or basic a solution is, ranging from reds (acidic) to violets (basic), including most of the colour spectrum.
unsaturated	(n). Organic chemistry: having double or triple bonds present.
unstable	(n). Chemistry or Nuclear Physics: prone to disintegrating or reacting.
urea	(n). $CO(NH_2)_2$. The substance used to remove excess nitrogen from animals via urination. Useful as a fertiliser.
V	
vapour pressure	(n). The pressure above a liquid caused by molecules evaporating from the surface of its liquid form, when in phase equilibrium (i.e. as many molecules leaving the liquid surface are condensing back into the liquid).
variable	(n., adj.). A letter used to represent an unknown quantity in algebra (n); a quantity that changes (n); subject to change (adj).
vessel	(n). Any container. Common use: a container or ship.
visible	(adj). Able to be seen by the human eye, opposite of invisible. Compare microscopic, macroscopic.
viscosity	(n). The thickness of a fluid. A viscous fluid flows slowly, e.g. syrup. Pronounced “viss-KOSS-itee” and “viss-k’s”.
volatility	(n). How easily something evaporates. E.g. Ether (C_2H_5OC) is more volatile than water.
volt	(n). Unit of potential difference in electricity. The difference of potential (E_p) that would carry one ampere of current against one ohm resistance. Same as emf. See emf, resistance, ohm, ampere.
voltage	(n). The measurement of volts.
voltaic	(n). The production of electricity in a cell. See battery, cell, electrochemistry, electrode, cathode, anode, galvanic.
volume	(n). A measure of the space occupied by an object, equal to length x breadth x height.
Y	
yield	(n., v.). The amount of substance produced in a chemical reaction (n); products of a process (n); to hand over or give up (v).

The maths you need

This section gives you the basic mathematical skills that you need to pass any subject that makes use of mathematics. Whether you're studying for Physical Science, Mathematics, or Mathematical Literacy, these basic skills are crucial. Do not go any further in this book until you have mastered this section.

1. Basic pointers

- If a formula does not have a multiplication (×) sign or a dot-product (·), and yet two symbols are next to each other, it means "times". So, m_1m_2 means *mass 1* times *mass 2*. You can also write it as $m_1 \times m_2$, or $m_1 \cdot m_2$
- Comma means the same as decimal point on your calculator (i.e. 4,5 = 4.5). Do not confuse the decimal point with dot product (multiply): $4.5 = 4\frac{1}{2}$ but $4 \cdot 5 = 20$. Rather avoid using the dot product for this reason.
- In science it is common to write divisors with an exponent. This means, for example, that 0,5 metres per second is usually written $0{,}5\ \text{m}\cdot\text{s}^{-1}$ rather than 0,5 m/s. Both notations are perfectly correct, however, and you may use either. It is important, however, that you either use –1 or / . If you just put 0,5 ms, that means 0,5 milliseconds, which is not a velocity (speed in a direction); it is a time.
- A variable is something that varies (means: changes). So, for example, the weather is a variable in deciding whether to go to the shops. Variables in science and mathematics are represented with letters, sometimes called algebraic variables. The most common you see in maths is x, probably followed by y, z. In science, variables are given their letter symbols specifically depending on what they stand for; so, for example, M or m are used for mass (amount of substance in kilograms); v is used for velocity (speed in a certain direction); a is used for acceleration (change in velocity), etc. You can guess for the most part what a variable is for by what its letter is; so V is voltage, R is resistance, P is pressure, and so on.

2. Subject of formula or solving for

Very often you have to "make something the subject of a formula" or "solve for something". This refers to finding the value of an unknown quantity if you have been given other quantities and a formula that shows the relationship between them.

Worked example 1

If John has 5 apples, and he gives some to Joanna, and he has two apples left, how many did he give to Joanna? Well, the formula would be something like this:

$$5 - x = 2$$

To solve for x, we simply have to swap the x and the 2. What we're actually doing is adding "x" to both sides:

$$5 - x + x = 2 + x$$

this becomes:

$$5 = 2 + x$$

then we subtract 2 from both sides to move the 2 over:

$$5 - 2 = 2 - 2 + x$$
$$5 - 2 = x$$
$$3 = x$$ ... so John gave Joanna three apples.

The same procedures apply no matter how complex the formula looks. Just either add, subtract, square, square root, multiply, or divide throughout to move the items around.

Worked example 2

Let's take an actual example from Electricity: $V = IR$. This means, the voltage in a circuit is equal to the current in the circuit times the resistance.

Suppose we know the voltage is 12 V, and the resistance is 3 Ω. What is the current?

$V = IR$

$12 = 3 \times I$

divide throughout by 3 so as to isolate the I

$\frac{12}{3} = \left(\frac{3}{3}\right) I$

remember that anything divided by itself is 1, so:

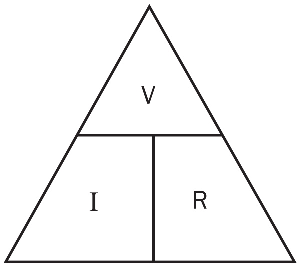
$\frac{12}{3} = (1) \times I$ ... and $\frac{12}{3} = 4$ ... so

$4 = I$ or

$I = 4$ A ... The circuit has a current of 4 amperes.

It is possible to remember how to solve for these equations using a triangle mnemonic as follows:

If you're solving for V, cover V with your hand. Then, I next to R means I times R, or IR. So, $V = IR$. If you're solving for R, cover R with your hand. V is over I. So $R = \frac{V}{I}$. While this is an easier way to do it, remember that many formulas do not consist of only three parts, so it is better to know how to make something the subject of a formula, or solve for something.



Worked example 3

Here's a more tricky example. Given

$K_c = 4{,}5$

$[SO_3] = 1{,}5\ \text{mol/dm}^3$

$[SO_2] = 0{,}5\ \text{mol/dm}^3$

$[O_2] \ = \frac{(x - 48)}{64}\ \text{mol/dm}^3$

solve for x.

$$\text{Kc} \ = \frac{[SO_3]^2}{[SO_2]^2[O_2]} \qquad \therefore 4{,}5 = \frac{(1{,}5)^2}{\frac{(0{,}5)^2\ (x - 48)}{64}}$$

$$\therefore x = 176\ \text{g}$$

How did we get that answer?

Step by step

Let's see how it works.

First, solve for the exponents (powers):

$$4{,}5 = \frac{2{,}25}{(0{,}25)\ \frac{(x - 48)}{64}}$$

Now, we can see that 2,25 and 0,25 are similar numbers (multiples of five), so let's divide them as shown.

$$4{,}5 = (2{,}25 / 0{,}25) \times (\ (x - 48) / 64\ )$$

That leaves us with

$$4{,}5 = 9 \times (\ (x - 48) / 64\ )$$

But if we're dividing a divisor, that second divisor can come up to the top row. Here's a simple example:

$$\begin{aligned} 1 \div (2 \div 3) \ &= \frac{1}{\frac{2}{3}} \\ &= \frac{1 \times 3}{2} \\ &= \frac{3}{2} = 1{,}5 \end{aligned}$$

If you doubt this, try it quickly on your calculator: 1 ÷ (2 ÷ 3) ... this means, one, divided by two-thirds. Well, two-thirds is 0,6667, which is almost one. So how many "two-thirds" do you need to really make up one? The answer is <u>one and a half</u> "two-thirds"... i.e. 0,6667 + (0,6667 ÷ 2) = 1. Hence the answer is <u>1,5</u>.

So, back to the original problem, we can bring the 64 up to the top line and multiply it by nine:

$$\begin{aligned} 4{,}5 \ &= \ 9 \times (\ (x - 48) / 64\ ) \\ 4{,}5 \ &= \ \frac{9 \times 64}{x - 48} \\ 4{,}5 \ &= \ \frac{576}{x - 48} \end{aligned}$$

Now we can inverse the entire equation to get the x onto the top:

$$\frac{1}{4{,}5} \ = \ x - \frac{48}{576}$$

Now we multiply both sides by 576 to remove the 576 from the bottom row

$$\frac{576}{4{,}5} = \frac{(x - 48)\,\cancel{576}}{\cancel{576}}$$

and we cancel the 576's on the right hand side as shown above.
Now, if 576 ÷ 4,5 = 128, then

$$128 = x - 48$$

Now we add 48 to both sides to move the 48 across

$$128 + 48 = x - 48 + 48 \qquad \text{... hence, } 128 + 48 = x = 176.$$

3. Statistics

Many experiments in science use statistics. You should therefore at least know the following:

Dependent variable: The thing that comes out of an experiment, the effect; the results.

Independent variable(s): The things that act as input to the experiment, the *potential* causes. Also called the *controlled variable*.

Control variable: A variable that is held constant in order to discover the relationship between two other variables. "Control variable" must not be confused with "controlled variable".

It is important to understand that in science, correlation does not mean causation. That is, if two variables seem to relate to each other (they seem to co-relate), it doesn't mean that one causes the other. A variable only causes another variable if one of the variables is a function $f(x)$ of the other. We will see more about this when we look at graphs, below.

Mean: The average. In the series 1, 3, 5, 7, 9, the mean is 1 + 3 + 5 + 7 + 9 divided by 5, since there are 5 bits of data. The mean in this case is 5.

Median: The datum (single bit of data) in the precise middle of a range of data. In the series 1, 3, 5, 7, 9, the median value is 5.

Mode: The most common piece of data. In the series 1, 1, 2, 2, 3, 3, 3, 4, 5, the mode is 3.

Often in scientific formulas it is said that things are proportional to each other. However, we cannot calculate the value of a force or energy output or mass etc., if we only know what things are in proportion (i.e. which things correlate).

Let's take momentum for example. Momentum (how forcefully something moves, more or less), is proportional to velocity (speed in a direction). So the faster something's moving, the more momentum it has. But p (momentum) can't be calculated if we only know velocity; we need to know mass as well. Why? Because momentum is also proportional to mass; the more massive something is, the more momentum it has. Thus, to get rid of the proportionality sign ($\propto$), we have to come up with a formula.

Many experiments in science serve to find out what the relationship is between two variables, i.e. if they're merely correlated — proportional — or if they're causally related. In the case of momentum, it's easy, because there are no further variables: p = mv. However, in the case of gravity or electric or magnetic field strengths, it's not that easy. In those cases, we have to introduce something called a "constant". A constant is a fixed value that is always multiplied into an equation. Constants are often written k. However, some specific constants, such as in the Law of Gravity, have their own symbol, in this case, G. These constants are given in the tables later in this book.

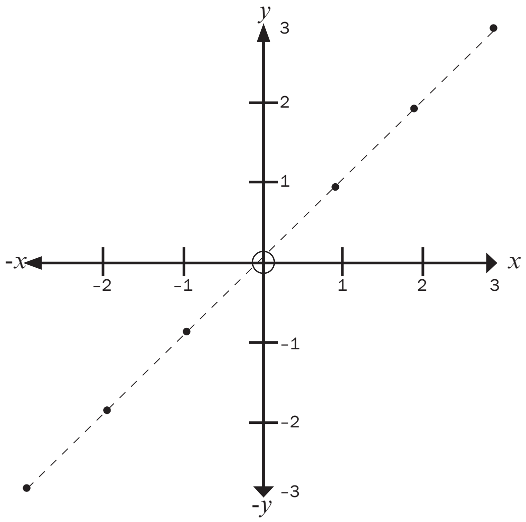
4. Graphs

A lot of work in science involves interpreting graphs. You get graphs of motion, graphs of rates of chemical reactions, graphs of distance-relative strengths of force fields, and so on. Before you can understand these graphs, it's probably best to start from scratch with Cartesian Coordinates.

"Coordinates" are numbers that refer to the distance of a point along a line, or on a surface, or in space, from a central point called the "origin". Graphs that you will use have only two dimensions (directions). The positions of points on these graphs are described using two coordinates: how far across (left-to-right) the point is, called the x-coordinate, and how far up-or-down on the page the point is, called the y-coordinate.

e.g. Worked example 4

Consider the following graph. It shows six points in a straight line.



The coordinates shown can be described using what are called "ordered pairs". For example, the furthest point in this graph is 3 units across on the "x-axis" or horizontal line. Likewise, it is also 3 units up on the y-axis, or vertical (up and down) line. So, its coordinates are (3;3). The point just below the midpoint or "origin", is one unit down of the x-axis, and one unit left of the y-axis. So its coordinates are (-1;-1). Note that anything to the left or below of the origin (the circle in the middle), takes a minus sign. In most cases in science, you'll only have graphs showing positive axes (plural of axis, pronounced aks-eez), since most graphs are of time.

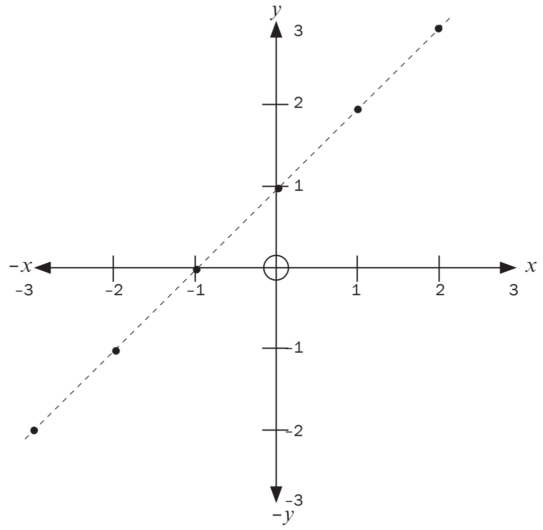
This series of dots look like they're related to each other, because they're falling on a straight line. If you see a result like this in an experimental situation, it usually means that you can predict what the next dot will be, namely, (4;4). This kind of prediction is called "extrapolation". If you carry out the experiment, and find that the result is (4;4), and then (5;5), you've established that there is a strong relation or correlation. You can therefore start thinking about a formula to describe your findings. For example, this might be a graph showing a measurement of voltage (x) against a measurement of resistance (y).

Now, another way of saying that x relates to y, or x is proportional to y, is to say that y is a function of x. This is written $y = f(x)$. So, in the example given above, voltage is a function of resistance. But how is y related to x in this graph? Well, it seems to be in a 1 to 1 ratio: $y = x$. So the formula for this graph is $y = x$. In this case, we're only dealing with two factors; x and y. In other graphs you'll find that sometimes more factors are involved, such as acceleration graphs, which have units of m/s^2. Don't worry about that; you treat them the same way (for example, m/s^2 vs. time).

e.g. Worked example 5

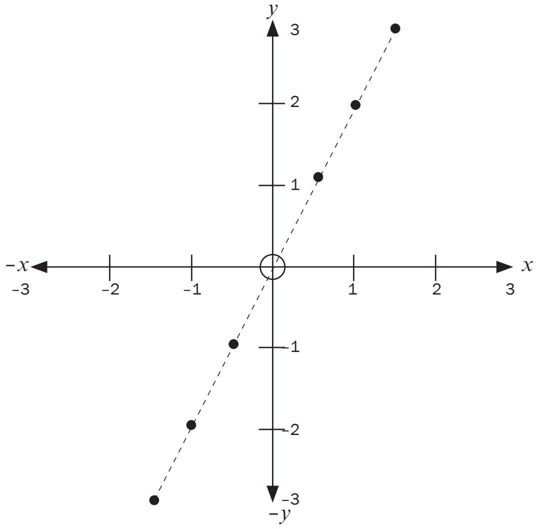
Now, let's take a slightly more complex case, illustrated next to this paragraph.

In this graph, we see that wherever x is equal to something, y is one more. So, trace your finger from the bottom left dot upwards. It meets the x-axis at the point -3. Do the same for the same point towards the y-axis. You'll see it meets the y-axis at -2. You'll see the next coordinates are (–2;–1), then (–1;0), then (0;1), (1;2), and finally (2;3). From this we can see that whatever x is, y is one more. So, $y = x + 1$ is the formula for this line.



Worked example 6

Let's take another case. In this next case, we see the following values: where x has a certain value, y has double that value. Let's tabulate it.



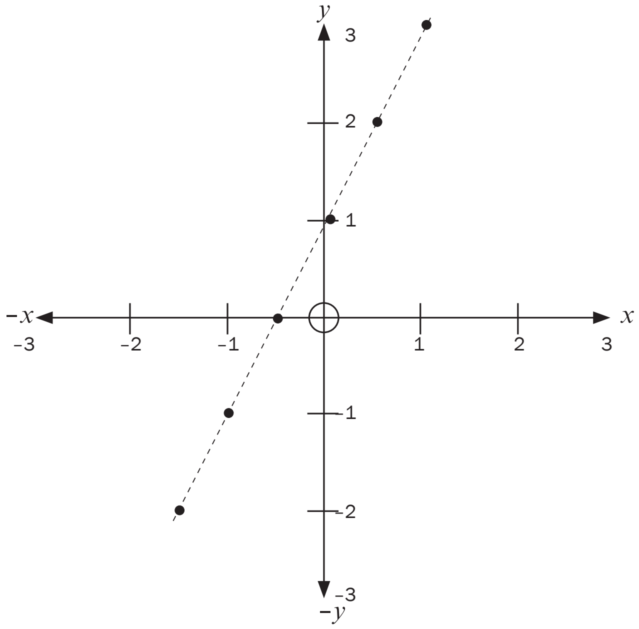
x	y
1,5	3
1	2
0,5	1
0	0
−0,5	−1
1	−2
−1,5	−3

So, when x is 1,5, y is 3, when x is 1, y is 2. Thus, the formula for this line is: $y = 2x$. This value next to x is called the "gradient" or "slope" of the line. The larger the value next to x is, i.e. the larger the gradient, the steeper the slope. The gradient is usually abbreviated as "m" when it is unknown.

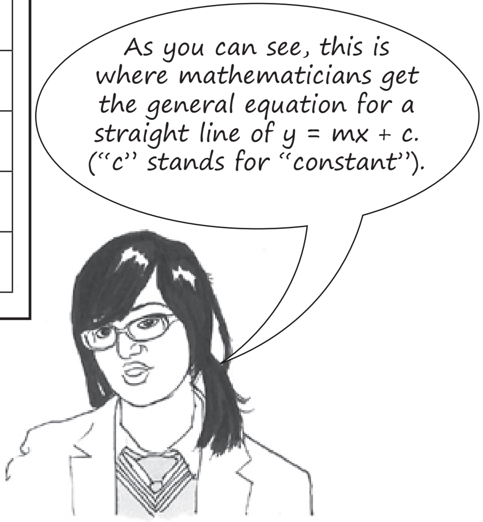
Now, how this applies to science is simple: if we are looking, for example, at a case of a graph of a chemical reaction, we will usually have the x-axis as time. And the y-axis will usually be the quantity (amount) of substances produced. So, if we have a graph of a chemical reaction with a large gradient, it means that the reaction is fast; a lot of substance (y) i s produced in a short time (x). If, for example, we heated the reaction, and saw that the gradient increased even more, that would show that the chemical reaction was sped up by heat, or, that reaction rate is proportional to heat. Likewise, if the gradient sloped downwards, it would show that the reaction slowed down over time, because y, the amount of substance produced, was decreasing, as x (time) increased, e.g. because the reactants were being used up.

e.g. Worked example 7

Let's do one more case. In this case, we can see that y is a function of x, since it's a straight line graph. However, it's not that easy to see the relationship between x and y. We can see that the slope is the same as the previous graph, so it must be something like $y = 2x$. However, it doesn't quite make sense, since 2(–1,5) is not –2. We see that where x is zero (at the origin), y is at 1. But the slope is the same, so it must be $y = 2(0) + 1$. So the formula is: $y = 2x + 1$.



x	y	2x + 1
-1,5	-2	2(-1,5)+1 = -3+1 = -2
-1	-1	2(-1)+1 = -2+1 = -1
-0,5	0	2(-0,5) +1 = -1+1 = 0
0	1	2(0)+1 = 0+1 = 1
0,5	2	2(0,5)+1 = 1+1 = 2
1	3	2(1)+1 = 2+1 = 3



Resource sheets

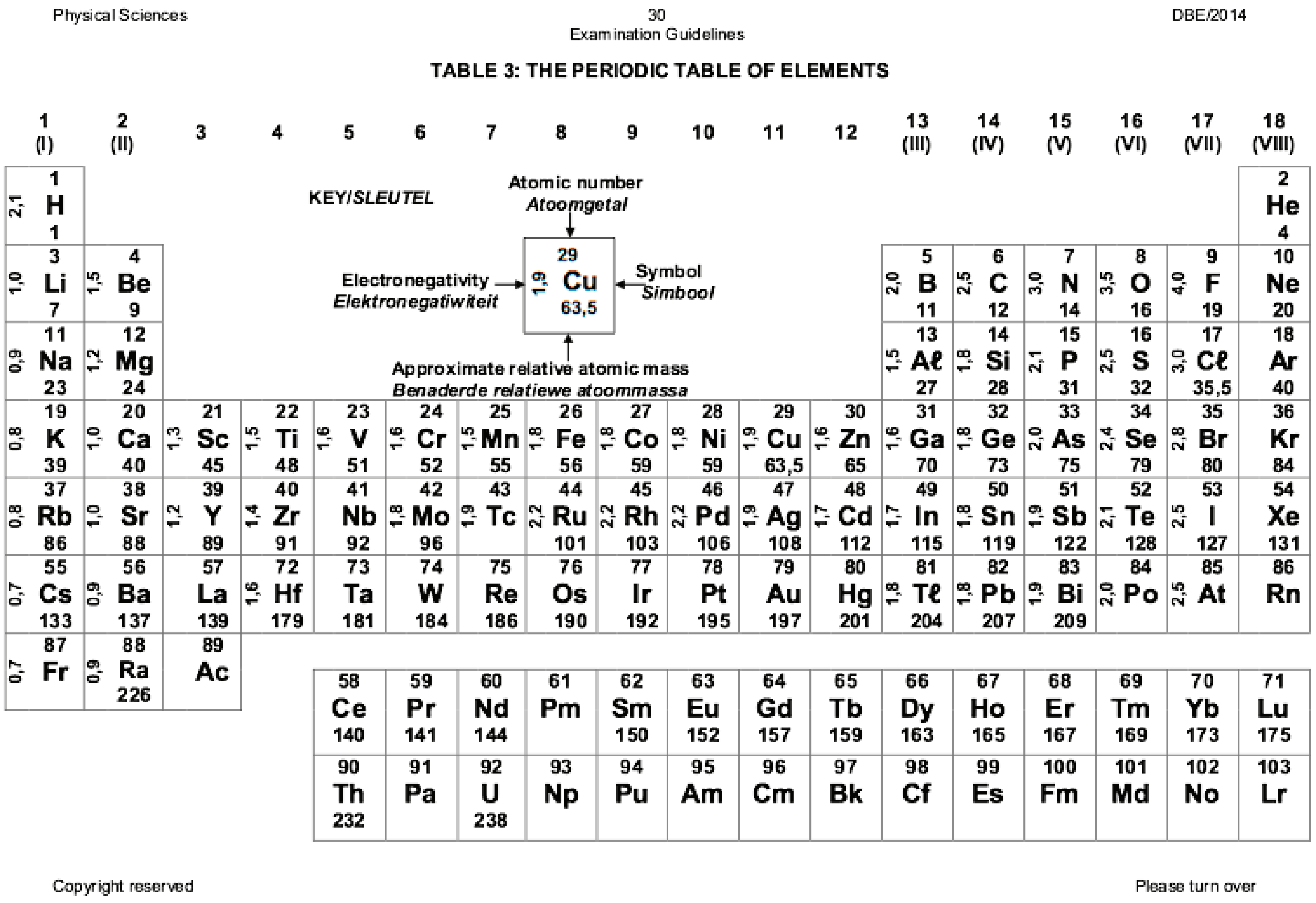
The following information sheets will be supplied to you in the exam. You do not need to memorise them.

SI Units: Multipliers

Prefix	Symbol	Value	Value written in full
tera	T	10^{12}	1 000 000 000 000
giga	G	10^{9}	1 000 000 000
mega	M	10^{6}	1 000 000
kilo	k	10^{3}	1 000
hecto	h	10^{2}	1 00
deka	da	10^{1}	1
deci	d	10^{-1}	0,1
centi	c	10^{-2}	0,01
milli	m	10^{-3}	0,00 1
micro	µ	10^{-6}	0,00 000 1
nano	n	10^{-9}	0,00 000 000 1
pico	p	10^{-12}	0,00 000 000 000 1
femto	f	10^{-15}	0,00 000 000 000 000 1

Constants

Name	SI Unit Symbol	Approximate Value	Easier to Understand
STP (Standard Temperature and Pressure), (in Physics).	not applicable, two conditions	1 ATM (101,3 kPa), 25°C (298 Kelvin (K))	You generally put two ATM (bar) pressure in car tyres, i.e. the pressure in a car tyre is twice atmospheric pressure
Standard Conditions (Chemistry)	not applicable, three conditions	STP plus 1 mol/dm^3	As above
Gas constant	R	8,3 J / mol·K	The R in PV = nRT
Molar gas volume at STP	V_0	22,4 dm^3 / mol	22,4 Litres of gas is made by a mole of a substance
Avogadro's constant	N_A	$6{,}022045 \times 10^{23}$ units/mol	6 022 000 000 000 000 000 000 00 particles is one mole



Physical Sciences | 30 Examination Guidelines | DBE/2014

TABLE 3: THE PERIODIC TABLE OF ELEMENTS

KEY/*SLEUTEL*

Atomic number / *Atoomgetal*: 29

Electronegativity / *Elektronegatiwiteit*: 1,9

Symbol / *Simbool*: Cu

Approximate relative atomic mass / *Benaderde relatiewe atoommassa*: 63,5

1 (I)	2 (II)	3	4	5	6	7	8	9	10	11	12	13 (III)	14 (IV)	15 (V)	16 (VI)	17 (VII)	18 (VIII)
1 2,1 **H** 1																	2 **He** 4
3 1,0 **Li** 7	4 1,5 **Be** 9											5 2,0 **B** 11	6 2,5 **C** 12	7 3,0 **N** 14	8 3,5 **O** 16	9 4,0 **F** 19	10 **Ne** 20
11 0,9 **Na** 23	12 1,2 **Mg** 24											13 1,5 **Aℓ** 27	14 1,8 **Si** 28	15 2,1 **P** 31	16 2,5 **S** 32	17 3,0 **Cℓ** 35,5	18 **Ar** 40
19 0,8 **K** 39	20 1,0 **Ca** 40	21 1,3 **Sc** 45	22 1,5 **Ti** 48	23 1,6 **V** 51	24 1,6 **Cr** 52	25 1,5 **Mn** 55	26 1,8 **Fe** 56	27 1,8 **Co** 59	28 1,8 **Ni** 59	29 1,9 **Cu** 63,5	30 1,6 **Zn** 65	31 1,6 **Ga** 70	32 1,8 **Ge** 73	33 2,0 **As** 75	34 2,4 **Se** 79	35 2,8 **Br** 80	36 **Kr** 84
37 0,8 **Rb** 86	38 1,0 **Sr** 88	39 1,2 **Y** 89	40 1,4 **Zr** 91	41 **Nb** 92	42 1,8 **Mo** 96	43 1,9 **Tc**	44 2,2 **Ru** 101	45 2,2 **Rh** 103	46 2,2 **Pd** 106	47 1,9 **Ag** 108	48 1,7 **Cd** 112	49 1,7 **In** 115	50 1,8 **Sn** 119	51 1,9 **Sb** 122	52 2,1 **Te** 128	53 2,5 **I** 127	54 **Xe** 131
55 0,7 **Cs** 133	56 0,9 **Ba** 137	57 **La** 139	72 1,6 **Hf** 179	73 **Ta** 181	74 **W** 184	75 **Re** 186	76 **Os** 190	77 **Ir** 192	78 **Pt** 195	79 **Au** 197	80 **Hg** 201	81 1,8 **Tℓ** 204	82 1,8 **Pb** 207	83 1,9 **Bi** 209	84 2,0 **Po**	85 2,5 **At**	86 **Rn**
87 0,7 **Fr**	88 0,9 **Ra** 226	89 **Ac**															
				58 **Ce** 140	59 **Pr** 141	60 **Nd** 144	61 **Pm**	62 **Sm** 150	63 **Eu** 152	64 **Gd** 157	65 **Tb** 159	66 **Dy** 163	67 **Ho** 165	68 **Er** 167	69 **Tm** 169	70 **Yb** 173	71 **Lu** 175
				90 **Th** 232	91 **Pa**	92 **U** 238	93 **Np**	94 **Pu**	95 **Am**	96 **Cm**	97 **Bk**	98 **Cf**	99 **Es**	100 **Fm**	101 **Md**	102 **No**	103 **Lr**

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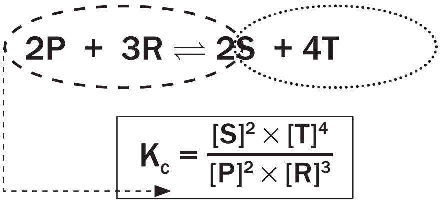
Formulas

Moles, Gas Laws, Chemical Equilibria:

R = gas constant
n = number of moles
m = mass
T = temperature
V = volume
c = concentration, also [ ]

$n = \frac{m}{M}$ $c = \frac{n}{V}$ $c = \frac{m}{MV}$

$PV = nRT$ $\frac{p_1V_1}{T_1} = \frac{p_2V_2}{T_2}$



$$2P + 3R \rightleftharpoons 2S + 4T$$

$$\boxed{K_c = \frac{[S]^2 \times [T]^4}{[P]^2 \times [R]^3}}$$

Where [S] is the concentration of S in mol/dm³

Notes:

- In most cases in chemistry, subscripts refer to how many atoms there are; e.g. H_2O = two atoms of H & 1 atom of O.

Standard reduction potentials

Notes:

- E^θ means the same as E^0.
- There are two versions of this table; they are identical except one is upside-down. Just memorise that Fluorine (F) has the greatest oxidising ability.
- A strong reducing agent will displace a weaker reducing agent from its salt.
- Always start with the oxidation half reaction.
- A redox reaction will take place when a reducing agent reacts with an oxidising agent.
- Balance the electron charge of each half-reaction by multiplying each with a suitable coefficient.
- Add the two half-reactions together, eliminating electrons from both sides.
- Eliminate common ions or molecules from both sides of the equation e.g. H^+ and H_2O.
- You can then combine the E^0 voltages to get the total voltage of a cell. Use the values exactly as they are; do not round off.

$E^0_{cell} = E^0_{cathode} - E^0_{anode}$

OR

$E^0_{cell} = E^0_{oxidising\ agent} - E^0_{reducing\ agent}$

- A positive answer means that the reaction will proceed spontaneously from left to right. A negative value means that it is not spontaneous.

Increasing oxidising ability ↑

Half-reactions			E^0 (V)
$F_2(g) + 2e^-$	⇌	$2F^-$	+ 2,87
$Co^{3+} + e^-$	⇌	Co^{2+}	+ 1,81
$H_2O_2 + 2H^+ + 2e^-$	⇌	$2H_2O$	+1,77
$MnO_4^- + 8H^+ + 5e^-$	⇌	$Mn^{2+} + 4H_2O$	+ 1,51
$C\ell_2(g) + 2e^-$	⇌	$2C\ell^-$	+ 1,36
$Cr_2O_7^{2-} + 14H^+ + 6e^-$	⇌	$2Cr^{3+} + 7H_2O$	+ 1,33
$O_2(g) + 4H^+ + 4e^-$	⇌	$2H_2O$	+ 1,23
$MnO_2 + 4H^+ + 2e^-$	⇌	$Mn^{2+} + 2H_2O$	+ 1,23
$Pt^{2+} + 2e^-$	⇌	Pt	+ 1,20
$Br_2(\ell) + 2e^-$	⇌	$2Br^-$	+ 1,07
$NO_3^- + 4H^+ + 3e^-$	⇌	$NO(g) + 2H_2O$	+ 0,96
$Hg^{2+} + 2e^-$	⇌	$Hg(\ell)$	+ 0,85
$Ag^+ + e^-$	⇌	Ag	+ 0,80
$NO_3^- + 2H^+ + e^-$	⇌	$NO_2(g) + H_2O$	+ 0,80
$Fe^{3+} + e^-$	⇌	Fe^{2+}	+ 0,77
$O_2(g) + 2H^+ + 2e^-$	⇌	H_2O_2	+ 0,68
$I_2 + 2e^-$	⇌	$2I^-$	+ 0,54
$Cu^+ + e^-$	⇌	Cu	+ 0,52
$SO_2 + 4H^+ + 4e^-$	⇌	$S + 2H_2O$	+ 0,45
$2H_2O + O_2 + 4e^-$	⇌	$4OH^-$	+ 0,40
$Cu^{2+} + 2e^-$	⇌	Cu	+ 0,34
$SO_4^{2-} + 4H^+ + 2e^-$	⇌	$SO_2(g) + 2H_2O$	+ 0,17
$Cu^{2+} + e^-$	⇌	Cu^+	+ 0,16
$Sn^{4+} + 2e^-$	⇌	Sn^{2+}	+ 0,15
$S + 2H^+ + 2e^-$	⇌	$H_2S(g)$	+ 0,14
$2H^+ + 2e^-$	⇌	**$H_2(g)$**	**0,00**
$Fe^{3+} + 3e^-$	⇌	Fe	– 0,06
$Pb^{2+} + 2e^-$	⇌	Pb	– 0,13
$Sn^{2+} + 2e^-$	⇌	Sn	– 0,14
$Ni^{2+} + 2e^-$	⇌	Ni	– 0,27
$Co^{2+} + 2e^-$	⇌	CO	– 0,28
$Cd^{2+} + 2e^-$	⇌	Cd	– 0,40
$Cr^{3+} + e^-$	⇌	Cr^{2+}	– 0,41
$Fe^{2+} + 2e^-$	⇌	Fe	– 0,44
$Cr^{3+} + 3e^-$	⇌	Cr	– 0,74
$Zn^{2+} + 2e^-$	⇌	Zn	– 0,76
$2H_2O + 2e^-$	⇌	$H_2(g) + 2OH^-$	– 0,83
$Cr^{2+} + 2e^-$	⇌	Cr	– 0,91
$Mn^{2+} + 2e^-$	⇌	Mn	– 1,18
$A\ell^{3+} + 3e^-$	⇌	$A\ell$	– 1,66
$Mg^{2+} + 2e^-$	⇌	Mg	– 2,36
$Na^+ + e^-$	⇌	Na	– 2,71
$Ca^{2+} + 2e^-$	⇌	Ca	– 2,87
$Sr^{2+} + 2e^-$	⇌	Sr	– 2,89
$Ba^{2+} + 2e^-$	⇌	Ba	– 2,90
$Cs^+ + e^-$	⇌	Cs	– 2,92
$K^+ + e^-$	⇌	K	– 2,93
$Li^+ + e^-$	⇌	Li	– 3,05

Increasing reducing ability ↓

Unit 1

Organic compounds and macromolecules

Organic chemistry is the chemistry of carbon compounds in living and non-living systems.

Organic molecules: molecules containing carbon atoms

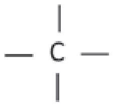
Note: Carbon dioxide (CO_2), carbon monoxide (CO), carbonates (CO_3^{2-}) and cyanides (CN^-) are exceptions because they are considered inorganic compounds. Organic compounds typically have a backbone of linked carbon atoms that other atoms attach to.

1.1 Organic compounds

1.1.1 Chemical bonding

The organic compounds that we study consist of Carbon, Hydrogen, Oxygen atoms and the Halogens (-Br, -Cℓ, -I), which are often represented collectively as –X).

NB

	Carbon is always surrounded by EXACTLY four bonds
— O —	Oxygen is always surrounded by EXACTLY two bonds
— H	Hydrogen is always attached to EXACTLY one bond
— X	Halogen is always attached to EXACTLY one bond

1.1.2 The homologous series

NB

DEFINITIONS

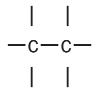
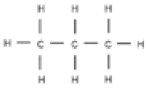
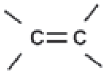
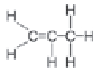
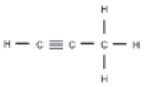
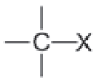
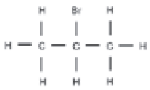
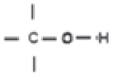
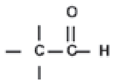
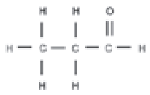
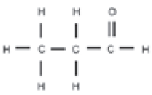
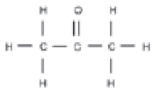
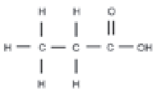
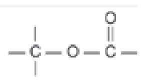
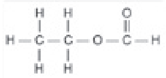
A **homologous series** is a series of compounds (molecules) that has the same general formula and the same functional group. Each member of a homologous series differs from the previous member by a – CH_2 group.

Saturated: compounds in which there are no multiple bonds between carbon atoms in their hydrocarbon chains

Unsaturated: compounds with one or more multiple bonds between carbon atoms in their hydrocarbon chains.

A **functional group** is a bond, an atom or a group of atoms that determine(s) the physical and chemical properties of a group of organic compounds.

Classification of organic molecules according to homologous series

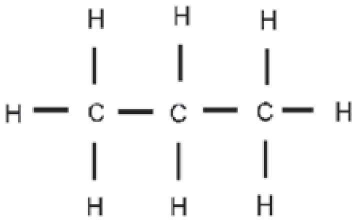
Homologous series		General formula	Functional Group	Suffix	Example name	Structural formula	Condensed structural formula	Molecular formula
Hydrocarbons	Alkanes	C_nH_{2n+2}		-ane	propane		$CH_3CH_2CH_3$	C_3H_8
	Alkenes	C_nH_{2n}		-ene	propene		$CH_2{=}CHCH_3$	C_3H_6
	Alkynes	C_nH_{2n-2}	$-C\equiv C-$	-yne	propyne		$CH\equiv CCH_3$	C_3H_4
Haloalkanes/ alkyl halides		$C_nH_{2n+}1X$ (X = F, $C\ell$, Br, I)		-ane	2-bromopropane		$CH_3CHBrCH_3$	C_3H_7Br
Alcohols		$C_nH_{2n+1}OH$		-ol	propan-2-ol		$CH_3CHOHCH_3$	C_3H_7OH
Aldehydes		$C_nH_{2n}O$ n =1, 2, ...		-al	propanal		CH_3CH_2CHO	C_3H_6O
Ketones		$C_nH_{2n}O$ n = 3, 4, ...		-one	propanone		CH_3COCH_3	C_3H_6O
Carboxylic acids		$C_nH_{2n}O_2$ n = 1, 2, ...		-oic acid	propanoic acid		CH_3CH_2COOH	$C_3H_6O_2$
Esters		$C_nH_{2n}O_2$ n = 2, 3, ...		-oate	ethyl methanoate		CH_3CH_2OOCH	$C_3H_6O_2$

NOTE:

Alkanes have the general formula C_nH_{2n+2}
In propane n = 3 and therefore the general formula is $C_3H_{2(3)+2} = C_3H_8$

In a **structural formula** all the bonds in the compound are shown. If any of these bonds are omitted, it is called a **condensed structural formula**.

E.g. **structural formula** for propane



possible **condensed structural formula** for propane

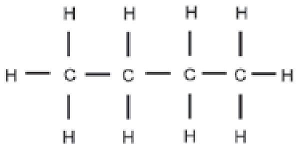
$CH_3 - CH_2 - CH_3$ or $CH_3CH_2CH_3$

1.1.3 Isomers

In isomers, the same atoms are used in different compounds, but they are assembled or connected in different ways. There are different kinds of isomers in organic chemistry. Structural isomers refer to the order in which different atoms in a compound are combined.

We will focus on **three types of structural isomers**, namely **chain isomers**, **positional isomers** and **functional isomers.**

Structural formula: structure 1

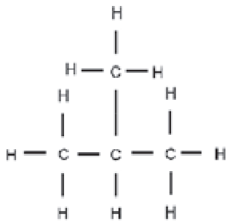


IUPAC name: butane

Molecular formula: C_4H_{10}

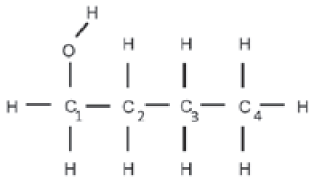
Chain isomers

Structural formula: structure 2



IUPAC name: 1-methylpropane
Molecular formula: C_4H_{10}

Structural formula

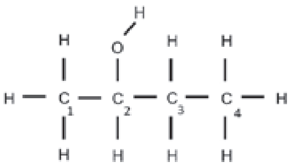


name: butan-1-ol

Molecular formula: $C_4H_{10}O$

Positional isomers

Structural formula



IUPAC name: butan-2-ol

Molecular formula: $C_4H_{10}O$

NB

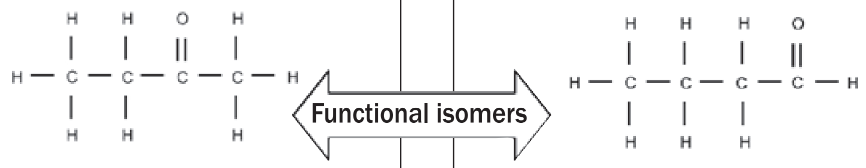
DEFINITIONS

1. **Structural isomers** are compounds with the same molecular formulae, but different structural formulae.
2. **Chain isomers:** Molecules with the same molecular formula and in the same homologous series but different types of chains e.g. **butane** and **methyl propane**.
3. **Positional isomers:** Molecules with the same molecular formula and in the same homologous series but the position of the functional group differs (e.g. **butan-1-ol** and **butan-2-ol**) or the *substituent* or *side chains* differ.
4. **Functional isomers:** Molecules with the same molecular formula but in different homologous series or have different functional groups e.g. **ketones** and **aldehydes**.

The numbering of the carbon chain:

In the naming of the organic compound, the longest carbon chain is numbered in such a way that the –OH functional group is attached to the carbon that is assigned the smallest number. Therefore, in this example, the first organic compound is called butan-1-ol.

Structural formula | **Structural formula**



Homologous series: ketone

IUPAC name: butanone

Molecular formula: C_4H_8O

Homologous series: ketone

IUPAC name: butanal

Molecular formula: C_4H_8O

In this example both organic compounds consist of the same number of carbon, hydrogen and oxygen atoms, but in the structure of the first compound, the (=) is attached to the middle of the carbon chain, which makes it a ketone. In the second example, the (=O) is attached to the beginning of the carbon chain, which makes it an aldehyde.

Activity 1

For each of the following isomers:

a) Write down the structural formula

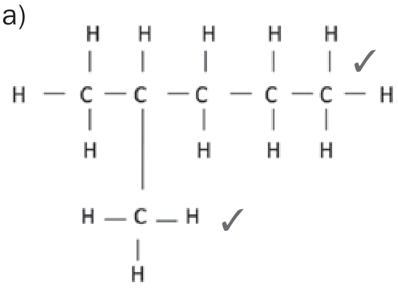
b) Identify the type of isomer

1. 2-methylpentane and 3-methylpentane.
2. 1-chlorobutane and 1-chloro-2-methylpropane
3. Propanoic acid and ethyl methanoate (13)

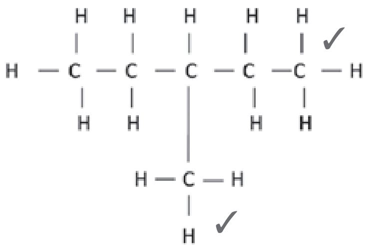
[13]

Solutions

1. a)



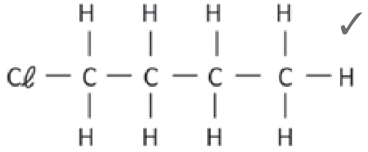
2-methylpentane



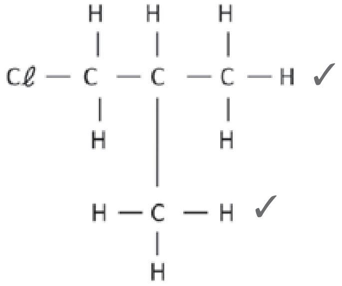
3-methylpentane

1. b) Positional isomers ✓

2. a)



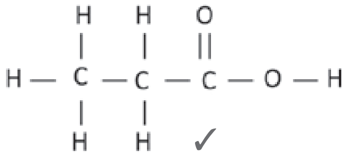
1-chlorobutane



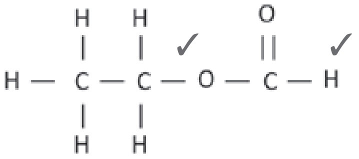
1-chloro-2-methylpropane

2. b) Chain isomers ✓

3. a)



propanoic acid



ethylmethanoate

3 b) Functional isomers ✓

[13]

Structural isomers have **different IUPAC names** and different physical properties.

1.1.4 Nomenclature (naming conventions or rules)

Each IUPAC name consists of three parts:

Prefix:	Root:	Suffix:
Position and names of substituents (side chains), listed alphabetically.	Number of C-atoms in the main C-chain.	Determined by the homologous series.

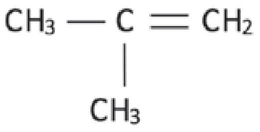
Organic compounds are named according to the IUPAC (**International Union of Pure and Applied Chemistry**) system.

Determine the root of the name from the number of C-atoms in the longest (main) C-chain.
1 = meth-
2 = eth-
3 = prop-
4 = but-
5 = pent-
6 = hex-
7 = hept-
8 = oct-
9 = non-
Note: old names: 1 = form- ;
2 = acet-

General steps for the IUPAC naming of all organic compounds

Step 1:

Identify the functional group in the compound and the homologous series it belongs to. This determines the suffix (ending). Example: Naming of 2-methylprop-1-ene



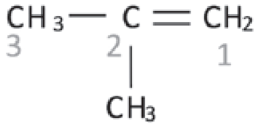
$$CH_3-\underset{\displaystyle CH_3}{\underset{|}{C}}=CH_2$$

In this case there are only carbons and hydrogens, with a double bond between the carbons. This indicates that this compound is an alkene and will end with the suffix -ene

Step 2:

- Find the longest chain of carbon atoms. It **must include the functional group**, and need not be in a straight line.
- **Number** the carbon atoms in this chain from the side **nearest to the functional group** e.g. a double or triple bond, a hydroxyl group, a carbonyl group or a carboxyl group.
- In the case of **alkanes or haloalkanes**, start numbering from the carbon **nearest to a substituent (side chain)** e.g. an alkyl group or halogen atom.

- Indicate the **position of the functional group** (except in the case of the alkanes). For alkenes and alkynes, give the smaller of the numbers of the C-atoms between which the double or triple bond exists. **Example: Naming of *2-methylprop-1-ene***

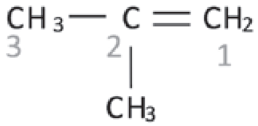


$$CH_3-\underset{\substack{|\\ CH_3}}{C}=CH_2$$

Example: The longest chain that includes the functional group, is numbered in the example above. Since the double bond is to the right of this example, we number the longest chain from right to left. The longest chain with the functional group contains three carbons and we know it must be a propene. Since the double bond is attached to the first carbon, it must be a *prop-1-ene*.

Step 3:

- Determine whether there are any substituents.
- Count the **number of C-atoms** in the substituent to determine the prefix and end it on **–yl.**
- Write the **number of the C-atom** on the main chain where the alkyl group is attached, in front of the alkyl name.
- Separate the number and the name with a **hyphen**, e.g. 2-methyl.
- If a substituent occurs more than once, use the appropriate prefix: twice – di; three times – tri; four times – tetra e.g. 3,4-dimethyl
- If there is more than one substituent, write their names and positions in **alphabetical order.**



$$CH_3-\underset{\substack{|\\ CH_3}}{C}=CH_2$$

Example: The methyl group is attached to the second carbon, hence the name *2-methyl prop-1-ene*

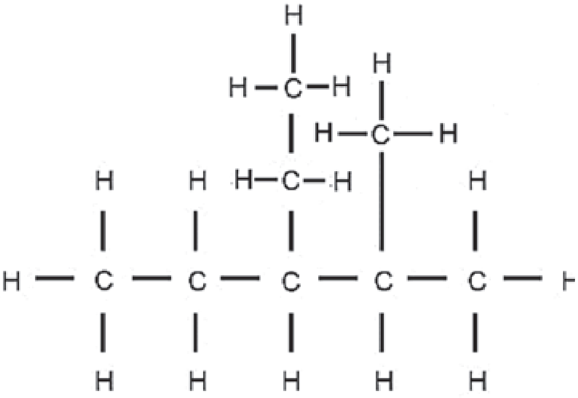
Step 4:

Naming the organic compound *with substituent(s) in front of the parent chain.* Example: the IUPAC name of the compound discussed above: *2-methylprop-1-ene*

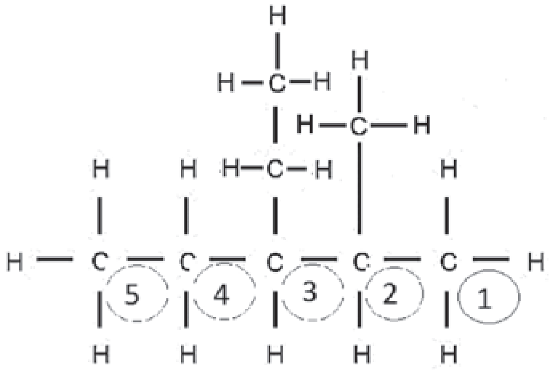
Worked example 1

Give the IUPAC name for the following organic compound:

Step 1: Identify the functional group, and the homologous series to which this compound belongs. *There are only C-atoms and H-atoms present, so this is a hydrocarbon. There are only single bonds between the C-atoms, therefore this is an alkane and the suffix will be –ane.*



Step 2: Find the longest C-chain and count the C-atoms in it, starting at the side closest to the functional group. *This is an alkane, so we start numbering from the side closest to a substituent*

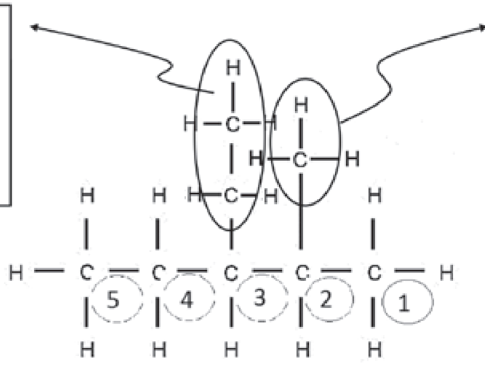


Step 3: Look at the substituents. Count the C-atoms in each substituent, determine the prefix and end it on –yl.

The alkyl groups must be listed alphabetically, so we write the ethyl before the methyl

There are 2 C-atoms in the substituent, so it is **ethyl**.

It is bonded to carbon number 3, so it is **3-ethyl**.



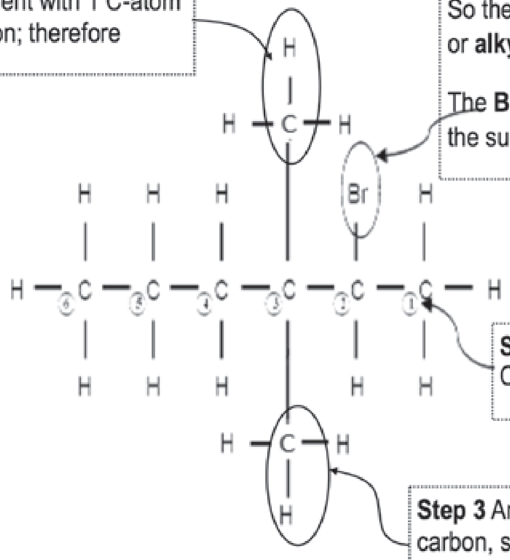
There is 1 C-atom in the substituent, therefore it is methyl. It is bonded to carbon number 2; therefore it is 2-methyl.

- **Numbers** and **letters** of the alphabet are separated by a **hyphen**. (e.g 2-methylpropane)
- Numbers are separated by the comma, and no space between the substituent(s) and the parent chain. (e.g. 2,2-dichloropentane)

Worked example 2

Give the IUPAC-name of the following haloalkane:

Step 3 Substituent with 1 C-atom on the 3rd carbon; therefore



Step 1 There is a **Br** atom as a substituent. So the compound belongs to the **haloalkane** or **alkyl halide** homologous series.

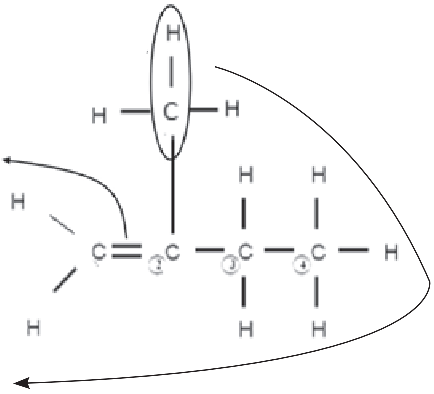
The **Br**-atom is on the 2nd carbon atom, so the substituent is labelled as **2-bromo.**

Step 2 The longest C-chain has 6 C-atoms. Count from the side closest to the **Br**-atom

Step 3 Another substituent with 1 C-atom on the 3rd carbon, so also **methyl**. The two identical substituents are labelled as **dimethyl** and their positions are separated by a comma: **3,3-dimethyl**

Worked example 3

Give the IUPAC-name of the following alkene:



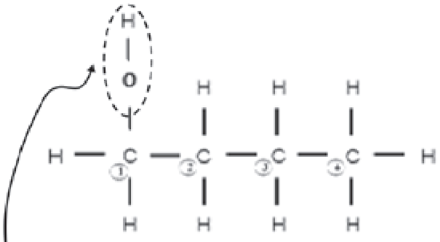
Step 1 The **double bond** between the two C-atoms indicates that this is an **alkene.**

Step 2 Count the longest C-chain from the side closest to the functional group i.e. the double bond. There are 4 C-atoms, therefore **but-**; the double bond starts at the 1st C atom, therefore **but-1-ene**

Step 3 Substituent with 1 C-atom on the 2nd carbon, therefore **2-methyl**

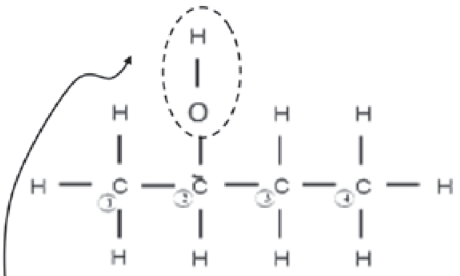
Solution: The compound is therefore **2-methylbut-1-ene.**

Worked example 4



Step 1 The **hydroxyl** group indicates that the compound is an **alcohol**.
Step 2: There are 4 C-atoms, therefore **but–** . Count from the left.
Step 3 The alcohol is bonded to the 1st C-atom, therefore **-1-ol.**

Solution: butan–1–ol

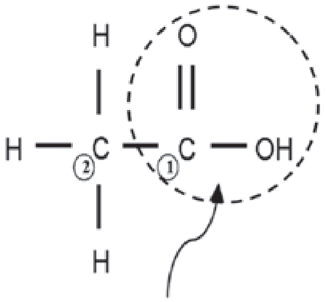


Step 1The **hydroxyl** group indicates that the compound is an **alcohol**.
Step 2 There are 4 C-atoms, therefore **but–** . Count from the left.
Step 3 the alcohol is bonded to the 2nd C-atom, therefore **-2-ol.**

Solution:: butan–2–ol

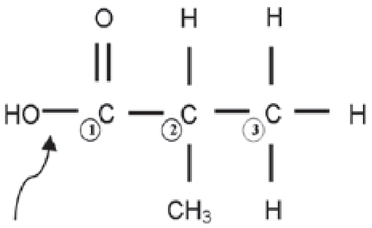
e.g. Worked example 5

Give the IUPAC name for the following carboxylic acids:



Step 1 The **carboxyl** group (-COOH) indicates that the compound is a **carboxylic acid (-oic acid)**.
Step 2 There are 2 C-atoms, therefore **eth–** . Count from the right.
Step 3 The C-atom in the carboxyl group is always counted as the 1st carbon atom, and the number is ***never*** included in the name.

Solution: **Ethanoic acid**

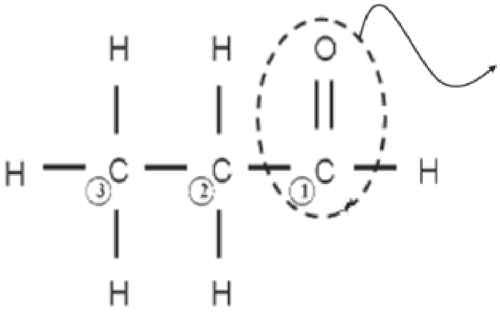


Step 1 The **carboxyl** group (-COOH) indicates that the compound is a **carboxylic acid (-oic acid)**.
Step 2 There are 3 C-atoms, therefore **prop–** . Count from the left.
Step 3 The C-atom in the carboxyl group is always counted as the 1st carbon atom, and the number is ***never*** included in the name.
There is a **methyl** group on the 2nd C-atom, he substituent is written as 2-methyl .

Solution: **2–methylpropanoic acid**

e.g. Worked example 6

Give the IUPAC name for the following aldehyde:

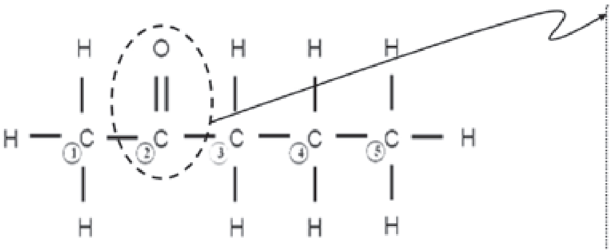


Step 1 The **carbonyl** group on an *end* C-atom indicates that the compound is an **aldehyde (-al)**.
Step 2 There are 3 C-atoms, therefore **prop–** Count from the right.
Step 3 The C-atom in the carbonyl group is always counted as the 1st carbon, and the number is not included in the name.

Solution: propanal

e.g. Worked example 7

Give the IUPAC name for the following ketone

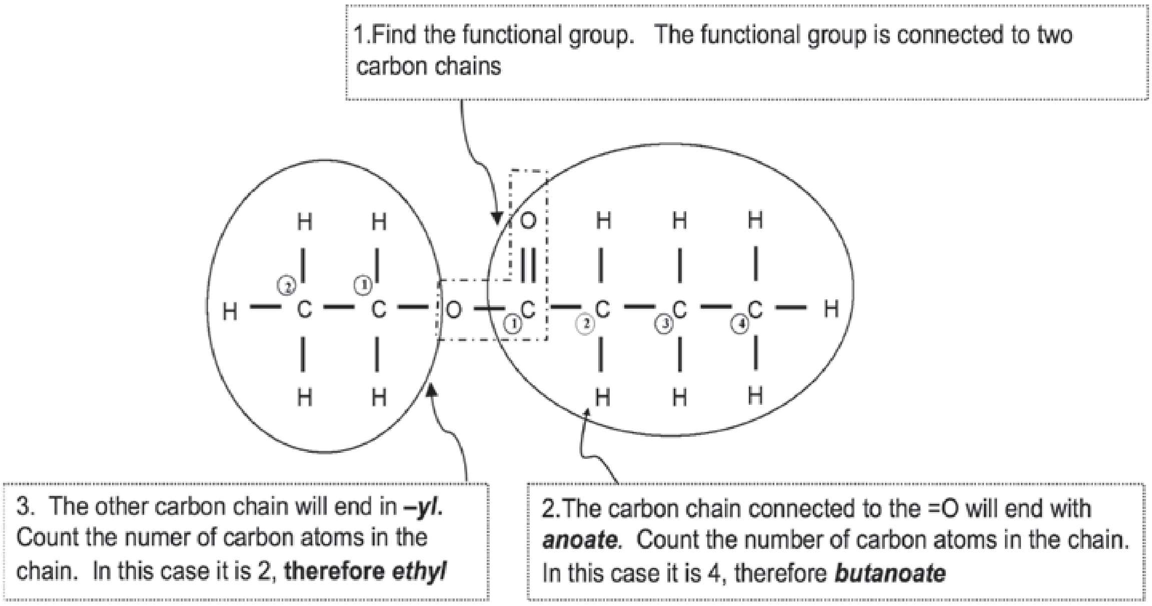


Step 1 The **carbonyl** group on a *middle* C-atom indicates that the compound is a **ketone (-one)**.
Step 2 There are 5 C-atoms, therefore **pent–** .
Step 3 Count from the side closest to the carbonyl group (in this case, from the left) and indicate the number of the C-atom of the carbonyl group (in this case the 2^{nd}), in the name.

Solution: pentan–2–one

e.g. Worked example 8

Give the IUPAC name for the following ester:



1.Find the functional group. The functional group is connected to two carbon chains

2.The carbon chain connected to the =O will end with ***anoate.*** Count the number of carbon atoms in the chain. In this case it is 4, therefore ***butanoate***

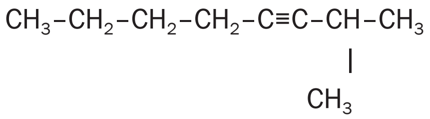
3. The other carbon chain will end in ***–yl.*** Count the numer of carbon atoms in the chain. In this case it is 2, **therefore *ethyl***

4. Finally. The chain ending with **–yl** will form the first part of the name, and the chain ending in **-anoate**, the last part. This ester is named **ethylbutanoate.**

Activity 2

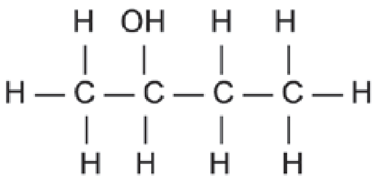
Write down the IUPAC names for the following organic molecules.

1.



$CH_3-CH_2-CH_2-CH_2-C\equiv C-\underset{CH_3}{\underset{|}{CH}}-CH_3$ (1)

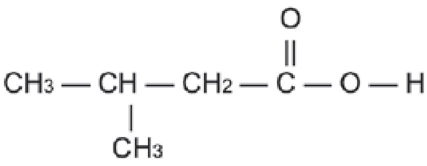
2.



(1)

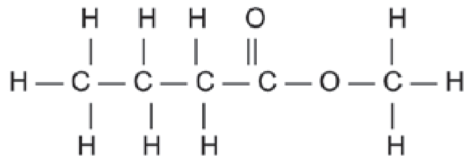
3. $C_3H_7COC_2H_5$ (1)

4.



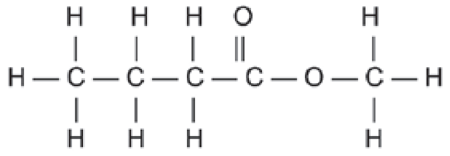
$CH_3-\underset{CH_3}{\underset{|}{CH}}-CH_2-\overset{O}{\overset{\|}{C}}-O-H$ (1)

5.



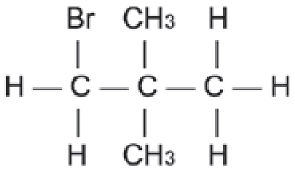
(1)

6.



(1)

7.



(1)

[7]

Solutions

1. 2-methyloct-3-yne ✓ (1)
2. butan-2-ol ✓ (1)
3. butanal ✓ (1)
4. hexan-3-one ✓ (1)
5. 3-methyl-butanoic acid ✓ (1)
6. methyl butanoate ✓ (1)
7. 1-bromo-2,2-dimethyl-propane ✓ (1)

[7]

IMPORTANT TO REMEMBER:

- When naming haloalkanes, the halogen atoms do not get preference over alkyl groups – numbering should start from the side nearest to the first substituent, either the alkyl group or the halogen. In haloalkanes, where e.g. a Br and a Cℓ have the same number when numbered from different sides of the chain, Br gets alphabetical preference.
- When writing IUPAC names, substituents appear as prefixes written alphabetically (bromo, chloro, ethyl, methyl), but the prefixes di- and tri- should not be used to determine the alphabetical order.
- In molecules where the functional group is ALWAYS on the first carbon (such as in the case of carboxylic acids, aldehydes there is NO number added to indicate the position of the fuctional group. (e.g. Ethanoic acid or pentanal.)

Activity 3

1. Which ONE of the following formulae represents an alkane?

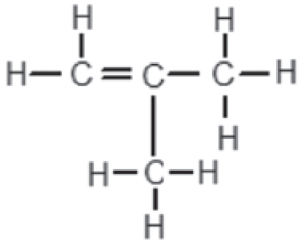
A C_2H_2

B C_3H_4

C C_3H_6

D C_3H_8 (2)

2. An organic compound has the structural formula shown below:



The correct systematic (IUPAC) name for the compound is ...

A but-1-ene.

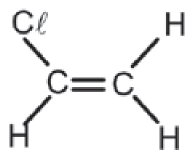
B but-2-ene.

C methylpropene.

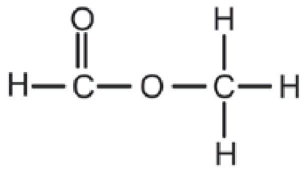
D methylpropane. (2)

3. Which ONE of the following compounds can exist as an isomer?

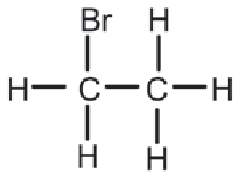
A



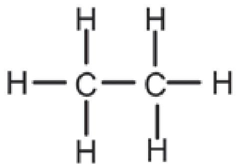
A



C



D



(2)

4. An example of an unsaturated hydrocarbon is:

A $C_2HC\ell_3$

B C_3H_6

C C_2H_6

D C_2H_5OH (2)

[8]

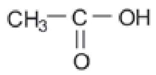
Solutions

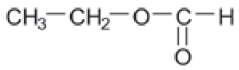
1. D ✓✓ (2)
2. C ✓✓ (2)
3. B ✓✓ (2)
4. B ✓✓ (2)
[8]

Activity 4

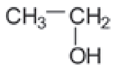
Consider the following list of organic compounds:

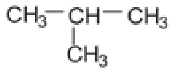
A: $CH_3-CH_2-CH_2-CH_3$

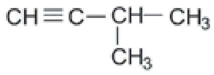
B: 
$CH_3-\underset{\underset{O}{\|}}{C}-OH$

C: 
$CH_3-CH_2-O-\underset{\underset{O}{\|}}{C}-H$

D: $CH_3-CH=CH-CH_3$

E: 
$CH_3-\underset{\underset{OH}{|}}{CH_2}$

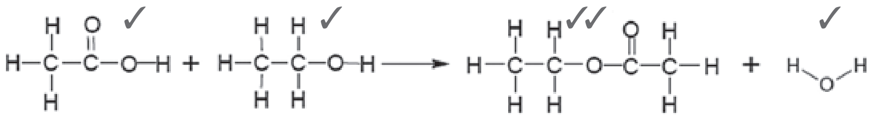
F: 
$CH_3-\underset{\underset{CH_3}{|}}{CH}-CH_3$

G: 
$CH\equiv C-\underset{\underset{CH_3}{|}}{CH}-CH_3$

1. Using **structural formulae**, write an equation for the preparation of an ester. Choose the reactants from the above list. (5)
2. Write the letters representing TWO compounds in this list that are isomers. (2)
   2.1 C
   2.2 D (2)
3. Write down the letter that represents the compound that is formed when ethanol is oxided. (1)
4. Give one use of esters. (1)

[11]

Solutions

1\. 

2. A ✓ & F ✓ (5)
   2.1 ethylmethanoate ✓ (2)
   2.2 but-2-ene ✓ (2)
3. B ✓ (1)
4. Manufacturing of perfumes/flavourants ✓ (1)

[11]

1.2 Physical properties and structure

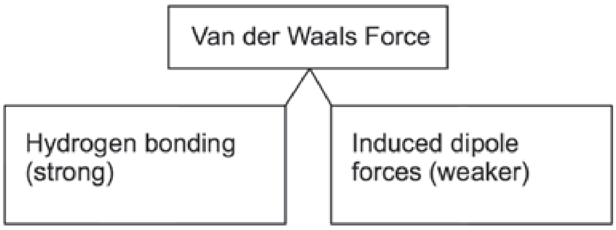
The structure of an organic compound – that includes the order in which atoms are connected in the compound, as well as the forces that is present between different molecules – has an influence on the physical properties of the compound. These physical properties include boiling points, melting points and the vapour pressure above a liquid organic compound. In the following section the influence of the structure of molecules on its physical properties will be discussed.

1.2.1 Intermolecular forces in organic compounds

Key for this section:

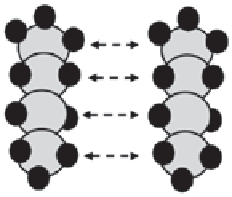
◍ Carbon ○ Oxygen ● Hydrogen

Intermolecular forces that act between DIFFERENT molecules of a compound are called Van der Waals forces. In the organic chemistry that we study, there are primarily two kinds of forces, namely Hydrogen bonds and Dipole-dipole forces.



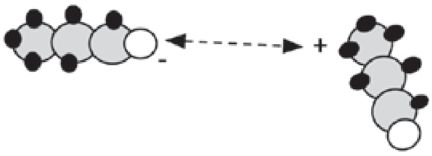
Induced dipole force: When two molecules come very close to each other, the electrons move and the distribution of electrons in the molecules temporarily shifts so that there is a slightly positive side and a slightly negative side on each molecule. The two molecules attract each other with a weak force.

NOTE:
The sketches that represent the forces between atoms relative to the size of the atoms are NOT drawn to scale. In reality, molecules are very close to each other and the intermolecular forces act over small distances.



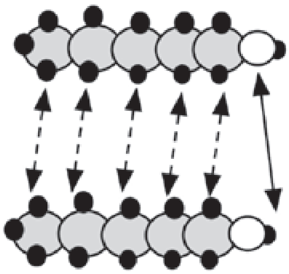
An example of induced-dipole forces between two molecules of butane

Dipole-dipole forces: When a molecule has a slightly positive side and another molecule has a slightly negative side, the two molecules will attract each other with a weak force.



An example of dipole-dipole forces between two molecules of propanal

Hydrogen bonds: A stronger type of dipole-dipole force. The definition of hydrogen bonding was discussed thoroughly in Grade 11, but for the sake of the organic structures studied in Grade 12 it is helpful to observe that hydrogen bonds are mostly found between different molecules where at least one molecule has an –OH group (hydroxide group). Hydrogen bonds are present between the -O atom connected to one molecule (which is slightly negative) and the -H atom of a different molecule (that is slightly positive).

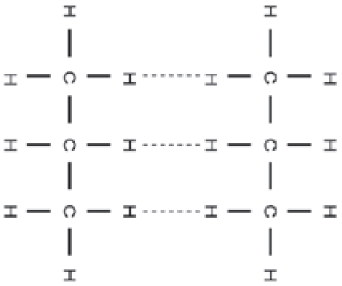


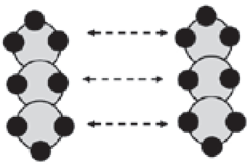
An example of hydrogen bonds between two molecules of pentan-1-ol

As indicated in this example, more than one type of force can act between molecules simultaneously.

Worked example 9

Identify the intermolecular forces found in propane.





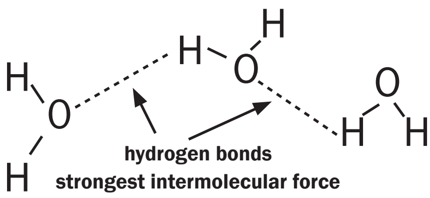
Solution

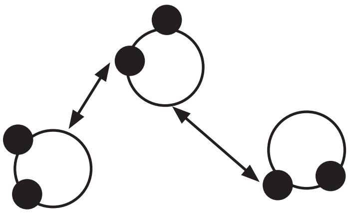
The intermolecular forces found between the molecules of propane are *induced dipole forces*.

The Van der Waals forces (induced dipole forces in this case) between the molecules are very weak, and are easily broken. This leads to the alkanes' relatively low boiling points.

Worked example 10

Identify the intermolecular forces found in water.





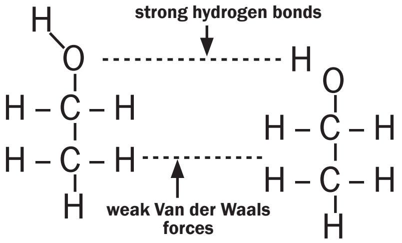
Solution

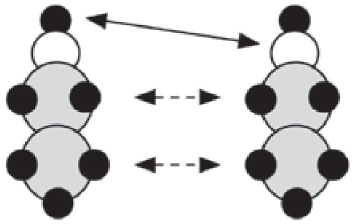
The intermolecular forces found between the molecules of water are hydrogen bonds.

The water molecules are strongly attracted to each other by the hydrogen bonds. Water has a relatively high boiling point due to the presence of the hydrogen bonds.

Worked example 11

Identify the intermolecular forces found between the molecules of ethanol.





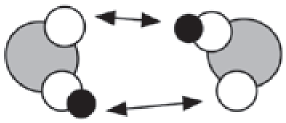
Solution

There are hydrogen bonds between the hydroxyl groups (–OH) of the different molecules. There are dipole-dipole forces between the hydrogen molecules connected to the different molecules.

Both hydrogen bonds and dipole-dipole forces exist between alcohol molecules. The hydrogen bonds exist between the polar **OH–** groups and the dipole-dipole forces exist between the non-polar hydrocarbon parts.

Worked example 12

Identify the intermolecular forces present in methanoic acid.



Solution

There are hydrogen bonds between the molecules of methanoic acid.

Intermolecular forces between carboxylic acids are stronger than those in alcohol because the molecules are bonded by two hydrogen bonds.

1.3 Physical properties of organic compounds

- Each chemical compound has **physical properties** such as its **phase, melting point, boiling point, vapour pressure, viscosity, density and solubility.** Note that the type of bonds affect all these properties.
- These properties are affected by the strength of the intermolecular forces between the molecules in the compounds.

DEFINITIONS

Vapour pressure: The vapour pressure of a liquid is the equilibrium pressure of a vapour above its liquid; that is, the pressure of the vapour resulting from evaporation of a liquid above a sample of the liquid in a closed container.

Boiling point: The temperature at which the vapour pressure of a substance equals atmospheric pressure. The stronger the intermolecular forces, the higher the boiling point. The boiling point of a substance is the temperature at which it changes from a **liquid** to a **gas** and is reached when the vapour pressure above the liquid equals the atmospheric pressure.

Melting point: The melting point of a substance is the temperature at which it changes from a solid to a liquid.

When the intermolecular forces between the molecules of a substance are strong:

- a lot of energy is required to overcome these intermolecular forces of attraction;
- the molecules aren't easily separated from one another.

NB

REMEMBER
In general:
As the strength of the intermolecular forces **INCREASES**:

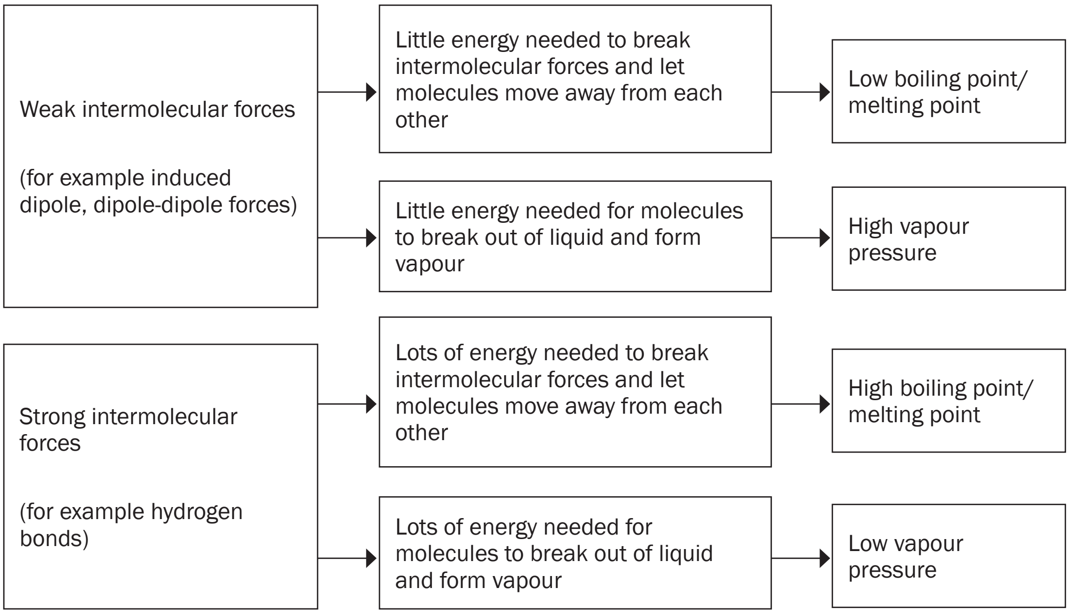
- Less vapour is produced hence vapour pressure above the liquid **DECREASES**;
- Melting and boiling points **INCREASE**.

1.4 Factors that have an influence on the physical properties of organic compounds

In the Grade 12 exam you will be asked to explain why the physical properties (melting point, boiling point, vapour pressure) of different organic compounds, differ.

In order to determine why the physical properties differ, you will need to find answers to one or more of the following questions:

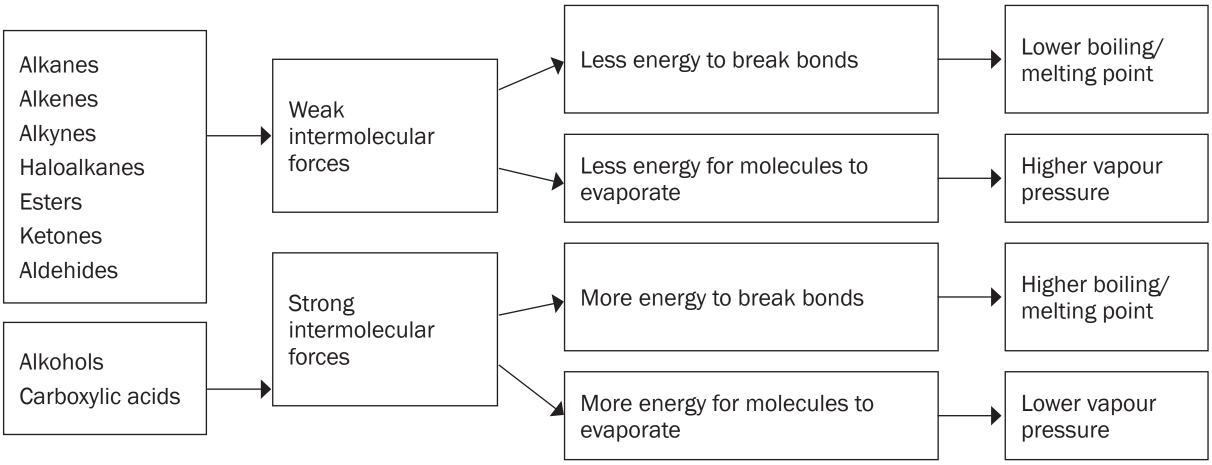
1. *What is the influence of the type of intermolecular forces present between the molecules of the organic compound on its physical properties?*



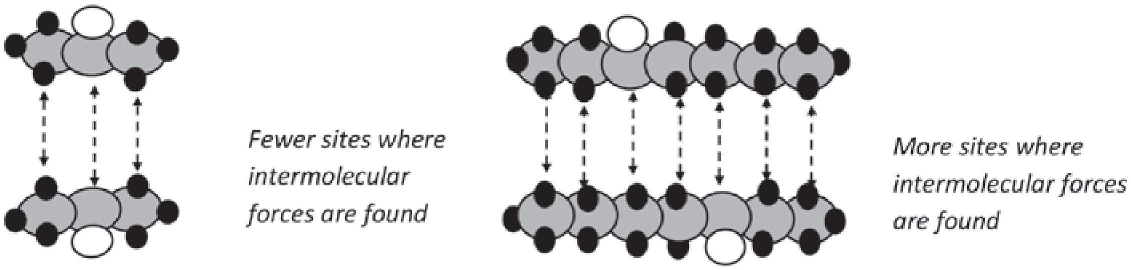
2. *What is the influence of the type of functional group that is found in the molecule on its physical properties?*

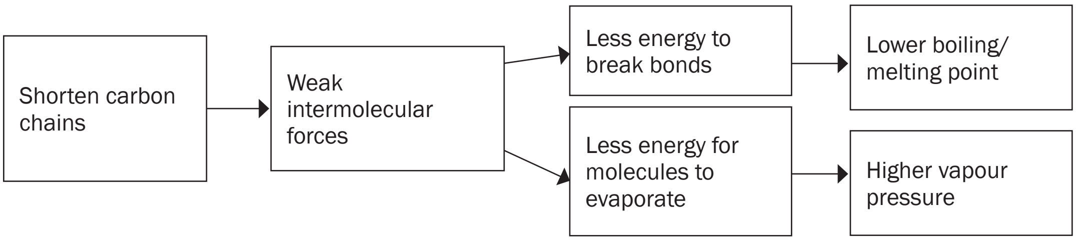
   In organic compounds where hydroxyl groups (-OH) are present (for example alcohols, carboxylic acids) you will find **hydrogen bonds and induced dipole forces.**

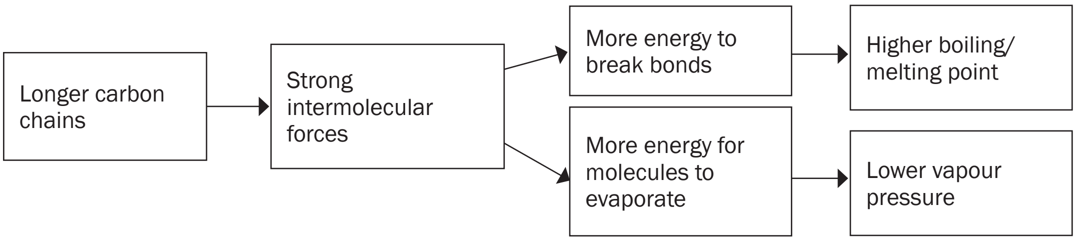
   In organic compound where hydroxyl groups are not present (for example alkanes, alkenes, alkynes, halo-alkanes, aldehydes, ketones and esters) you will find **induced dipole forces** or **dipole-dipole forces.**



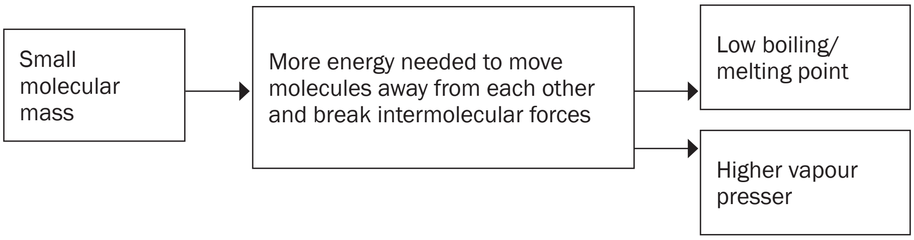
3. *What is the influence of the chain length of the molecule on its physical properties?*
   As the length of the carbon chain in the organic compound increases, the number of sites where you will find the intermolecular forces will increase. Therefore, the longer the carbon chain, the stronger the intermolecular forces between the molecules.

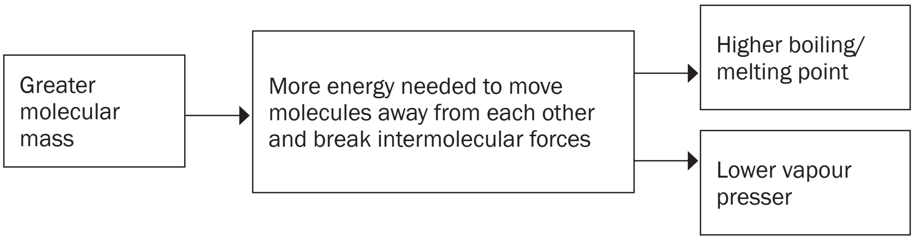






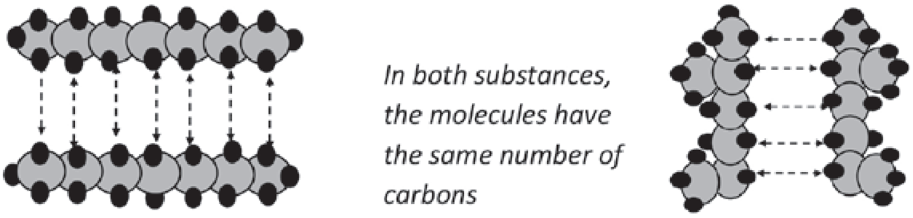
4. *What is the influence of the molecular mass of an organic compound on its physical properties?*





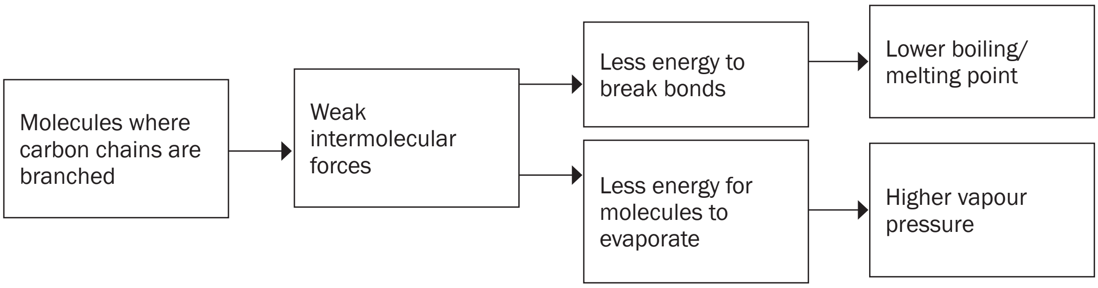
5. *What will the influence on the physical properties of an organic compound be if the compound is made up of branched carbon-chains?*

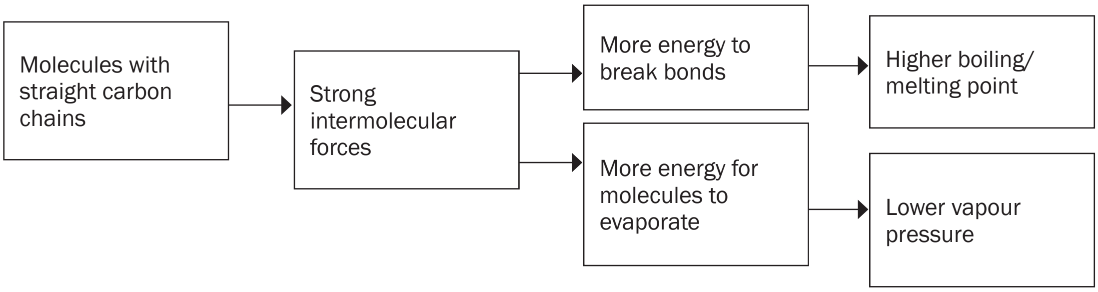
As the number of branches (alkyl groups) increases, the shape of the molecule changes to a more compact, spherical shape with a smaller surface area, resulting in a smaller contact area between the molecules and weaker net Van der Waals forces.



long chain length gives greater surface area over which intermolecular forces can act

short or branched chains give less surface area over which intermolecular forces can act





Activity 5

1.1 The boiling points of branched alkanes are lower than those of straight chain alkanes containing the same number of carbon atoms because branched alkane chains have

A Large molecular masses
B Longer chain lengths
C More electrons
D Smaller effective molecular surface areas (2)

1.2 Which ONE of these compounds has the highest vapour pressure at room temperature?

A Propane
B Ethane
C Ethanol
D Fluoroethane (2)

2. Will the boiling point of hexane be HIGHER THAN or LOWER THAN that of pentane? Refer to MOLECULAR STRUCTURE, INTERMOLECULAR FORCES and ENERGY needed to explain the answer. (4)

3. How will the boiling point of an ISOMER of Butane compare to that of Butane? Write down HIGHER THAN, LOWER THAN or EQUAL TO. Refer to MOLECULAR STRUCTURE, INTERMOLECULAR FORCES and the ENERGY needed to explain the answer. (4)

4. Consider the boiling points of compounds propan-1-ol (97˚C) and ethanoic acid (118˚C).

4.1 Give a reason for this difference in boiling points by referring to the intermolecular forces present in EACH of these compounds. (3)

4.2 Which ONE of the compounds propan-1-ol or ethanoic acid has a higher vapour pressure? Refer to their boiling points to give a reason for the answer. (3)

[18]

Solutions

1.1 D ✓✓ (2)

1.2 A ✓✓ (2)

2 Higher ✓

<u>Structure</u>: Hexane has a <u>longer chain length</u> than pentane. OR Hexane contain more C- atoms than pentane. OR Hexane has a greater molecular size than pentane. OR Hexane has a larger surface area than pentane. ✓

<u>Intermolecular forces</u>: Between the different molecules of hexane you will find <u>stronger or more intermolecular forces</u> than between the different molecules of pentane. ✓

<u>Energy</u>: <u>More energy needed to overcome or break intermolecular forces</u> between hexane molecules than you need between pentane molecules. ✓ (4)

3. Lower than ✓

Isomers of Butane: More branching / Smaller surface area (over which the intermolecular forces act.) ✓ Weaker/less intermolecular forces. ✓ Less energy needed to overcome intermolecular forces. ✓ (4)

4.1 Ethanoic acid: Two sites for hydrogen bonding/forms dimers ✓

Propan-1-ol: One site for hydrogen bonding. ✓ Therefore it will require more energy to break the bonds between the ethanoic acid molecules than to break the bonds between the propan-1-ol molecules, ✓ which explains why ethanoic acid has the lower boiling point. (3)

4.2 Propan-1-ol has the highest vapour pressure. ✓Because propan-1-ol has a lower boiling point it means less energy is required to break the bond between the particles of propan-1-ol ✓and therefore more molecules will be present in the vapour state and therefore vapour pressure will increase. ✓ (3)

[**18**]

1.5 Solids, liquids and gases

Solids, liquids and gases are all phases of matter.

SOLIDS	LIQUIDS	GASES
Strong intermolecular forces	Weaker intermolecular forces.	Very weak intermolecular forces.
Have a specific shape.	Particles are freer to move, liquid takes the shape its container.	Particles move freely, body of gas takes the shape its container.
Alkanes of C_{18} and bigger are waxy solids at STP	**Alkane** members from C_5 – C_{17} are liquids at STP	The first four members of the **alkanes** C_1 – C_4 (methane to butane) are gases at STP
Alkenes of C_{15} and bigger are solids at STP	Alkene members from C_5 – C_{15} are liquids at STP	The **first three members of the alkenes** C_2 – C_4 (ethene to butene) are gases at STP
Haloalkanes are mostly liquids and solids at STP.		A few **haloalkane** gases exist at room temperature.

SOLIDS	LIQUIDS
The bigger molecules of **alcohols, aldehydes, ketones, ethers, carboxylic acids** and **esters** are solids, as a result of the increasing strength of the Van der Waals forces.	The smaller molecules of **alcohols, aldehydes, ketones, ethers, carboxylic acids** and **esters** are liquids at STP.

1.6 Chemical properties of organic compounds

Alkanes our most important fossil fuel and are good sources of heat and energy.

1.6.1 HYDROCARBONS		
ALKANES C_nH_{2n+2}	**ALKENES** C_nH_{2n}	**ALKYNES** C_nH_{2n-2}
• Are saturated hydrocarbons and **therefore** relatively **unreactive**.	• Are **unsaturated** hydrocarbons and therefore **reactive**.	• Are highly **unsaturated** hydrocarbons and therefore **very reactive**.
• Have low boiling points and evaporate easily. • Cause suffocation if inhaled. • Have characteristic odours. • Previously known as the 'paraffins' (meaning without affinity or reactivity). • Weak Van der Waals intermolecular forces • Non-polar	• Ethene, C_2H_4, is the simplest alkene. • Most are produced by cracking of alkanes. Cracking is defined further on.	• Ethyne
• All are volatile, explosive and flammable and are used as fuels because their oxidation (with oxygen) is **exothermic**, and releases large amounts of energy.		
• **Butane** is used in cigarette lighters. • 'Handigas' (in camping gas bottles) is a mixture of **propane** and **butane**. • Petrol is a mixture of different alkanes, mainly iso-octane and heptane.	• Ethene is used in the manufacturing of plastic (polymer of ethane).	• **Ethyne** used to be known as acetylene and is used on a large scale as fuel for the oxyacetylene blowtorch used to cut and weld metals. When ethyne burns in the presence of oxygen, a flame temperature of 2 800 °C can be reached.

1.6.2 HALOALKANES

Are

- alkanes with halogen (Br, $C\ell$ or I) substituents;
- **saturated** and therefore
- relatively **unreactive**.

Are

- bonded by weak Van der Waals intermolecular forces
- poisonous
- mostly liquids at room temperature.

The more halogen atoms on a haloalkane,

- the more poisonous the substance and
- the less flammable e.g. $CH_3C\ell \rightarrow CH_2C\ell_2 \rightarrow CHC\ell_3 \rightarrow CC\ell_4$

Tetrachloromethane $CC\ell_4$ is

- a non-polar molecule;
- used as a non-polar solvent;
- insoluble in water;
- inflammable and has
- very weak London Van der Waals intermolecular forces.

Other haloalkanes are

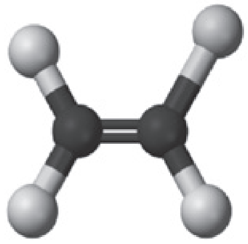
- **very slightly** polar and have
- **slightly stronger dipole-dipole Van der Waals** intermolecular forces.

- **Tetrachloromethane** $CC\ell_4$
  used to be used in dry cleaning but is toxic, also called "carbon tetrachloride".
- **Trichloromethane (chloroform)** $CHC\ell_3$
  used to be used as an anaesthetic
- **Tetrachloroethene** (persolve), C_2H_4, is a haloalkane that is used in the dry cleaning industry.

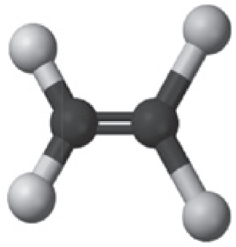
DID YOU KNOW?

Chlorofluorocarbons (CFCs) like dichlorodifluoromethane ($CC\ell_2F_2$) were previously used for cooling and as propellants in aerosol cans, because of their low boiling point.

CFCs contribute to the depletion of the ozone layer that protects us from the sun's UV radiation; which has contributed to global warming; their use is therefore being phased out.



Chlorotrifluoroethene



Dichlorodifluoroethene

By Jynto and Ben Mills [Public domain], via Wikimedia Commons

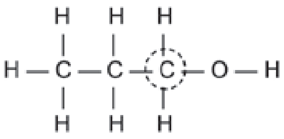
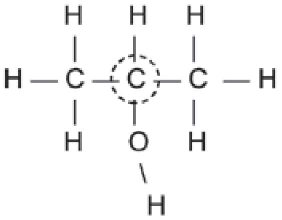
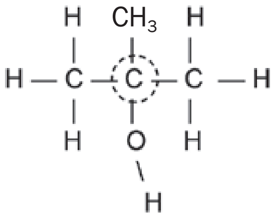
1.6.3 ALCOHOLS

$C_nH_{2n+1}OH$

Are
- **saturated** and
- have a **hydroxyl** functional group.

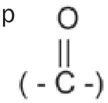
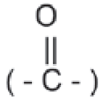
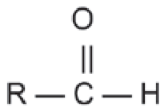
Are
- bonded by strong hydrogen bonds and by weak Van der Waals forces;
- less polar as the number of C-atoms in the molecule increases;
- generally soluble in **polar** and in **non-polar solvents**;
- **flammable**;
- mostly liquids at room temperature.

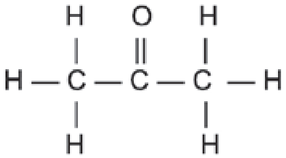
If the carbon that is bonded to the hydroxyl group (-OH) is bonded to:

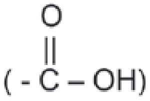
ONE other C-atom it is a **PRIMARY ALCOHOL**	**TWO** other C-atoms it is a **SECONDARY ALCOHOL**	**THREE** other C-atoms it is a **TERTIARY ALCOHOL**
		
propan-1-ol	propan-2-ol	methyl propan-2-ol

- Methanol (CH_3OH):
  - a poisonous liquid that can cause blindness;
  - used as a solvent and sold as methylated spirits.
- Ethanol (CH_3CH_2OH)
  - a colourless liquid found in alcoholic beverages like beer and wine;
  - prepared through the fermentation of starches (beer) or sugars (wine):

$$C_6H_{12}O_6 \xrightarrow[\text{yeast}]{\text{enzymes}} 2C_2H_5OH + 2CO_2$$

1.6.4 KETONES	1.6.5 ALDEHYDES
$C_nH_{2n}O$	
Are saturated molecules with • a carbonyl functional group • on a central C-atom.  $\overset{\overset{O}{\parallel}}{(-C-)}$ **In these structures, you will often see an R attached to part of the carbon chain. R refers to the rest of the molecule. It can be (but is not limited to) a chain of carbon atoms or substitutents.**	**Are saturated molecules with** • a carbonyl functional group (–C–)  $\overset{\overset{O}{\parallel}}{(-C-)}$ • on the first C-atom.  $R-\overset{\overset{O}{\parallel}}{C}-H$

Are - functional isomers of the aldehydes; - liquids at room temperature; - abundant in nature and often have pleasant scents (smell); - used to produce perfumes.	Are - functional isomers of the ketones; - liquids at room temperature except for methanal which is gaseous; - responsible for pleasant smells (long C-chain aldehydes) and odours (unpleasant smells) in short chain aldehydes.
Intermolecular forces: - weak induced dipole forces and - stronger dipole-dipole forces.	**Intermolecular forces:** - weak induced dipole forces and - stronger dipole-dipole forces.
Solubility in H_2O: - Short C-chain ketones form hydrogen bonds with H_2O molecules ∴ are soluble in H_2O; - Long C-chain ketones are insoluble in H_2O.	**Solubility in H_2O:** - Short C-chain aldehydes form hydrogen bonds with H_2O molecules ∴ are soluble in H_2O; - Long C-chain aldehydes are insoluble in H_2O.
Propanone is also known as acetone and is used as nail polish remover. 	

1.6.6 CARBOXYLIC ACIDS	1.6.7 ESTERS
$C_nH_{2n}O_2$	
Are saturated molecules with - a carboxyl functional group.  $(-\overset{\displaystyle O}{\overset{\|}{C}}-OH)$	**Are saturated molecules with** - an ester functional group.
Are - functional isomers of the esters; - liquids at room temperature; - weak acids; - very polar molecules.	Are - functional isomers of the carboxylic acids; - liquids at room temperature; - produced when an alcohol reacts with a carboxylic acid; - responsible for pleasant smells (long C-chain esters); - volatile (evaporate easily).
Intermolecular forces: - weak induced dipole forces and - hydrogen bonds. - Soluble in H_2O due to hydrogen bonds that form between the carboxylic acid and H_2O molecules.	**Intermolecular forces:** - weak induced dipole forces and - stronger dipole-dipole forces but - NO hydrogen bonds. - Oily and become more so as the C-chain increases in length, due to stronger net intermolecular forces. - Only short C-chain esters are soluble in H_2O.

Boiling points: • Similar to those of aldehydes and ketones with similar molecular mass.	**Boiling points:** • Similar to those of aldehydes and ketones with similar molecular mass; • Lower than those of alcohols and carboxylic acids with similar molecular mass due to absence of hydrogen bonds.

Usage and Occurrence:
• Methanoic acid (CHOOH) is
  • known as formic acid (Latin: Formica = ant);
  • found in sting nettles and in the poison of ants when they bite.
• Ethanoic acid (CH_3COOH), also known as acetic acid, is vinegar. (Latin: Acetum = vinegar).
• Butanoic acid ($CH_3CH_2CH_2COOH$) is
  • also known as butyric acid and
  • gives rancid butter its unpleasant smell.
• Benzoic acid is used as a food preservative.
	Used in the manufacture of:
	• perfumes (pleasant smell)
	• solvents
	• artificial fruit flavours. E.g. butanoic acid + ethanol catalysed by H_2SO_4 yields ethyl butanoate, a.k.a apple flavour.

NB

VOCABULARY

- **rancid:** old, stale and with an unpleasant smell
- **preservative:** prevents food from going off or decaying
- **readily:** easily

1.7 Reactions of organic compounds

1.7.1 Types of chemical reactions

Organic compounds take part in different types of reactions which can be grouped into:

- **Oxidation**
- **Substitution**
- **Addition** and
- **Elimination** reactions.

1.7.1.1 Oxidation reactions:

Reaction with oxygen (O_2)

Exothermic (release energy)

Excess O_2 alkane + $O_2(g) \rightarrow CO_2(g) + H_2O(g)$ + energy

1.7.1.2 Substitution reactions:

- Take place when **saturated compounds** react and an atom bonded to the carbon chain is substituted by another atom or another group of atoms.
- Produce products which are also saturated.
- Are slow.
- Are not spontaneous – additional energy (e.g. sunlight *hf* or heat Δ) is needed for the reactions to take place.

SUBSTITUTION REACTIONS	Reaction conditions	Reaction equations
Halogenation	**Endothermic:** **Sunlight or heat** **hf or Δ**	**alkane** + halogen $\xrightarrow{\text{hf or }\Delta}$ **haloalkane** + HX
Hydrolysis	**Endothermic** **VERY slow**	**haloalkane** + H_2O → **alcohol** + HX
	Slow	**haloalkane** + NaOH (diluted) → **alcohol** + NaX

1.7.1.3 Addition reactions:

- Take place when atoms attach to the double or triple bond of an **unsaturated compound** (alkenes or alkynes), breaking the double or triple bond during the reaction.
- Form products which are more saturated than the reactants.
- Are faster than substitution reactions.
- Are usually spontaneous.

ADDITION REACTIONS	Reaction conditions	Reaction equations
Hydrogenation	Catalyst: Pt, Pd or Ni	**alkene** + $H_2(g) \xrightarrow{Pt}$ **alkane**
Halogenation	No catalyst	**alkene** + X_2 → **haloalkane**
Hydrohalogenation	No catalyst.	**alkene** + HX → **haloalkane**
Hydration	Concentrated H_2SO_4	**alkene** + $H_2O \xrightarrow{H_2SO_{4\,(conc)}}$ **alcohol**

NB

REMEMBER

Markovnikov's rule:

Two products are formed during addition of water or of HX to an alkene.

The **major product** is formed when the H-atom from the added molecule bonds to the C-atom which is already bonded to the most other H-atoms.

The **secondary product** is formed when the H-atom from the added molecule bonds to the C-atom which is bonded to the least other H-atoms.

1.7.1.4 Elimination reactions:

- Occur when two atoms or groups of atoms are removed from adjacent carbon atoms in a **saturated compound** (like an alkane, a haloalkane or an alcohol) to form two compounds;
- are always **endothermic** i.e. the reactants must be **heated.**

ELIMINATION REACTIONS	Reaction conditions	Reaction equations
Cracking	Catalyst (Pt), Heat	**alkane** $\xrightarrow{Pt\Delta}$ alkene + alkane (long chains form shorter structures)
Dehydrogenation	Catalyst (Pt), Heat	**alkane** $\xrightarrow{Pt\Delta}$ alkene + H_2
Dehydrohalogenation	Concentrated strong base (NaOH), Heat	**haloalkane** $\xrightarrow{NaOH_{(c)}\Delta}$ alkene + HX
Dehydration	Concentrated H_2SO_4, Heat	**alcohol** $\xrightarrow{H_2SO_{4(c)}\Delta}$ alkene + H_2O

1.8 Reactions of different homologous series

1.8.1 Reactions of the ALKANES

As alkanes are saturated hydrocarbons, they are relatively unreactive.

Alkanes burn in excess oxygen to produce carbon dioxide and in limited oxygen, to produce carbon monoxide. In both cases water vapour is produced and both reactions are exothermic ($\Delta H < 0$). Alkanes are therefore sources of energy and can be used as fuel.

NB

Zaitsev's* rule:

If more than one elimination product is possible

- the **major product** is formed when the **H-atom** is removed from the **C-atom** with the **least H-atoms** bonded to it and
- the **secondary product** is formed when the **H-atom** is removed from the C-atom with the most H-atoms bonded to it.

* If you look this rule up online, you might find it is spelled 'Saytseff' as well.

STEPS to balance reaction equations for the oxidation of alkanes, alkenes and alkynes.

1. Write the standard reaction equation, with the correct formula for the alkane.

$$\text{alkane} + \text{(excess) } O_2(g) \rightarrow CO_2(g) + H_2O(g) + \text{energy}$$

2. Put a 2 in front of the alkane, alkene or alkyne.
3. Balance the C-atoms on the right hand side.
4. Balance the H-atoms on the right hand side.
5. Balance the O-atoms on the left hand side.
6. Check whether the balancing ratio is in the simplest form.

e.g. Worked example 13

Write the balanced reaction for the reaction of ethane burning in excess oxygen, using molecular formulae.

Solution

$C_2H_6(g) + O_2(g) \rightarrow CO_2(g) + H_2O(g) + \text{energy}$ (unbalanced)

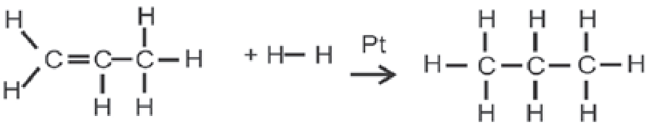
$2C_2H_6(g) + 7O_2(g) \rightarrow 4CO_2(g) + 6H_2O(g) + \text{energy}$ (balanced)

SUBSTITUTION	**HALOGENATION** (+ X_2, hf, Δ)	• Alkanes react with halogens X_2 (X = Br, $C\ell$) when heated (indicated with Δ) or in the presence of light (indicated with hf). • The reaction adds a halogen atom to the molecule, so it is known as **halogenation.**
		Example: 1. Write a balanced reaction for the reaction of methane with chlorine gas, using molecular formulae. Name the products. ***Solution:*** $CH_4(g) + C\ell_2(g) \xrightarrow{\text{hf or } \Delta} CH_3C\ell(g) + HC\ell(g)$ methane chloromethane hydrochloric acid

SUBSTITUTION	CRACKING
	(Δ, Pt)
		• This involves breaking up large alkane molecules into smaller and more useful molecules.
		• Reaction conditions:
		  • high pressure and
		  • high temperature without a catalyst (thermal cracking), or
		  • lower temperatures and pressures in the presence of a catalyst (Pt) (catalytic cracking).

		Examples: • $CH_3CH_2CH_2CH_3 \xrightarrow{Pt\Delta} H_2 + CH_2{=}CHCH_2CH_3$ butane hydrogen + but-1-ene • $CH_3CH_2CH_2CH_3 \xrightarrow{Pt\Delta} CH_2{=}CH_2 + CH_3CH_3$ butane ethene + ethane

1.8.2 Reactions of the ALKENES

ADDITION	HYDROGENATION (+ H_2, Pt)	alkene + $H_2(g) \xrightarrow{Pt\Delta}$ alkane • The alkene must first be dissolved in a non-polar solvent (e.g. $CC\ell_4$) • Catalyst: Pt, Pd or Ni • Margarine is manufactured by the hydrogenation of unsaturated plant oils such as sunflower oil in the presence of platinum as the catalyst. These unsaturated oils are then changed to saturated soft solids.
		Examples: 1. Write an equation for the hydrogenation of ethene using condensed structural formulae. Name the product. ***Solution:*** $CH_2{=}CH_2 + H_2 \xrightarrow{Pt\Delta} CH_3{-}CH_3$ ethene ethane 2. Write an equation for the hydrogenation of propene, using structural formulae. Name the product. ***Solution:***  propene propane

REMEMBER

- The reaction of a haloalkane with water to form an alcohol is called **hydrolysis**. Any splitting of a molecule by water is also called hydrolysis.
- However other reactions between organic compounds and water are called hydration reactions as the hydrogen from the water becomes part of the product.

REMEMBER

- Saturated compound $\xrightarrow{\text{elimination}}$ unsaturated compound
  alkane / haloalkane / alcohol alkene
- Unsaturated compound $\xrightarrow{\text{addition}}$ saturated compound
  alkene alkane / haloalkane / alcohol

ADDITION

HALOGENATION

(+ X_2)

alkene + X_2 → haloalkane ($X = C\ell$, Br, F, I)

- NO catalyst is needed – the reaction is spontaneous.
- The reaction with fluorine is highly exothermic and explosive.

Examples:

1. Write an equation for the addition of bromine to ethene, using condensed structural formulae. Name the product.

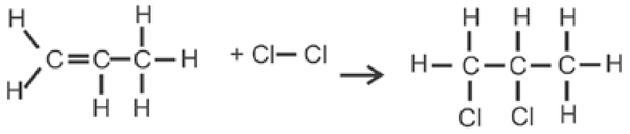
Solution:

$CH_2{=}CH_2 + Br_2 \rightarrow CH_2Br{-}CH_2Br$

ethene 1,2-dibromoethane

2. Write an equation for the addition of chlorine to propene, using structural formulae. Name the product.

Solution:



propene 1,2-dichloropropane

ADDITION

HYDROALOGENATION

(+ HX)

alkene + HX → haloalkane ($X = F, C\ell$, Br, I)

- NO catalyst is needed – the reaction is spontaneous.
- The reaction must take place in the absence of water.

hint Apply Markovnikov's rule as discussed earlier, in order to determine the major product!

Examples:

1. Write an equation for the reaction between ethene and hydrogen fluoride, using condensed structural formulae. Name the product.

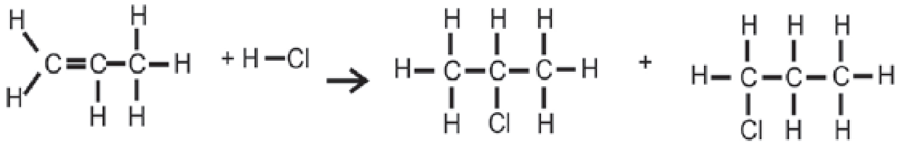
Solution:

$CH_2{=}CH_2 + HC\ell \rightarrow CH_3CH_2C\ell$

ethene chloroethane

2. Write an equation for the reaction of propene with hydrogen chloride (hydrochloric acid), using structural formulae. Name the two products and identify the major product.

Solution:



propene 2-chloropropane 1-chloropropane

Major product

(apply Markovnikov)

ADDITION

HYDRATION (+ H_2O, H_2SO_4 concentrated)

$$\text{alkene} + H_2O \xrightarrow{H_2SO_4\text{ (conc)}} \text{alcohol}$$

- Catalyst: concentrated strong acid: H_2SO_4 or H_3PO_4
- The reaction must take place in excess H_2O

hint Apply Markovnikov's rule as discussed earlier, in order to determine the major product!

Examples:

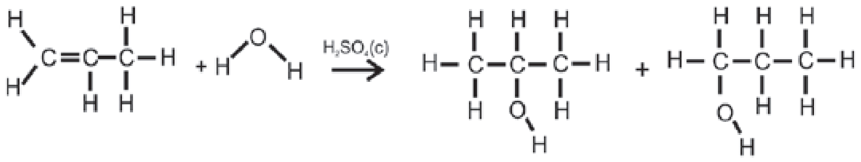
1. Write an equation for the reaction between ethene and water, using condensed structural formulae. Name the product.

Solution:

$$CH_2{=}CH_2 + H_2O \xrightarrow{H_2SO_4\text{ (conc)}} CH_3\,CH_2OH$$

2. Write an equation for the hydration of propene, using structural formulae. Name the two products and identify the major product.

Solution:



propene propan-2-ol propan-1-ol

Major product

1.8.3 Reactions of the HALOALKANES

SUBSTITUTION

WITH DILUTE STRONG BASE (NOH OE KOH) TO PRODUCE AN ALCOHOL

haloalkane + NaOH (dilute) → alcohol + NaX

- Reactions with **dilute strong bases (KOH or NaOH)** produce **alcohols**.
- The haloalkane must be **dissolved in ethanol** before treatment with **dilute sodium hydroxide (aq)** or potassium hydroxide (aq).
- The halogen atom is removed from the haloalkane and is replaced by the OH^- -ion from the KOH or NaOH.
- The K^+ or Na^+ -ion bonds to the substituted halogen atom, forming NaX as a by-product.

Examples:

1. Write an equation for the reaction of bromo methane with a dilute sodium hydroxide solution, using condensed structural formulae. Name the products.

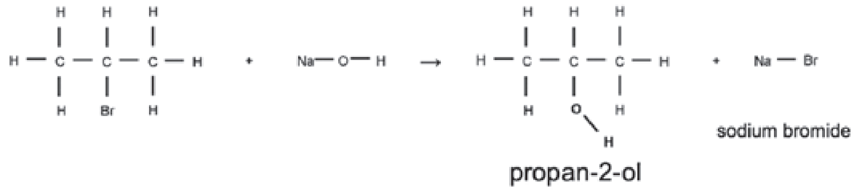
Solution:

$CH_3Br + NaOH \rightarrow CH_3OH + NaBr$

bromo methane methanol sodium bromide

2. Write an equation for the reaction of 2-bromopropane with a dilute potassium hydroxide solution, using structural formulae. Name the products.

Solution:



NB

REMEMBER

The reaction of a haloalkane with water to form an alcohol is called hydrolysis. Generally, splitting any molecule with water is also called **hydrolysis**.

However other reactions between organic compounds and water are called hydration reactions, particularly when OH is added to the compound.

NB

VOCABULARY

Heated under reflux: A solution is heated and the vapour is cooled down so that it condenses and return to the reaction vessel.

SUBSTITUTION

HYDROLYSIS WITH WATER (H_2O) TO PRODUCE ALCOHOLS

Haloalkane + H_2O → alcohol + HX

- Reactions with **water (+ heat)** produce **alcohols.**
- The haloalkane must first be **dissolved in ethanol**
- The reaction is slower than the reaction between a haloalkane and a strong base.
- The halogen atom is removed from the haloalkane and is replaced by the OH^- from the water molecule.
- The H^+ -ion from the water then bonds to the substituted halogen atom, forming HX as a byproduct.

Example:

1. Write an equation for the reaction of chloroethane with a dilute sodium hydroxide solution, using condensed structural formulae. Name the products.

Solution:

$CH_3CH_2C\ell$ + NaOH(dil) → CH_3CH_2OH + $NaC\ell$

ethanol — sodium chloride

2. Write an equation for the reaction of 1-bromopropane with water, using condensed structural formulae. Name the products.

Solution:

$CH_3CH_2CH_2Br + H_2O \rightarrow CH_3CH_2\,CH_2OH + HBr$

propan-1-ol — hydrogen bromide

ELIMINATION

DEHYDROHALOGENATION (NaOH (c), Δ)

Haloalkane $\xrightarrow{NaOH(c)\Delta}$ alkene + HX (X = $C\ell$, Br, I)

- Heating a haloalkane under reflux in a **concentrated** solution of **NaOH or KOH** in pure **ethanol** as the solvent (hot ethanolic NaOH / KOH) produces an alkene.
- The **halogen atom** is **eliminated** from the haloalkane.
- A **hydrogen atom** is **eliminated** from a neighbouring C-atom.

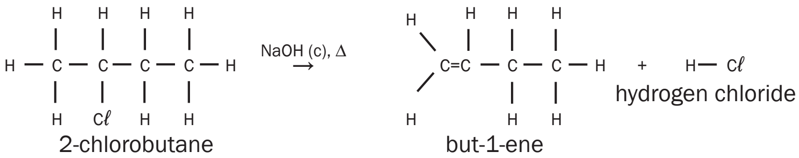
hint

Apply Zaitsev's rule as discussed earlier, in order to determine the major product!

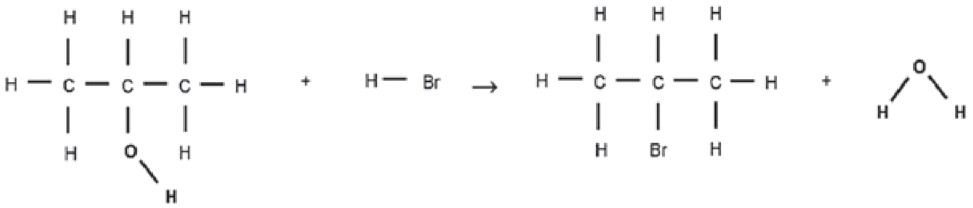
Example:

Write an equation for the reaction of 2-chlorobutane with concentrated sodium hydroxide when heated under reflux, using structural formulae. Show the major organic product only and name it and the by-product.

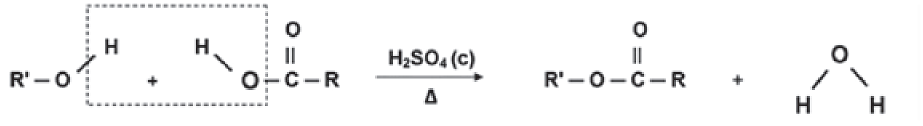
Solution:



1.8.4 Reactions of ALCOHOLS

SUBSTITUTION	**HALOGENATION** (+ NaX)	alcohol + NaX → haloalkane + H_2O 1. Tertiary alcohols react with HX (X = Cℓ, Br) to produce haloalkanes and water. 2. Secondary and primary alcohols react slowly and at high temperatures.
		Example: Write an equation for the reaction of propan-2-ol with hydrogen bromide, using structural formulae. Name the products. ***Solution:***  propan-2-ol 2-bromobutane water
ELIMINATION	**DEHYDRATION** (H_2SO_4 concentrated)	alcohol $\xrightarrow{H_2SO_4(c)\Delta}$ alkene + H_2O • **Acid catalysed dehydration** takes place when an alcohol is heated in the presence of a dehydrating catalyst. • Dehydrating catalyst: **Concentrated sulphuric acid, H_2SO_4.** • **The hydroxyl group** is **eliminated** from the alcohol. • A **hydrogen atom** is **eliminated** from a neighbouring C-atom. **hint** Apply Zaitsev's rule as discussed earlier, in order to determine the major product!
		Example: Write an equation for the elimination reaction of butan-2-ol, using condensed structural formulae. Show and name only the major organic product and the by-product. ***Solution:*** $CH_3\ CH_2CHOHCH_3 \xrightarrow{H_2SO_4(c)\Delta} CH_3\ CH{=}CHCH_3 + H_2O$ butan-2-ol but-2-ene water

1.8.5 Reactions of ESTERS

ESTERFICATION (alcohol + carboxylic acid, H_2SO_4 concentrated)	• **Esterfication** takes place when an **alcohol** and a **carboxylic acid** are heated in the presence of a **concentrated H_2SO_4 (c)**. • The reaction is a **acid catalysed condensation** reaction. • Water is produced during the reaction. • The product is an ester which is named as an **alkyl alkanoate.** • The **alkyl** is formed from the C-chain in the **alcohol.** • The **alkanoate** is formed from the C-chain in the **carboxylic acid.**  alcohol carboxylic acid ester water *alkyl alkanoate* *-ol* *-oic acid* *-yl* *-oate*

Examples:

1. What ester will form during the acid catalysed reaction of ethanol and propanoic acid?

Solution:

Ethyl propanoate

Which two compounds need to be heated in the presence of concentrated sulphuric acid in order to form butyl methanoate?

Solution:

butanol + methanoic acid

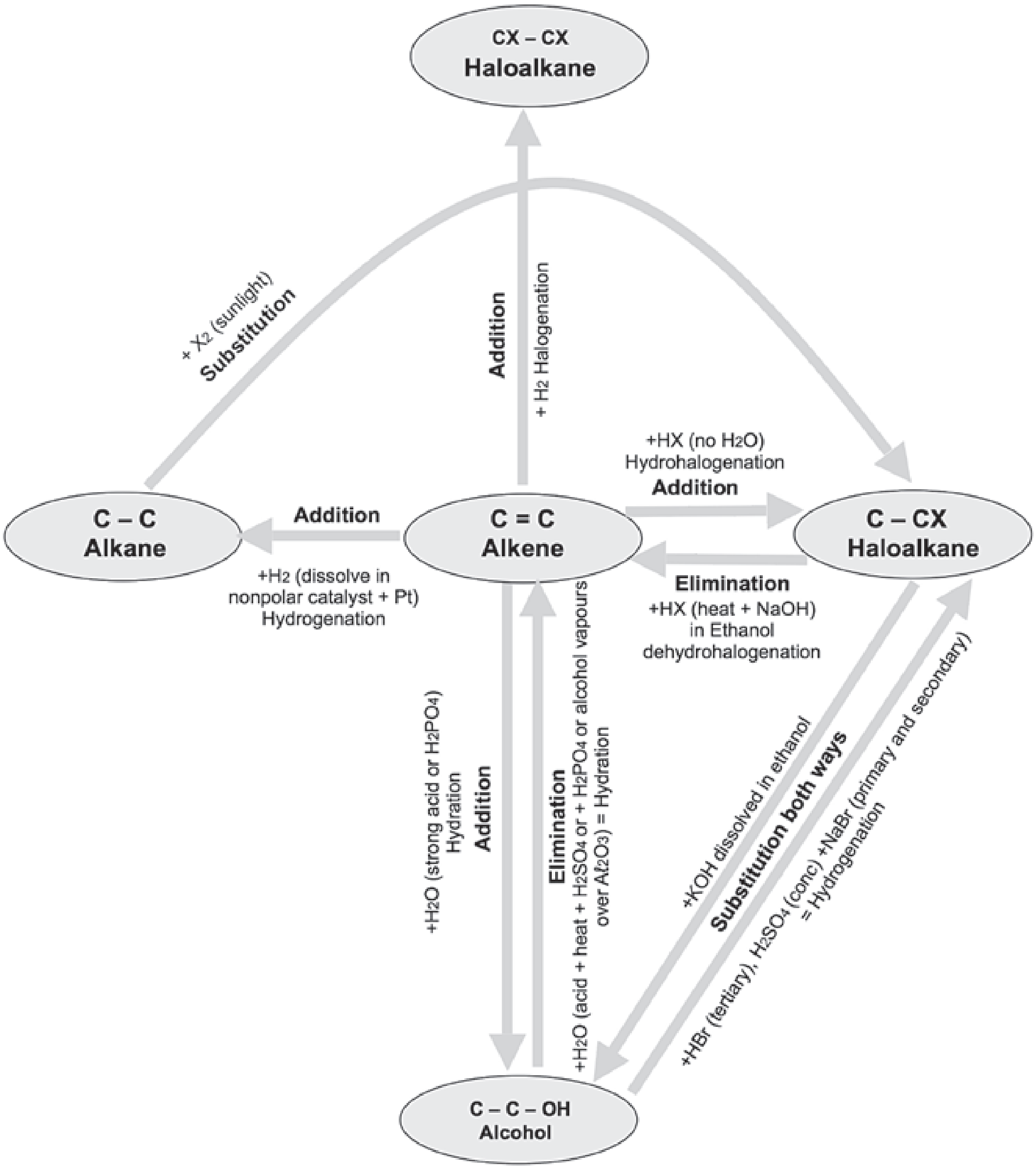
hint

REMEMBER

- Reaction conditions in Addition, Elimination and Substitution
- The role of Sulphuric acid in Esterification, Addition & Elimination

1.9 Creating one hydrocarbon from another

The diagram below illustrates how to use Elimination, Substitution and Addition reactions to create one hydrocarbon from another.



Activity 6

1. Unsaturated vegetable oils are hardened to make margarine. The reaction that takes place during the hardening process can be described as:

I Addition
II Hydrogenation
III Substitution

A I and II
B II and III
C Only I
D Only II (2)

2. Which ONE of the following compounds has the highest melting point?

A Butane
B Butene
C 1-bromobutane
D 1-methylpropane (2)

3. Which ONE of the following pairs of compounds correctly represents the products formed during the COMPLETE combustion of Octane?

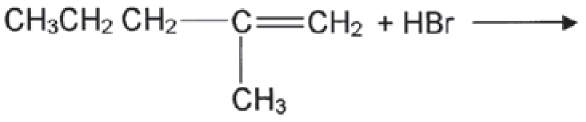
A CO and H_2O
B CO and H_2
C CO_2 and H_2
D CO_2 and H_2O (2)

4. Most organic compounds can undergo substitution or addition or elimination reactions to produce a variety of organic compounds. Some incomplete reactions are shown below:

Reaction I

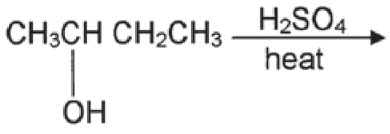
$$CH_3{-}CH_2{-}CH{=}CH_2 + H_2O \longrightarrow$$

Reaction II



$$CH_3CH_2\,CH_2{-}\underset{\displaystyle CH_3}{\underset{|}{C}}{=}CH_2 + HBr \longrightarrow$$

Reaction III



$$CH_3\underset{\displaystyle OH}{\underset{|}{CH}}\,CH_2CH_3 \xrightarrow[heat]{H_2SO_4}$$

4.1 Name the type of reaction represented by Reaction III. (1)

4.2 Both Reactions I and II are examples of addition reactions. Name the type of addition reaction that is represented by each reaction. (2)

4.3 Write down the IUPAC name of the major product formed in Reaction I. (1)

4.4 Reaction I only takes place in the presence of a catalyst. Write down the formula of the catalyst used in Reaction I. (1)

4.5 Write down the structural formula and the IUPAC name of the major product in Reaction II. (3)

4.6 To which homologous series does the organic product formed in Reaction III belong? (1)

[15]

Solutions

1. A ✓✓ (2)

2. C ✓✓ (2)

3. D ✓✓ (2)

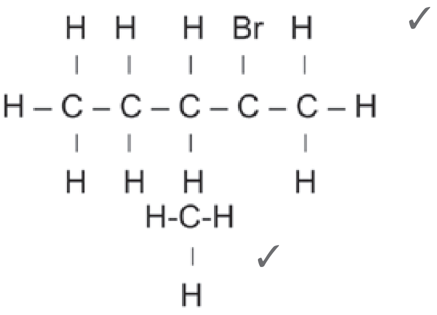
4.1 Elimination ✓ (1)

4.2 I- hydration ✓
II- hydrohalogention ✓ (2)

4.3 Butan-2-ol ✓ (1)

4.4 H_2SO_4 ✓ (1)

4.5 2-bromo-2-methylpentane ✓ (3)



4.6 Alkene ✓ (1)

[15]

1.10 Plastics and polymers

1.10.1 Polymers

NB

DEFINITION

Polymers:

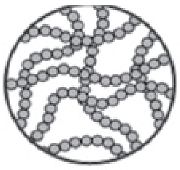
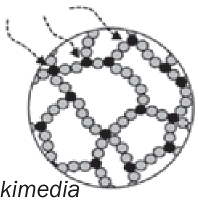
- are a type of macromolecule which
- form when monomers bond to each other chemically
- to produce large molecules that are built up of repeating units in chains
- that vary in length depending on the number of monomers that bond.

Many polymers occur in nature (wood, carbohydrates, proteins etc.) while a large number are produced synthetically (most are plastics) as they are very useful.

1.10.2 Synthetic polymers: Plastics

- All contain carbon in their basic structure.
- Are light because they have a less dense structure than other solids.
- Longer polymers have stronger intermolecular forces between them.
- Cross linking between molecules increases their strength.
- Do not conduct heat or electricity.
- Are versatile and can be used as foam, can be moulded or extruded into fibres.

Synthetic polymers (plastics) can be divided into two main types, namely thermoplastic and thermoset polymers.

THERMOPLASTIC POLYMERS	THERMOSET POLYMERS
Can be softened by heating and hardened by cooling repeatedly therefore can be remoulded into different shapes and so can be recycled.	Are melted when they are made and set into a hard insoluble mass but can't be softened again and therefore can't be remoulded into different shapes, so can't be recycled.
• Consist of long chains • that slide past each other when melted.	• **Cross-links** in the molecule • prevent molecules from sliding past each other.
 *Source: Wikimedia*	 *Source: Wikimedia*

Examples:  *http://en/wikipedia.org/ wiki?File:Recyclables.JPG*	*Examples:*  **Melamine** *http://en.wikipedia.org/wiki/Melamine*  **Bakelite** *http://en.wikipedia.org/wiki/Bakelite*

1.10.3 Properties of plastics, nylons and polyesters

Plastics	Nylons	Polyesters
Are formed by addition polymerisation	Are formed by condensation polymerisation between a dicarboxylic acid and a diamine.	Are formed by condensation polymerisation between a dicarboxylic acid and a diol.
• If the chains are lined up in a regular way, the plastic is hard and strong. • If the chains are irregular or there are many side chains the plastic is softer and can bend.	• Molecular chains are drawn into thin fibres. • Are very strong.	• Depending on the chain they may be stronger or weaker than nylon.
Examples: • Polyethene (plastic bags, shopping bags, plastic containers) • Polypropene Hard (Piping, bottle crates) • PVC (water pipes, artificial leather)	*Examples:* • Nylon (ropes, carpets, clothes)	*Examples:* • Used for clothing fibres • cold drink bottles

Properties of polymers are determined by the intermolecular forces between the chains.

Polymers

- with carbonyl groups can form strong hydrogen bonds and are strong with high melting points;
- like polyesters have dipole-dipole bonds (that are weaker than hydrogen bonds) between the chains, so have lower melting points and are more flexible (bendable);
- with only Van der Waals forces between the chains have low melting points and are flexible.

1.10.4 Polymerisation

Polymerisation

- is a chemical process in which monomers combine to form polymers;
- takes place in three steps:
  - initiation (the step that starts the reaction)
  - propagation (the steps that allow the reaction to continue) and
  - termination (the step that ends the reaction).
- is either addition polymerisation or condensation polymerisation.

ADDITION POLYMERISATION	CONDENSATION POLYMERISATION

• The monomer must be unsaturated – it must contain a double bond or a triple bond, e.g. an alkene like ethene.
• Is the direct addition of the **same monomer molecules** to form a single **product.**
• No atoms are lost or gained during the reaction.
• The empirical (simplest) formulae of the monomer and of the polymer are the same.
• The chain is bonded by strong covalent bonds.
	• Instead of double bonds, these monomers have functional groups like an alcohol (-diol), or dicarboxylic acid.
	• Each monomer must have two or more active groups – to link the molecules.
	• Is the reaction between **monomers** which are **not always the same** to form **two products** – the polymer and a molecule like H_2O or $HC\ell$.
	• The polymers that form are
	  • polyesters or
	  • nylon.

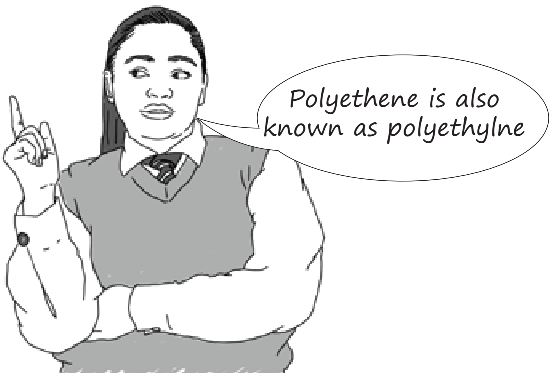
• Reaction conditions:
  • High temperature (± 200 °C)
  • High pressure (± 1000 atm)
  • A small amount of a very reactive initiator.
	• Reaction conditions:
	  • High temperature
	  • Concentrated sulphuric acid, H_2SO_4

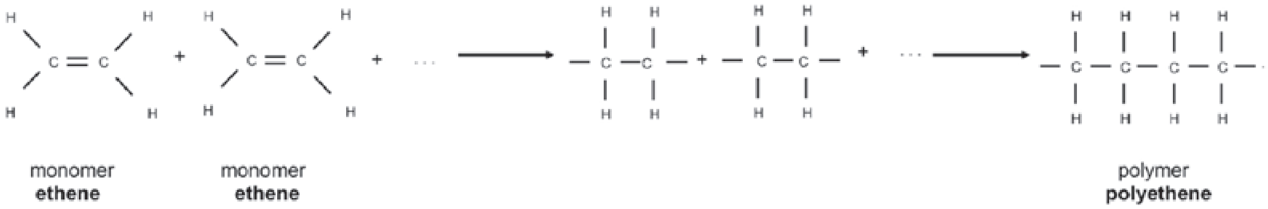
Example: Polimerisation of **ethene** to form polythene • $N(CH_2{=}CH_2) \rightarrow (-CH_2-CH_2-)$	***Example:*** Polymerisation to produce **polyesters** is called **esterfication** • during which a water molecule **H_2O** is **eliminated** and • the organic product contains an ester functional group.
• The name of the polymer is derived from the monomer used. • E.g. If the monomer is **ethene** the *polymer* will be **polyethene.**	• The name of the polymer is deduced from the names of the 2 bonding molecules – an organic alcohol and a carboxylic acid.

1.10.5 Addition polymerisation of ethene to produce polyethene

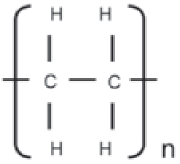
Example 1:

(Note: This is the only addition polymerisation example you need to learn.)



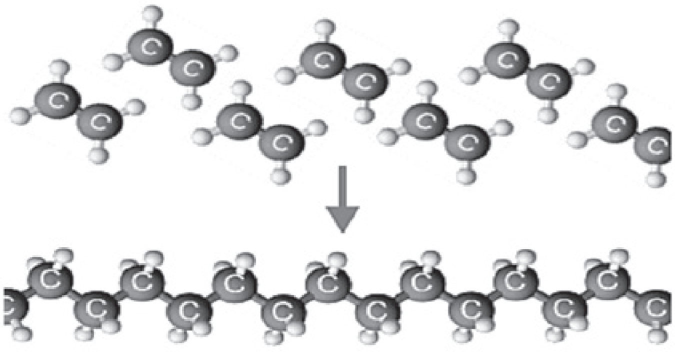


- The length of the polyethene macromolecule depends on the number of ethene monomers that bond.
- The structural formula of the polymer polyethene can therefore be abbreviated as follows:

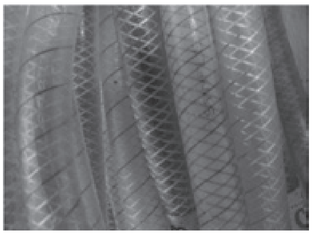
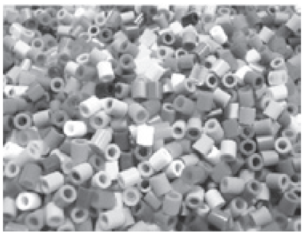


$$\left[-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{H}{C}}- \right]_n$$

where n is the number of monomers that joined.



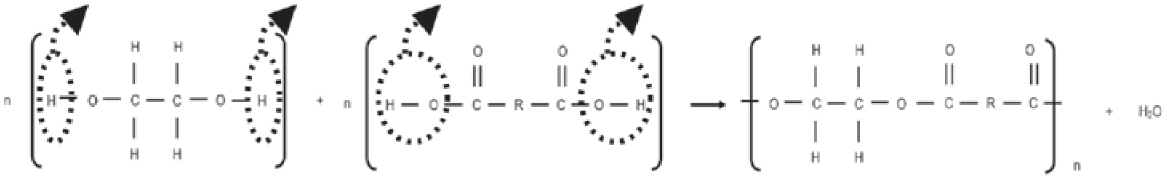
http://www.bbc.co.uk/schools/gcsebitesize/science/images/ocrchem17.gif

	There are two types of polyethene	
	Low density polyethene **LDPE**	**High density polyethene** **HDPE**
Relative strength	Weak	Strong
Number of branches on the polymer	Many	Few
Maximum usable temperature (°C)	85	120
Uses:	Freezer bags Soft bottles Bendable cables  *http://en.wikipedia.org/wiki/Hose_%28tubing%29*	Shopping bags Plastic crates Plastic pipes Toys  *http://commons.wikimedia.org/wiki/File:Plastic_beads2.jpg*
	• Easily moulded • Can be made in any colour • Light • Hardness can be manipulated during manufacture • Not affected by water, air etc. • Can be used to pack food – hygenic	

1.10.6 Condensation polymerisation to produce a polyester

- The alcohol has a hydroxyl group on each end of its carbon chain, so it is a -diol.
- A H-atom is removed from the hydroxyl group on the alcohol and a hydroxyl group is lost from the dicarboxylic acid.
- The −H and the −OH bond to form a water molecule, H_2O.
- A new bond forms between the O-atom on the alcohol and the C-atom on the carboxylic acid. This is an ester linkage.
- The carboxyl group on the other end of the dicarboxylic acid can now react further with another -diol, while the hydroxyl on the other end of the -diol can now react with another dicarboxylic acid.
- This results in a long chain-like compound – a polymer.
- This polymer is known as polyester.

Example:



- There are many different polyester fibres with a wide range of uses. Kevlar and Mylar are two examples.

	KEVLAR	MYLAR
Properties	• Much stronger than nylon or steel • Fire resistant	• Stretched polyester film • High tensile strength • Transparent
Uses	• Bulletproof vests • Boat hulls • Aeronautical industry	• Helium balloons • Space / rescue blankets • Isolators
	 *http://en.wikipedia.org/wiki/ File:Kevlar-vest-ct-wiki.jpg*  *http://en.wikipedia.org/wiki/ File:Kevlar_canoe_algonquin.JPG*	 *http://en.wikipedia.org/wiki /File:Balloonsanimals.jpg*  *http://en.wikipedia.org/wiki/File: RescueFoil.jpg*

1.11 Plastics and pollution

http://en.wikipedia.org/wiki/File:Canal-pollution.jpg

1.11.1 Disadvantages of polymer usage

Although synthetic plastics are light, easy to shape and relatively cheap, there is widespread opposition to the use of these materials.

- Most are not bio-degradable.
- When burned to dispose of them, poisonous gases may be released.
- Landfill sites use up land and fill quickly.
- Litter causes ecological problems.

1.11.2 Recycling

- Biodegradable plastics would solve most problems, but are expensive.
- Responsible recycling is essential.

http://www.flickr.com/photos/dave-goodman/3609172860/

Problems with Recyclability:

- Not possible in very rural areas.
- High costs.
- Not all plastics can be recycled.
- Communities are not all aware of the problems.

High density polythene (HDPE)	Low density polythene (LDPE)
	
Recycled to produce • plastic wood for garden furniture • rubbish bins • rulers	Recycled to produce • fibres for clothing • plastic liners for rubbish bins

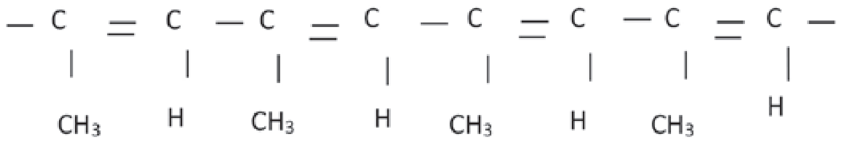
Activity 7

1. Give the definition of a macromolecule (1)

2. Explain the difference between a monomer and a polymer. (2)

3. What is the chemical reaction in which a monomer molecules join to form a polymer called? (1)

4. The polymer below is the product of a polymerisation reaction

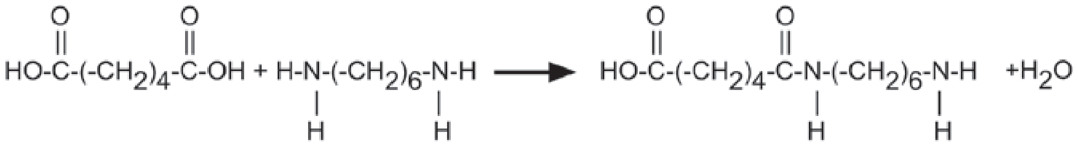


4.1 What is the IUPAC name of the monomer used to form this polymer? (1)

4.2 Give the structural formula of the monomer used to form this polymer. (2)

4.3 Is this an example of an addition or condensation polymerisation? Give a reason for your answer. (2)

5. A carboxylic acid monomer and an amine monomer has joined in an amide linkage as shown below.



$$HO\text{-}\overset{\overset{O}{\|}}{C}\text{-}(\text{-}CH_2)_4\text{-}\overset{\overset{O}{\|}}{C}\text{-}OH + H\text{-}\underset{\underset{H}{|}}{N}\text{-}(\text{-}CH_2)_6\text{-}\underset{\underset{H}{|}}{N}\text{-}H \longrightarrow HO\text{-}\overset{\overset{O}{\|}}{C}\text{-}(\text{-}CH_2)_4\text{-}\overset{\overset{O}{\|}}{C}\text{-}\underset{\underset{H}{|}}{N}\text{-}(\text{-}CH_2)_6\text{-}\underset{\underset{H}{|}}{N}\text{-}H \; + H_2O$$

adipic acid 1,6-diaminohexane

Name the type of polymerisation that occurs in this equation. Give a reason for your answer. (2)

6. Write an equation for polymerisation of ethane to form polyethene. (2)

7. Is (6) an example of addition or condensation polymerisation? Give a reason for your answer. (2)

8. Name at least three industrial uses of polythene. (3)

[18]

Solutions

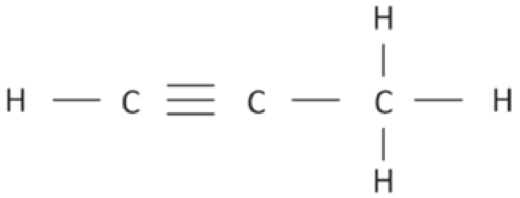
1. A molecule that consists of a large number of atoms. ✓ (1)

2. A polymer is a large molecule that is made up of smaller units, covalently bonded to each other in a repeating pattern. ✓ Each of these smaller units are called a momomere. ✓ (2)

3. Polymerisation ✓ (1)

4.1 prop-(1)-yne (1)

4.2



$H-C\equiv C-\underset{H}{\overset{H}{C}}-H$

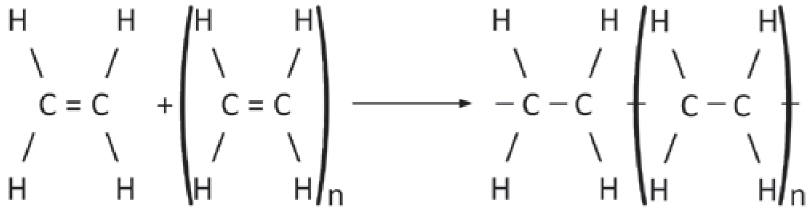
✓ ✓

(2)

4.3. Addition polymerisation ✓ monomers combined through an addition reaction. ✓ (2)

5. Condensation polymerisation. Two monomers with different functional groups are joined ✓ and when they join it leads to the "loss" of a small molecule, in this case, water. ✓ (2)

6. ✓ ✓



(2)

7. Addition polymerisation ✓ monomers combinded through an addition reaction. ✓ (2)

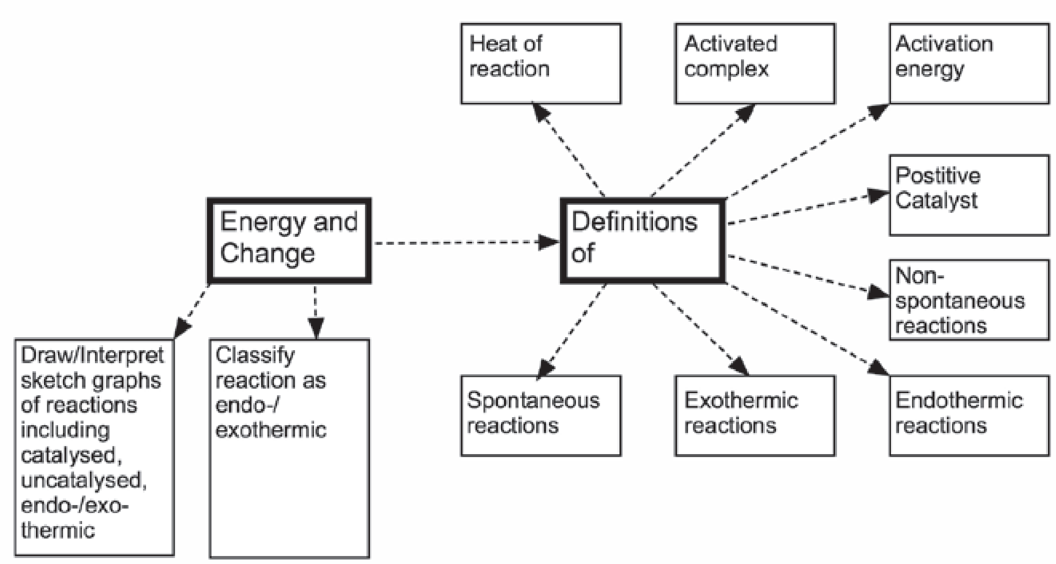
8. Any of the following: sandwich bags, ✓cling wrap, ✓ car covers, ✓ squeeze bottles, liners for tanks and ponds, moisture barriers in construction, freezer bags, water pipes, wire and cable insulation, extrusion coating. (3)

[18]

Unit 2

Rate and extent of reactions

2.1 Summary



2.2 Energy changes during chemical reactions

$$\underbrace{A \quad + \quad B}_{\text{Reactants}} \quad \rightarrow \quad \underbrace{C \quad + \quad D}_{\text{Products}}$$

During a chemical reaction, the **reactants** (written on the left hand side of the equation) react to produce **products** (written on the right hand side of the equation).

Chemical reactions take place in steps

Step 1: The reactant particles need energy so that the existing bonds (covalent, ionic or metallic bonds) between the particles in the reactants can break;

Step 2: The separated particles that are present in the activated complex move and collide;

Step 3: Energy is released by the particles as new bonds form when the products are produced. However, endothermic reactions, as we will later see, take in energy from the surroundings as they come to completion.

2.3 Activation energy and the activated complex

NB

DEFINITIONS

Activation energy is the **minimum kinetic energy** required for a chemical reaction to take place.

The **activated complex** is a temporary, unstable, high energy intermediate state between the reactants and the products.

Activation energy is usually absorbed in the form of heat, light or mechanical energy and is required to change reactants into an activated complex. It is the energy required to break the bonds in the reactant particles to form the **activated complex**.

- **Spontaneous reactions** take place when the reactants have enough energy to start the reaction without additional heat.
- **Non-spontaneous reactions** take place when the reactants do not have enough energy themselves to start a reaction, and additional energy needs to be added.

hint "Spontaneous" means "of its own accord" or "by itself" or "without intervention".

NB

A spontaneous reaction takes place without any addition of energy.

The mass of a catalyst remains constant during a chemical reaction.

2.4 Catalysts

A positive catalyst increases the rate at which a reaction takes place while a negative catalyst (also called an inhibitor) decreases the reaction rate.

If you hear someone talk about a "catalyst", they usually mean a positive catalyst.

Positive catalysts increase the rate of a chemical reaction…

- by providing an alternative path for the reaction to take place
- which requires less energy for the reactants to change into the activated complex,
- by decreasing the activation energy.

NB

DEFINITIONS

A **catalyst** is a substance that changes the rate of a chemical reaction without undergoing a permanent change during the reaction, by decreasing the activation energy of the reaction.

The heat of reaction or enthalpy (ΔH) is the net change in energy in a chemical system when a chemical reaction takes place.

2.5 Energy changes during chemical reactions: ΔH

We know that energy

- is absorbed by the reactant particles when the intramolecular bonds break to form the activated complex, and is
- is released when the particles in the activated complex form new bonds when the products form.

In symbols:

ΔH = Energy of products – Energy of reactants

$= E_{products} - E_{reactants}$

$= E_{final} - E_{initial}$

OR

$\Delta H = H_{products} - H_{reactants}$

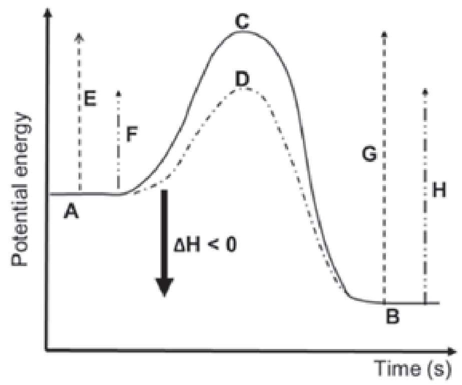
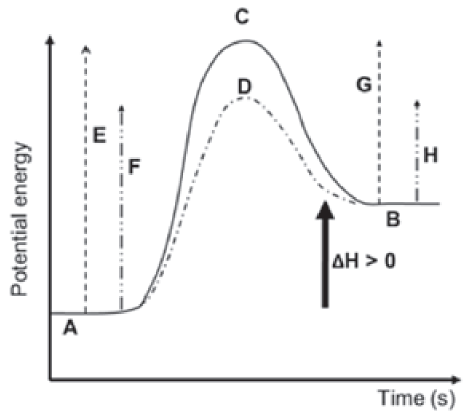
$= H_{final} - H_{initial}$

2.6 Endothermic and exothermic reactions

When we refer to a reversible reaction, the enthalpy (ΔH) is always stated for the forward reaction.

It is important:

- to know the differences between exothermic and endothermic reactions
- to be able to identify whether a given reaction is exothermic or endothermic and
- to be able to interpret graphs for exothermic and endothermic reactions.
- Endo- means “into” or “inwards”, and “exo-” means “outwards”; so, “**endothermic**” means heat goes in (the reaction vessel will feel cold after the reaction completes), whereas “**exothermic**” means “heat goes out”, so the reaction vessel will feel hot when the reaction completes.

2.6.1 EXOTHERMIC REACTIONS	**2.6.2 ENDOTHERMIC REACTIONS**
More energy is released when the new bonds form than is absorbed when the existing bonds break.	More energy is absorbed when the existing bonds break than is released when the new bonds form.
• $E_{reactants} > E_{products}$ • ΔH is **negative** $\Delta H < 0$ • $\Delta H = E_{products} - E_{reactants} < 0$ • Net energy is **released** to the surroundings in the form of heat. • The **temperature** of the reaction mixture **increases**.	• $E_{reactants} < E_{products}$ • ΔH is **positive** $\Delta H > 0$ • $\Delta H = E_{products} - E_{reactants} > 0$ • Net energy is **absorbed from** the surroundings in the form of heat. • The **temperature** of the reaction mixture **decreases**.
Example: fire: C (coal) + O_2 (in air) → CO_2	**Example:** dissolving ammonium nitrate in water.
Writing conventions: $CO(g) + NO_2(g) \rightarrow CO_2(g) + NO(g)\ \ \Delta H = -226\ kJ\cdot mol^{-1}$ $CO(g) + NO_2(g) \rightarrow CO_2(g) + NO(g)\ \Delta H < 0$ $CO(g) + NO_2(g) \rightarrow CO_2(g) + NO(g) + Energy$ $CO(g) + NO_2(g) \rightarrow CO_2(g) + NO(g) + 226\ kJ\cdot mol^{-1}$	Writing conventions: $H_2O(\ell) \rightarrow H_2O(g)\ \ \Delta H = 41\ kJ\cdot mol^{-1}$ $H_2O(\ell) \rightarrow H_2O(g)\ \ \Delta H > 0$ $H_2O(\ell) + Energy \rightarrow H_2O(g)$ $H_2O(\ell) + 41\ kJ\cdot mol^{-1} \rightarrow H_2O(g)$
Graphic representation:  	**Graphic representation:** 

Key to the symbols on the graphs:

A: reactants (for the forward reaction) / products (for the reverse reaction)
B: products (for the forward reaction) / reactants (for the reverse reaction)
C: activated complex (without a catalyst)
D: activated complex (with a catalyst)
E: activation energy for the forward reaction (without a catalyst)
F: activation energy of the forward reaction (with a catalyst)
G: activation energy of the reverse reaction (without a catalyst)
H: activation energy of the reverse reaction (with a catalyst)

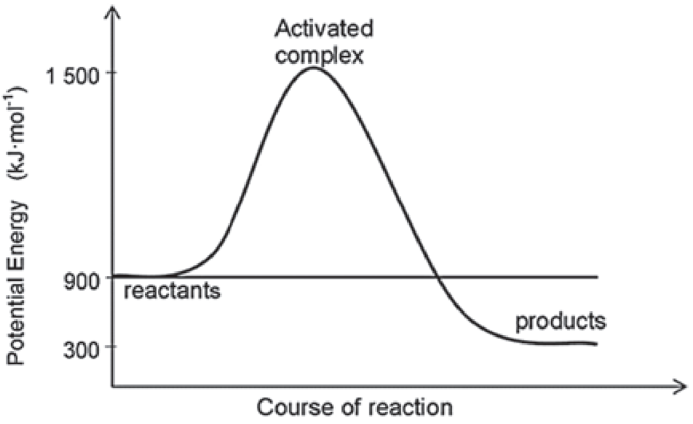
2.6.3 Law of conservation of energy

The release of energy in chemical reactions occurs when the reactants have higher chemical energy than the products. The chemical energy in a substance is a type of potential energy stored within the substance. This stored chemical potential energy is the **heat content** or **enthalpy** of the substance. The collection of substances that is involved in a chemical reaction is referred to as a system and anything else around it is called the **surroundings**. If the enthalpy decreases during a chemical reaction, a corresponding amount of energy must be released to the surroundings. Conversely, if the enthalpy increases during a reaction, a corresponding amount of energy must be absorbed from the surroundings. This is simply the **Law of Conservation of Energy**. Now, to break a chemical bond, requires energy. Some substances need more and some substances need less energy to break the bond – depending on the bond energy (measure of the bond strength of the chemical bond) i.e. potential energy of the bonds of the initial reactants. Some reactants obtain the energy required to break the bonds from the surroundings, which might include the energy that is released when the bonds in the products are formed. To form a bond releases energy; when the bond is formed in the product, the product releases energy, of which some energy is "given back" to break the bonds of the reactants – so they can break! For our purpose it is enough to simply talk about 'the total energy released' when the product is formed in an exothermic reaction is more (entalphy decreases) than the amount of energy required to break the initial reactants' bonds.

e.g. Worked example 1

When there is a limited supply of oxygen, such as in a car which is not tuned properly, octane burns incompletely to produce carbon monoxide (amongst other emissions).

The graph alongside represents the energy changes that take place during this reaction and the balanced chemical equation is given:



$$2C_8H_{18}(\ell) + 17O_2(g) \rightleftharpoons 16CO(g) + 18H_2O(\ell) \qquad \Delta H < 0$$

1. What is the activation energy for the forward reaction?
2. What is the activation energy of the reverse reaction?
3. What is the heat of reaction for this reaction?

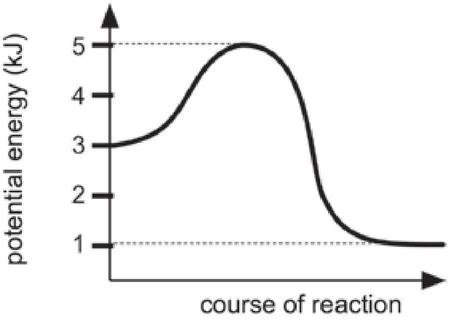
4. Is this reaction exothermic or endothermic? Motivate.

5. Use the chemical equation above and give a reason why vehicles with incorrectly tuned engines are a health hazard.

6. Part of the action of catalytic converters is to speed up the complete oxidation of carbon monoxide (CO) and petrol (C_8H_{18}) from incorrectly tuned engines to CO_2.

Why should people support legislation that makes catalytic converters a necessary component of exhaust systems of automobiles?

7. The graph below represents the relationship between potential energy and course of a reaction for a certain chemical reaction.



The activation energy of this reaction is:

A 1kJ

B 2kJ

C 3kJ

D 4kJ

Solutions

1. $E_{Activated} = E_{Activated\ Complex} - E_{reactants} = 1\,500 - 900$
$= 600\ kJ{\cdot}mol^{-1}$

2. $E_{Activated} = E_{Activated\ Complex} - E_{reactants} = 1\,500 - 300$
$= 1\,200\ kJ{\cdot}mol^{-1}$

3. $\Delta H = E_{products} - E_{reactants} = 300 - 900 = -600\ kJ{\cdot}mol^{-1}$

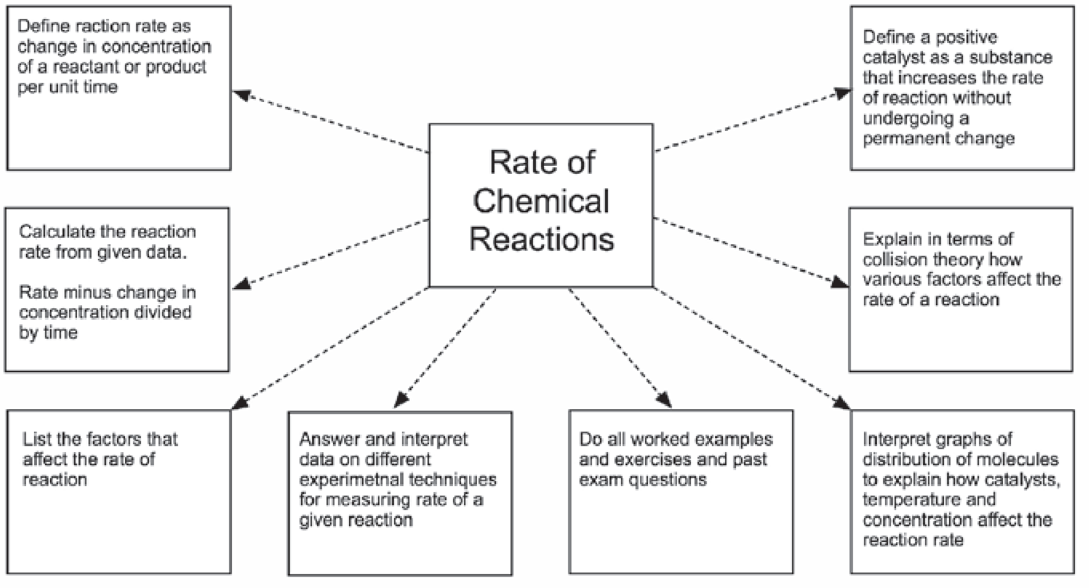
4. The reaction is exothermic because ΔH is negative.

5. CO is poisonous.

6. Catalytic converters ensure conversion of products to CO_2 so that the danger of CO poisoning is minimised.

7. $E_{activated} = E_{complex} - E_{reagents}$
$= 5 - 3 = 2$
(B): 2kJ

2.7 Rates of reactions



Rate of Chemical Reactions

Define raction rate as change in concentration of a reactant or product per unit time

Define a positive catalyst as a substance that increases the rate of reaction without undergoing a permanent change

Calculate the reaction rate from given data.

Rate minus change in concentration divided by time

Explain in terms of collision theory how various factors affect the rate of a reaction

List the factors that affect the rate of reaction

Answer and interpret data on different experimetnal techniques for measuring rate of a given reaction

Do all worked examples and exercises and past exam questions

Interpret graphs of distribution of molecules to explain how catalysts, temperature and concentration affect the reaction rate

NB

DEFINITION

The rate of a reaction (**reaction rate**) is the change in concentration of reactants or products per unit time.

In symbols:

$$rr = \frac{\Delta[\text{reactants}]}{\Delta t}$$

OR

$$rr = \frac{\Delta[\text{products}]}{\Delta t}$$

Where:

rr : reaction rate ($mol{\cdot}dm^{-3}{\cdot}s^{-1}$)

Δ[reactants] : change in concentration of reactants ($mol{\cdot}dm^{-3}$)

Δ[products] : change in concentration of products ($mol{\cdot}dm^{-3}$)

Δt : change in time (s)

Activity 1

Consider the reaction

$H_2 + I_2 \rightarrow 2HI$ ($\Delta H < 0$)

1. Is this reaction exothermic or endothermic? (1)
2. State a reason for your answer in 1.1. (1)
3. How does energy of the products compare to that of the reactants? (2)

[4]

Solutions

1. Exothermic (reaction). ✓ (1)
2. $\Delta H < 0$ ✓ (1)
3. The energy of the products is less than ✓ that of the reactants. ✓ (2)

[4]

2.8 Factors which affect reaction rate

The rate at which a chemical reaction takes place depends on the reaction conditions. In industry it is important to make sure that the chemical reactions take place at a rate as high as is safely and economically possible.

The 5 factors that affect the rate of a chemical reaction are:	
FACTOR	**EFFECT ON REACTION RATE**
• The nature of the reactants.	• The higher the reactivity of a reactant, the higher the reaction rate (E.g. reactive metals like Mg react faster than metals like Cu). • Inorganic reactions are faster than organic reactions.
• The concentration of the reactants for gases (g) and aqueous (aq) solutions. • The pressure of gas (g) reactants.	• The higher the concentration of a reactant, the higher the reaction rate. • The higher the pressure of a gas reactant, the higher its concentration and the higher the reaction rate.
• The surface area (state of division) of solid reactants (marked (s)).	• A powder has a large surface area. • Lumps and strips have a smaller surface area. • The larger the surface area, the higher the reaction rate.
• The temperature of the reaction system.	• The higher the temperature of the reaction system, the higher the reaction rate. However, if the temperature goes too high, a different reaction might take place (e.g. the reactants might burn up instead of reacting as expected).
• The presence of a suitable catalyst.	• A suitable positive catalyst increases the reaction rate.

2.9 The Collision Theory

The **collision theory** is applied to explain **how** these factors affect the rates of chemical reactions.

- According to the Kinetic Molecular Theory, the particles in a reaction mixture are in a state of **perpetual random motion** and therefore **collide** with one another.
- Only **effective collisions** between reactant particles lead to chemical reactions and the formation of new products.

An **effective collision** between reactant particles takes place if:
- the colliding particles have **enough kinetic energy** to form an activated complex i.e. if the energy of the colliding particles is equal to or more than the activation energy for the reaction AND
- the particles are **correctly orientated** when they collide.

hint

REMEMBER

If a reaction is fast, it has a short reaction time but a high reaction rate.

The rate of a chemical reaction depends on the number of effective collisions between the reactant particles per second; the number of collisions for which the particles have energy more than or equal to the activation energy and on the number of collisions that are correctly orientated. Hence, smaller particles e.g. dust or gas, react more violently than larger particles, e.g. crystals, since the reactants can mix more thoroughly and therefore increase the number of effective collisions. Compare, for example, the explosive quality of gunpowder to say, lumps of solid ingredients like sulphur, potassium nitrate, and coal.

hint **REMEMBER**

The more effective collisions that occur between the reactant particles per second, the faster the reaction will occur.

In symbols:

reaction rate $\propto$ (number of effective collisions per unit time)

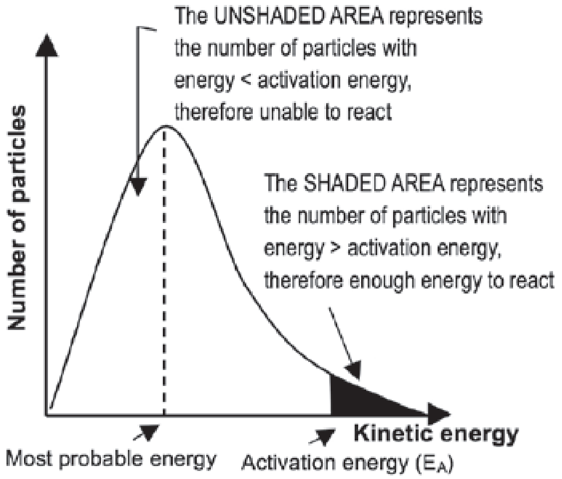
$\propto$ (particles with correct orientation)

$\propto$ (particles with sufficient (enough) E_k)

2.10 The mechanism of reactions

The Maxwell-Boltzmann distribution diagram shown below shows the distribution of the kinetic energy of the particles in a reaction system. The distribution of the kinetic energies of the reactant particles is used to explain the reaction rate in the system.

- The graph shows the number of particles (on the vertical axis) versus their kinetic energy (on the horizontal axis).



- The curve always passes through the origin — this means that no molecules have zero kinetic energy since all molecules are in motion — unless they reach the temperature of 0 K or –273˚C.
- The curve does not touch the x-axis at high kinetic energy i.e. there are always some molecules with very high kinetic energy.
- The energy value that corresponds with the **peak** of the curve represents the **most probable energy.**
- The **area** below the curve is equal to the **total number of molecules** in the system.

- The **shaded area** below the curve and to the **right** of the activation energy, equals the number of reactant particles that have enough energy to collide effectively and therefore **can react.**
- The area below the curve and to the **left** of the activation energy, equals the number of reactant particles that can't collide effectively and therefore **can't react.**
- If the **shaded area is bigger**, there are **more particles** that can **collide effectively** and the **reaction rate** is higher.

a) The effect of increasing the temperature of the reaction mixture

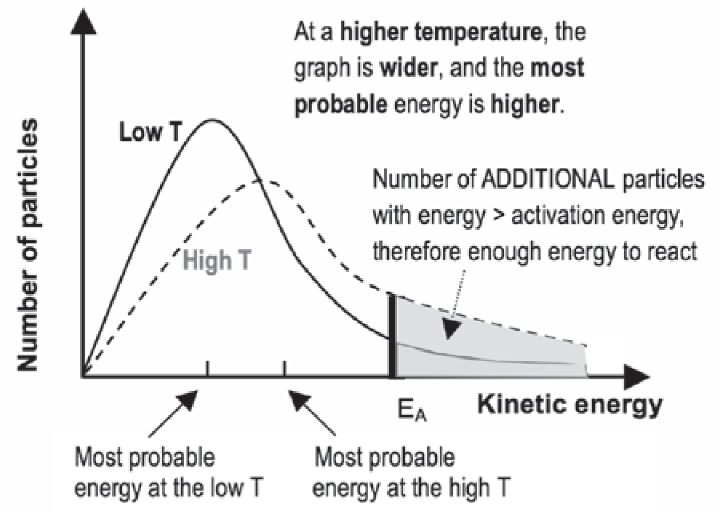
If the **temperature increases**:

- The particles in the sample have a **higher average kinetic energy** and the **most probable energy** is **higher** than at a low temperature.
- The graph is **wider** and the peak is **lower.**
- The total number of particles is the same, so the **total area** below the graph is the **same.**
- **More** particles have kinetic energy > than the activation energy (the shaded area is bigger)
- ∴ **more effective collisions** take place **per second** and
- the collisions are **more energetic**
- ∴ the **reaction rate increases.**

NB

DEFINITION

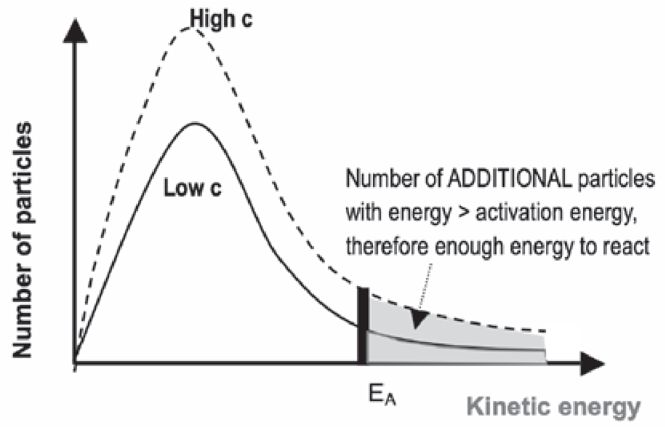
Temperature is a measure of the average kinetic energy of the particles in a sample.



b) The effect of increasing the concentration of the reactants

If the **concentration** of the reactants **increases**:

- The particles in the sample have the same **average kinetic energy** and the **most probable energy** is **the same** ∴ the graph has the same curve/shape
- The graph is **higher** as there are now more particles per unit volume;
- The total number of particles is greater, so the **total area** below the graph is **bigger.**
- **More** particles have energy > than the activation energy (the shaded area is bigger)
- ∴ **more effective collisions** take place **per second**
- ∴ the **reaction rate increases.**



c) The effect of adding a catalyst

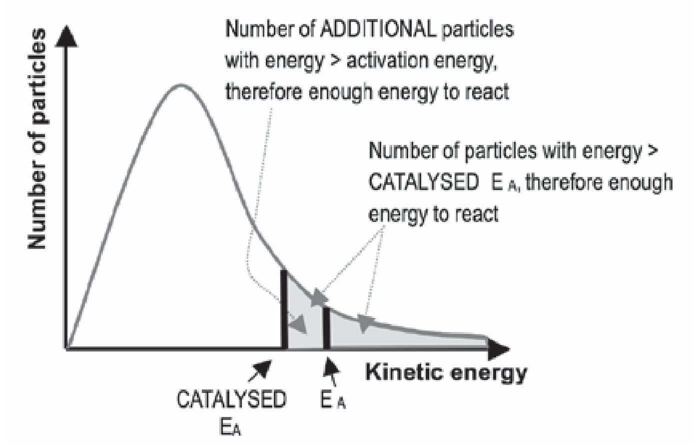
Adding a **suitable positive catalyst:**

- **decreases** the **activation energy** needed to change the reactants into an activated complex so
- **more** particles have **enough energy** to form an activated complex
- ∴ the **number** of possible **effective collisions per second increases** and
- ∴ the reaction **rate increases.**

hint **REMEMBER**

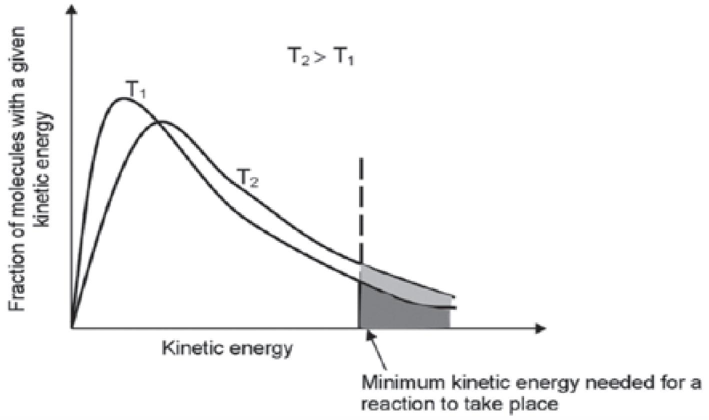
When adding a suitable catalyst:

- the total number of reactant particles stays constant and
- the average kinetic energy of the reactant particles remains constant as the temperature does not change.



e.g. Worked example 2

Consider the following Maxwell-Boltzman distribution diagram for a chemical reaction system and answer the questions that follow.



1. Did all the molecules have the same kinetic energy at low temperature? Motivate your answer.
2. What does the shaded area to the right of the vertical line represent?
3. If a catalyst is added to the reactants, will it cause the vertical dotted line to move to the left or right? Explain your answer.

Solutions

1. No. Together they will have the same average kinetic energy, but each molecule's kinetic energy is determined by its mass and the square of its own average speed (remember, $E_k = \frac{1}{2} mv^2$).
2. It indicates the % of molecules which will have more energy than the activation energy at that temperature. In other words, the % of molecules which are capable of colliding effectively and reacting. At the higher temperature, there is a higher % of molecules which are capable of colliding effectively (bigger area below the graph).
3. To the left. The activation energy of the reaction is decreased by adding a suitable catalyst. The line thus shifts to the left. It implies that at both the low and the high temperatures there will now be a greater % of molecules available for effective collisions.

2.11 Measuring rates of reactions

We measure the rate of a reaction by studying the rate at which (how fast) the products appear or the rate at which the reactants are used up while the reaction takes place.

Experimental techniques for measuring the rate of a given reaction include the following:

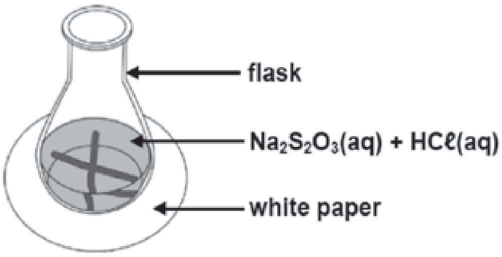
- measuring of gas volumes produced,
- turbidity (e.g. precipitate formation),
- change of colour and
- the change of the mass of the reaction vessel if a gaseous product is allowed to escape from it.

Experimental Technique 1: Measuring turbidity

$$Na_2S_2O_3(aq) + 2HC\ell(aq) \rightarrow 2NaC\ell(aq) + H_2O(\ell) + SO_2(g) + S(s)$$

Sodium thiosulphate reacts with diluted hydrochloric acid to form a yellow sulphur precipitate. The formation of the precipitate can be used to measure the reaction rate.

Apparatus:



DEFINITIONS

Turbidity is the cloudiness or haziness of a fluid (liquid or solution) that is caused by particles in the fluid which prevent light from passing through the liquid.

Opaque: not transparent, does not allow light to pass through.

Method:

1. Draw a black cross on a piece of paper.
2. Add an exact volume of $Na_2S_2O_3$ to a conical flask and place it on the cross.
3. Quickly add $HC\ell$ to the solution and start the stopwatch.
4. Swirl (turn) the flask carefully and allow the reaction to continue until the black cross can no longer be seen.
5. Record the time.

In this experiment, the concentration of the $HC\ell(aq)$ and $Na_2S_2O_3(aq)$ can be changed, keeping the temperature constant OR In another experiment, the temperature can be changed, but keeping the concentrations constant. The time it takes for the solution to become **opaque** is a measure of the reaction rate.

Experimental Technique 2: Measuring the volume of a gas product

Consider the following reactions:

$Mg(s) + 2HC\ell(aq) \rightarrow MgC\ell_2(aq) + H_2(g)$ OR

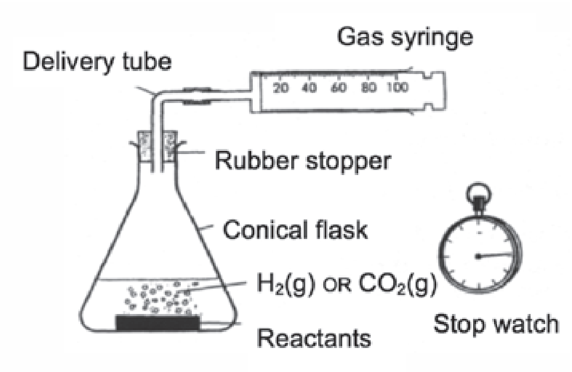
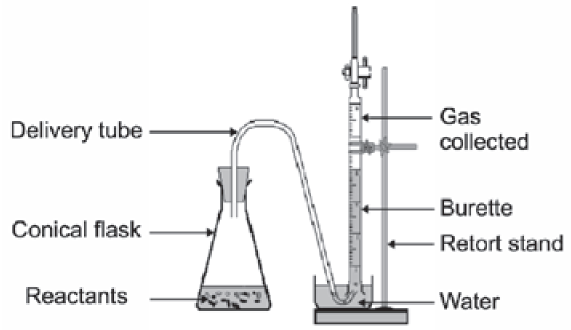
$CaCO_3(s) + 2HC\ell(aq) \rightarrow CaC\ell_2(aq) + H_2O(\ell) + CO_2(g)$ OR

$$2KC\ell O_3(s) \xrightarrow{MnO_2(s)} 2\ KC\ell(s) + 3O_2(g)$$

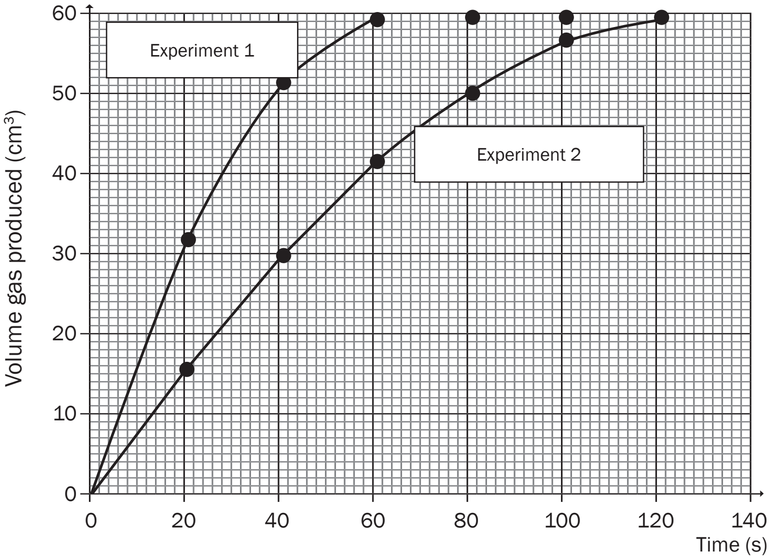
(The catalysed decomposition of potassium chlorate)

1. The rate of the reaction is determined by measuring the volume of the gas produced (the dependent variable) in specific time intervals (the independent variable). If you can't recall what the terms "independent" and "dependent variables" mean, see the introduction section of this book.
2. The gas is collected in a graduated gas syringe or by the downward displacement of water in a burette. The volume of the gas produced can be determined accurately.
3. The stopwatch is started when the reactants are added and stopped when no new bubbles form – i.e. when the volume of gas produced stays constant.

Apparatus:

Measuring volume with a gas syringe:	Measuring volume by the downward displacement of water
	

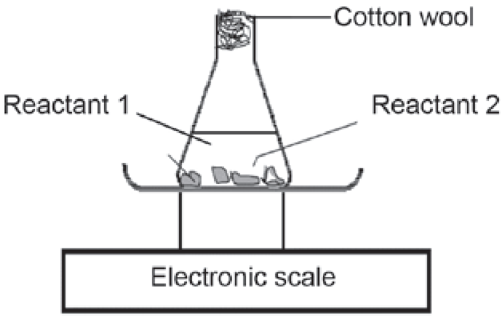
<u>Graph of volume of gas produced vs. time</u>



Experimental Technique 3: Measuring the total mass of reactants and the mass loss:

Consider the same reactions as used in Technique 2.

Apparatus:

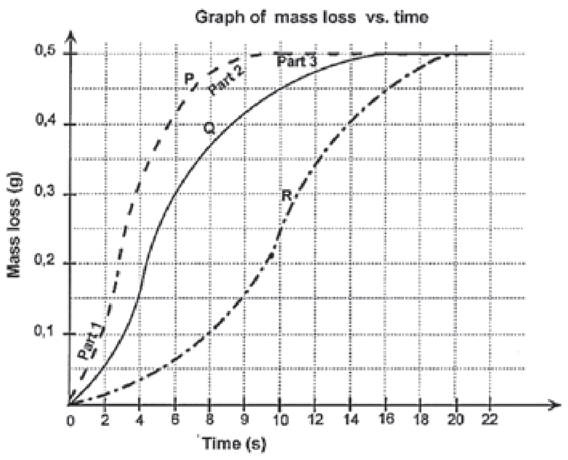


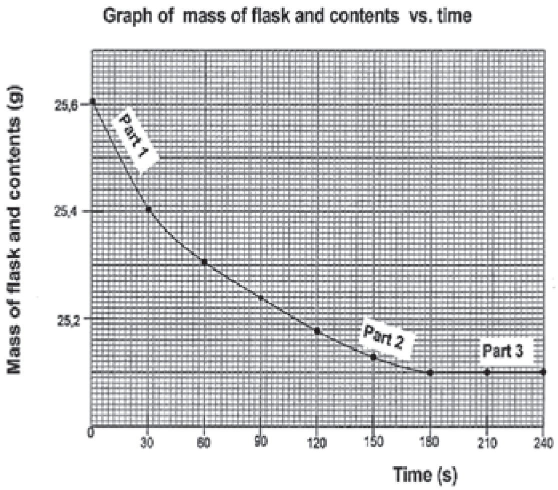
Method:

- The rate of the reaction is determined by measuring the mass of the gas produced (the dependent variable) in specific time intervals (the independent variable).
- The reactants are added to the flask and the mouth of the flask is plugged with some cotton wool.
- The mass of the reaction system (the reactants, flask and cotton wool) is recorded at the start of the experiment and the stop watch is started.
- The gas that is produced passes through the cotton wool plug and escapes from the system, so the mass (the reading on the scale) decreases.
- The mass of the system is recorded at regular time intervals e.g. every 30 seconds.
- The stopwatch is stopped when no new bubbles form – i.e. when the mass reading on the scale stays constant.
- The results are used to plot a graph of: mass of the flask and contents versus time OR mass loss (mass of gas escaped) versus time.

hint

The mouth of the flask is plugged with cotton wool because it is porous and allows the gas to escape from the reaction system but prevents liquid spray that forms during the reaction, from escaping.





hint

- The **gradients** of the graphs indicate the rates of the reactions.
- The **steeper (more vertical)** the gradient of the graph, the **higher** the reaction rate, because more happens in less time.

Limiting reactant: The reactant that is used up during a chemical reaction – all of the reactant reacts.

Excess reactant: The reactant that is not all used up during a chemical reaction – there is always some of this reactant left in the reaction system once the reaction has stopped.

Interpreting the graphs that use Techniques 2 and 3:

There are three time intervals shown in the graphs:

Stage in the reaction	Explanation
Part 1 of both graphs • has the biggest slope (gradient) so • the reaction rate is the highest.	• The concentration of the reactants (usually the acid) is the highest and • the reaction surface area (the solid), is the biggest therefore • the number of effective collisions taking place will be high • so the reaction rate is high and • the volume of gas produced per second is high.
Part 2 shows • a gradual decrease in the slope so • the reaction rate decreases gradually.	• The reactants are being used to produce the products so • the concentration of the acid is decreasing and • the reaction surface area of the solid reactant is decreasing therefore • the number of effective collisions taking place decreases and • the reaction rate decreases and • the volume of gas produced per second will decrease so that • fewer gas molecules escape per second and the rate at which the mass changes, decreases.
Part 3 is where • each graph ends horizontally • which means that the reaction is complete.	When the **limiting reactant** has been **used up** (all of it has reacted) • the reaction is complete and • no more products are produced so • no more gas escapes from the system and • the mass remains constant.

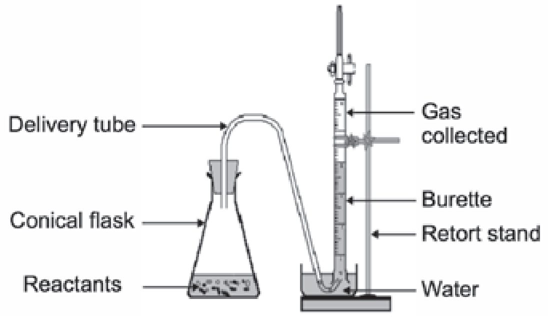
e.g. Worked example 3

A group of learners use the reaction between hydrochloric acid and magnesium powder to investigate one of the factors that influence the rate of a chemical reaction.

The reaction that takes place is:

$Mg(s) + 2HC\ell(aq) \rightarrow MgC\ell_2(aq) + H_2(g)$

The learners use the apparatus and follow the method shown below to conduct the investigation.



<u>Method for Experiment 1</u>:

Step 1: Place a spatula (spoon) of magnesium powder in a conical flask and add 50 cm^3 $HC\ell(aq)$ of known concentration.

Step 2: Simultaneously start the stopwatch and close the flask with the rubber stopper containing the delivery tube.

Step 3: Measure the volume of the $H_2(g)$ formed in time intervals of 20 seconds.

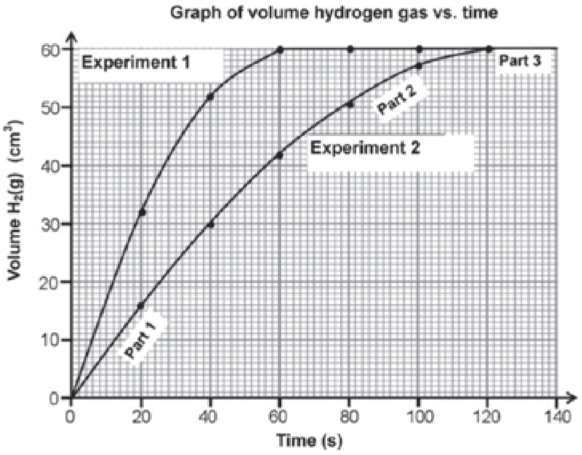
<u>Method for Experiment 2</u>:

Repeat steps 1 to 3 above, but use only 25 cm^3 of the same $HC\ell(aq)$ diluted to 50 cm^3 with distilled water.

1. How does the concentration of the acid used in Experiment 2 differ from the concentration of the acid used in Experiment 1? Write down only **greater than**, **lower than** or **equal to**.
2. Write down a hypothesis for this investigation.
3. Why should the learners ensure that equal amounts of magnesium powder are used in each of the two experiments?
4. The learners use an excess of $HC\ell(aq)$ for the two experiments. What meaning does the term ‘excess’ have in this situation? Give a reason why the excess $HC\ell(aq)$ will not influence the results.
5. If the Mg powder used in Experiment 1 was impure with particles of dirt in between, describe and explain how the shape of the graph would be influenced.

e.g. Worked example 3 (continued)

6. After completing the investigation, the learners represent the results obtained during each experiment on the graph below.



Write down the volume of hydrogen gas formed during the first minute in:

6.1 Experiment 1

6.2 Experiment 2

7. Which one of the experiments took place at the faster rate? Refer to the shape of the curves to motivate your answer.

8. Give a reason why the final volume of gas produced is the same in both experiments.

9. What conclusion can the learners draw from the results obtained?

10. How will an increase in the temperature influence the following? Write down **increases**, **decreases** or **remains the same**.

10.1 The final volume of gas obtained in each experiment

10.2 The volume of gas obtained in each experiment after 40 s

11. Why do both graphs form horizontal lines respectively at t = 60 s and t = 120 s?

12. Give two reasons why the rate of formation of hydrogen gas is lower at t = 50 s than at t = 20 s.

13. Determine the rate of formation of hydrogen gas in Experiment 2 at t = 20 s.

14. In a third experiment, Experiment 3, half the mass of magnesium was used in powder form.

14.1 How will this change influence the final volume of gas compared to Experiment 1 and 2?

14.2 Explain your answer.

Solutions

1. Smaller than or lower than (not ‘less’ or ‘diluted’).
2. Possible answer:
   If the concentration of the reactants in a chemical reaction increases, the reaction rate will increase.
3. The mass of the Mg is a controlled variable to ensure a fair test. There is only one independent variable which changes from the one experiment to the next i.e. the concentration of the acid.

hint

The hypothesis must refer to the relationship between dependent and independent variables. It must be a statement that can be proved to be correct or incorrect, it is a prediction based on (prior) knowledge.

Worked example 3 (continued)

4. ‘Excess’ means that there is more than enough hydrochloric acid for the reaction to take place. When the reaction is complete, all the Mg will have reacted, but some of the acid will be left over. The Mg is the limiting reactant and when it has all reacted, the reaction will stop.

5. The gradient would be less steep, indicating that the reaction rate is lower. Because the reaction surface area of the magnesium is smaller, fewer particles are available to collide, thus fewer effective collisions will occur. The final volume of hydrogen gas formed will be less, because the magnesium is the limiting reagent and a smaller mass of pure magnesium was reacting, because of the dirt in between.

6.1 60 cm^3

6.2 42 cm^3

7. Experiment 1.The gradient or slope (of the tangent to the graph) is steeper.

8. The mass of Mg used in both experiments was the same. Mg is the limiting reagent and the limiting reagent determines the yield of the products.

9. If the concentration of the reactants in a chemical reaction increases, the reaction rate will increase.

10.1 Remains the same.

10.2 Increases.

11. The horizontal lines mean that the reactions are complete; all the magnesium has reacted with the excess $HC\ell$.
Experiment 1 reaches completion first because of the higher concentration of $HC\ell$ (more particles per unit volume to react), so more effective collisions will occur and the reaction rate is higher.

12. At 50 s the concentration of $HC\ell$ has already decreased notably, and there is much less magnesium left, with a smaller exposed surface area. Thus the collisions are less effective and the reaction rate is lower.

13. Reaction rate = slope (gradient)

$$= \frac{\Delta y}{\Delta x}$$

$$= \frac{\Delta \text{volume } H_2}{\Delta \text{time}}$$

$$= \frac{(16-0)}{(20-0)}$$

$$= \frac{0{,}8 \text{ cm}^3}{\text{s}}$$

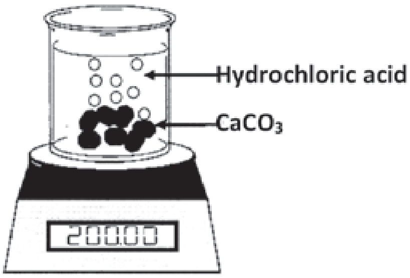
14.1 The final volume of hydrogen gas in Experiment 3 will be half the volume of hydrogen gas produced in Experiment 1 and 2.

14.2 Mg is the limiting reagent which determines the yield.
From the balanced equation: 1 mol Mg(s) produces 1 mol $H_2(g)$, thus $\frac{1}{2}$ mol Mg(s) produces $\frac{1}{2}$ mol $H_2(g)$

e.g. Worked example 4

A certain mass of calcium carbonate chunks is added to a hydrochloric acid solution in an open beaker on a scale as shown here. The equation for the reaction is as follows:

$$CaCO_3(s) + 2HC\ell(aq) \rightarrow CaC\ell_2(aq) + H_2O(\ell) + CO_2(g)$$

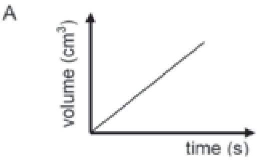


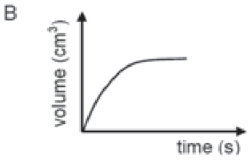
$CO_2(g)$ is allowed to escape from the beaker. The data in the table below was obtained for a time interval of 8 minutes.

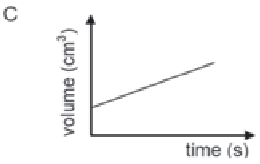
Time (min)	Mass of beaker and contents (g)
0	200,00
1	197,50
2	195,45
3	193,55
4	191,70
5	189,90
6	188,15
7	186,45
8	184,80

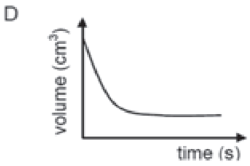
1. Explain the term 'reaction rate'.
2. Calculate the change in the mass of the beaker and its contents during the 8 minutes.
3. Use your answer to Question 2 to show that the average reaction rate during the 8 minutes is 1,9 $g{\cdot}min^{-1}$.
4. Calculate the mass of calcium carbonate which reacted during the 8 minutes.
5. "The use of the beaker in this experiment influences the readings and therefore the calculation of the rate of the reaction and mass of the CO_2 formed". Explain this statement and suggest TWO ways to rectify this experimental problem and to make this a reasonable test.
6. One of the products formed in a chemical reaction is a gas. Which ONE of the following graphs of volume versus time best represents the formation of this gas until the reactants are used up?

e.g. Worked example 4 (continued)









Solutions

1. The change in amount/mass/volume/concentration of products formed per unit time.
   OR
   The change in amount/mass/volume/concentration of reactants used per unit time.
2. Change in mass = 200 – 184,8 = 15,2 g
3. Rate of reaction = $\frac{\text{change in mass}}{\text{time taken}} = \frac{15,2}{8}$
   $= 1,9\ \text{g} \times \text{min}^{-1}\ CO_2$ produced
4. mol CO_2 formed:
   $M(CO_2) = 44\ \text{gmol}^{-1}$ and $M(CaCO_3) = 100\ \text{g·mol}^{-1}$ (for all the calculating molar masses)
   Mass CO_2 produced = $\Delta m = 200 - 184,8 = 15,2$ g
   ∴ mol CO_2 produced:
   $n = \frac{m}{M} = \frac{15,2}{44} = 0,35\ \text{mol}\ CO_2$
   From the balanced equation:
   1 mol $CaCO_3$: 1 mol CO_2
   ∴ 0,35 mol $CaCO_3$: 0,35 mol CO_2
   So the mass $CaCO_3$ that reacted:
   $n = \frac{m}{M} \therefore 0,35 = \frac{m}{100} \therefore m = (0,35)(100) = 35$ g
5. Use a conical flask instead of a beaker and plug the mouth of the flask with cotton wool. The plug prevents the acid spray and water vapour from escaping from the flask. The CO_2 gas can escape through the cotton wool. Escaping vapour from the beaker originally used will affect the change in mass readings and thus cause inaccurate measurement of the rate of reaction.

   The calcium carbonate must be placed in a small test tube that fits into the flask. When the flask is lightly shaken, the test tube falls over and the acid reacts. This also prevents acid spray and water vapour from splashing out. Ensure that the stop watch is started when the two reactants come into contact and that it is stopped as soon as all the Mg has reacted.
6. B.

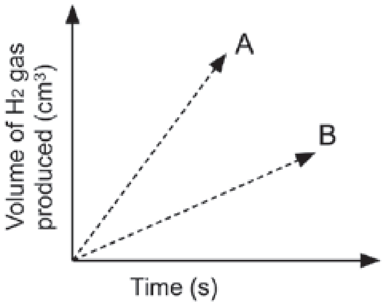
NOTE:
In the calculation, n = 0,3454 was rounded off to 0,35 so that:
Mass = m(100) = 34,54 g

Activity 2

1. Hydrogen gas may be prepared by the reaction of zinc metal with dilute hydrochloric acid. The chemical equation for this reaction is :

$$Zn(s) + 2HC\ell(aq) \rightarrow ZnC\ell_2(aq) + H_2(g) \quad \Delta H < 0$$

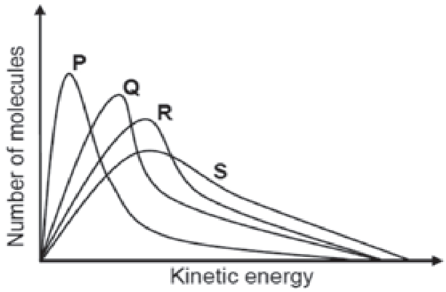
A learner determined the volume of the hydrogen produced with time at two temperatures and two grades of Zn; powder and solid pellets. He used the same mass of zinc and the same volume and concentration of hydrochloric acid for each experiment and plotted the following graphs.



Which combination of temperature and surface area will be represented by A? (2)

	Temperature	State of Zn
A	High	Pellets
B	High	Powder
C	Low	Pellets
C	Low	Powder

2. The graphs below represent the molecular distribution for a reaction at different temperatures.



Which ONE of the graphs above represents the reaction at the highest temperature? (2)

A P
B Q
C R
D S **[4]**

Solutions

1. B ✓✓ (2)
2. D ✓✓ (2)
[4]

Activity 3

Give ONE term for each of the following descriptions by choosing a term from the list above. Write down only the term next to the question number.

Surface Area; Catalyst; Elastic collision; Effective collision; Activated complex; Concentration; Temperature; Heat of reaction; Activation energy.

1. A chemical substance that speeds up the rate of a chemical reaction by lowering the net activation energy. (1)
2. A collision in which the reacting particles have sufficient kinetic energy and correct orientation. (1)
3. The factor responsible for increasing the rate of a reaction when a solid is broken up into smaller pieces. (1)
4. The temporary unstable state that is formed during the course of a chemical reaction. (1)
5. A measure of the average kinetic energy of the particles in a gas. (1)
6. The net amount of energy released or absorbed during a chemical reaction. (1)

[6]

Solutions

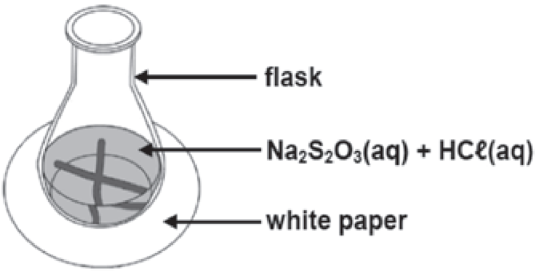
1. Catalyst. ✓ (1)
2. Effective collision. ✓ (1)
3. Surface Area. ✓ (1)
4. Activated complex. ✓ (1)
5. Temperature. ✓ (1)
6. Heat of reaction. ✓ (1)

[6]

e.g. Worked example 5

Learners use hydrochloric acid and a sodium thiosulphate ($Na_2S_2O_3$) solution to investigate the relationship between rate of reaction and temperature. The reaction that takes place is represented by the following equation:

$$Na_2S_2O_3(aq) + 2HC\ell(aq) \rightarrow 2NaC\ell(aq) + S(s) + H_2O(\ell) + SO_2(g)$$

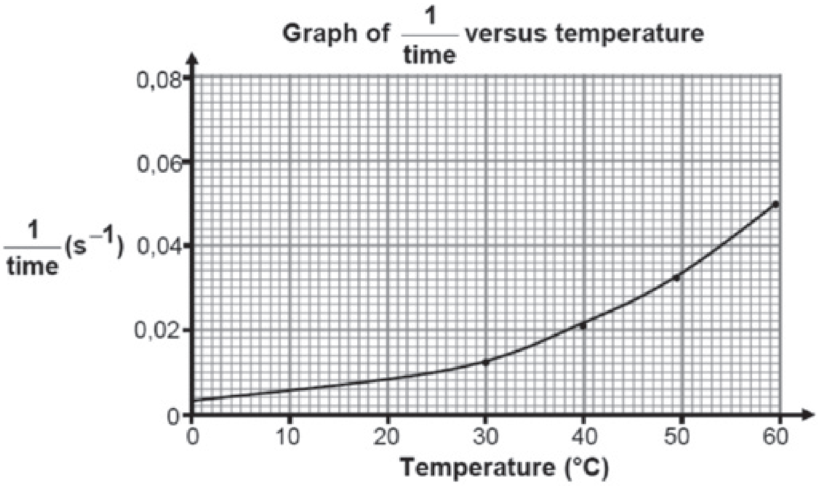


e.g. Worked example 5 (continued)

They add 5 cm^3 2 $mol·dm^{-3}$ hydrochloric acid solution to 50 cm^3 sodium thiosulphate solution in a flask placed over a cross drawn on a sheet of a white paper, as shown in the diagram below. The temperature of the mixture is 30°.

They measure the time it takes for the cross to become invisible. The experiment is repeated with the temperature of the mixture at 40˚C, 50˚C and 60˚C.

1. Write down:
   1.1 The possible hypothesis for this investigation.
   1.2 NAME or FORMULA of the product that requires the need to work in a well-ventilated room.
   1.3 NAME or FORMULA of the product that causes the cross to become invisible.
2. Apart from the volume of the reactants, state ONE other variable that must be kept constant during this investigation.
3. Why is it advisable that the same learner observes the time that it takes for the cross to become invisible?
4. What experimental technique was used to measure the rate of reaction in this investigation?
5. The shown graph below is obtained from the results.



   5.1 What is the relationship represented by $\frac{1}{time}$ on the vertical axis?
   5.2 What conclusion can be drawn from the results obtained?
6. The learners collected washed and dried sulphur. They weighed the dry sulphur and its mass was 0,12g. Calculate the percentage yield of sulphur.

Solutions

1.1 E.g. The <u>rate of reaction</u> <u>increase</u> with <u>increase</u> in <u>temperature</u>.
1.2 Sulphur dioxide/SO_2.
1.3 Sulphur/S.

2. Concentration of reactants ($HC\ell$ and $Na_2S_2O_3$).

3. Different people have different sight abilities/reaction times. (To ensure that the results are reliable).

4. Turbidity.
5.1 Reaction rate.
5.2 The reaction rate increases with increase in temperature.

6. $Na_2S_2O_3(aq) + 2HC\ell(aq) \rightarrow 2NaC\ell(aq) + S(s) + H_2O(\ell) + SO_2(g)$

$n_{(HC\ell)} = CV$

$n_{(HC\ell)} = (2)(0{,}005)$

$n_{(HC\ell)} = 0{,}01 \text{ mol}$

$2\ n_{(HC\ell)} = 1\ n(S)$

$n(S) = 0{,}005 \text{ mol}$

$n = \frac{m}{M}$

$0{,}005 = \frac{m}{32}$

$m(s) = 0{,}16 \text{ g}$

$\text{Percentage Yield} = \left(\frac{0{,}12}{0{,}16}\right) \times 100$

$\text{Percentage Yield} = 75\ (\%)$

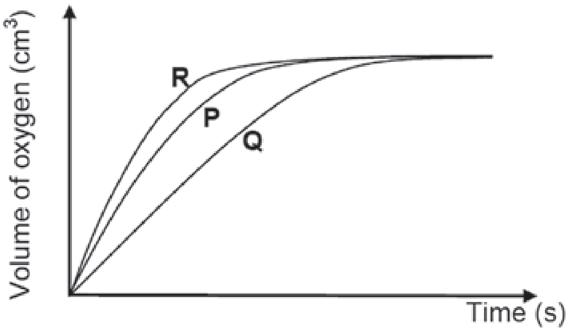
e.g. Worked example 6

A hydrogen peroxide solution dissociates slowly at room temperature according to the following equation:

$$2H_2O_2(aq) \rightarrow 2H_2O(\ell) + O_2(g)$$

During an investigation, learners compare the effectiveness of three different catalysts on rate of decomposition of hydrogen peroxide. They place EQUAL AMOUNTS of sufficient hydrogen peroxide into three separate containers. They add EQUAL AMOUNTS of THREE catalyst, P, Q and R, to the hydrogen peroxide in the three containers respectively and measure the rate at which oxygen gas is produced.

1. For this investigation, write down the:
   - **1.1** Independent variable.
   - **1.2** Dependent variable.



2. Which catalyst is the most effective? Give a reason for your answer.

Worked example 6 (continued)

3. Fully explain, by referring to the collision theory, how the catalyst increases the rate of reaction.

   In another experiment, the learners obtain the following results for the decomposition of hydrogen peroxide:

TIME(s)	H_2O_2 CONCENTRATED ($mol{\cdot}dm^{-3}$)
0	0,0200
200	0,0160
400	0,0131
600	0,0106
800	0,0086

4. Calculate the AVERAGE rate of decomposition (in $mol{\cdot}dm^{-3}$) of $H_2O_2(aq)$ in the first 400s.
5. Will the rate of decomposition at 600 s be GREATER THAN, LESS THAN or EQUAL TO the rate calculated in QUESTION 4.4? Give a reason for the answer.
6. Calculate the mass of oxygen produced in the first 600 s if the 50 cm^3 of hydrogen peroxide decomposes in this time interval.

Solutions

1.1 (Type of) catalyst.

1.2 Rate (of reaction).

2. R. It has the fastest reaction rate./ steepest gradient or slope./ Produces oxygen in a fastest or in shorter time. (Any of these reasons)

3. A catalyst provides an alternative reaction path with a lower activation energy.

More molecules have sufficient/enough kinetic energy.

OR

More molecules have kinetic energy equal to or greater than activation energy.

More effective collisions per unit time./Rate of effective collisions increases.

4. Average rate $= \frac{\Delta[H_2O_2]}{\Delta t}$

$$= \frac{(0{,}0131 - 0{,}020)}{400\text{-}0}$$

$$= 1{,}73 \times 10^{-5}\ mol{\cdot}dm^{-3}{\cdot}s^{-1}$$

5. Less than. The concentration of hydrogen peroxide is decreasing as the reaction proceeds.

6. **OPTION 1**

$c = \frac{n}{V}$

$(0{,}0200 - 0{,}0106) = \frac{n}{(50 \times 10^{-3})}$

$n(O_2) = \frac{1}{2} n(H_2O_2) = \frac{1}{2} (4{,}7 \times 10^{-4})$

$n(O_2) = 2{,}35 \times 10^{-4}$ mol

$n = \frac{m}{M}$

$2{,}35 \times 10^{-4} \text{ mol} = \frac{m}{32}$

$m(O_2) = 0{,}008\text{g} \approx 0{,}01\text{g}$

OPTION 2

$\Delta c(H_2O_2) = (0{,}0200 - 0{,}0106) = 0{,}0094$

$\Delta c(O_2) = \frac{1}{2} n(H_2O_2) = \frac{1}{2} (0{,}0094)$

$= 4{,}7 \times 10^{-4}$

$c = \frac{m}{MV}$

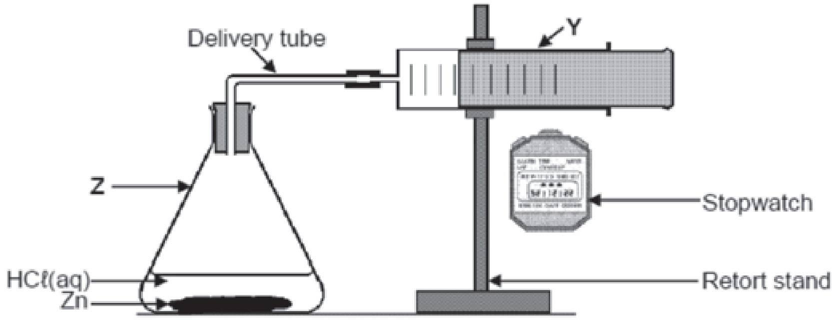
$m(O_2) = cMV$

$m(O_2) = (0{,}0047)(3)(50 \times 10^{-3})$

$m(O_2) = 0{,}008\text{g} \approx 0{,}01\text{g}$

Worked example 7

The apparatus shown below is used to investigate the rate at which hydrogen gas produced when a 6,5 g of zinc reacts with 30 ml of 1mol·dm^{-3} HCℓ.



The reaction that takes place is represented by the following balanced equation:

$$2HC\ell(aq) + Zn(s) \rightarrow ZnC\ell(aq) + H_2(g)$$

1. What experimental method is used to measure the reaction rate in this experiment?
2. What other experimental method can be used to measure the (reaction) rate for this reaction?
3. Determine the limiting reagent (using calculations).
4. Write down:
   - **4.1** The name of the flask labelled Z.
   - **4.2** ONE function of the item of apparatus labelled Y in THIS investigation.

Worked example 7 (continued)

Two experiments are conducted using apparatus above. The conditions for each experiment are given below.

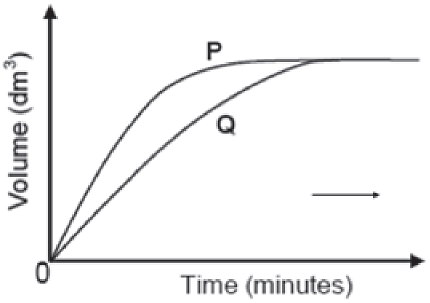
	Experiment 1	Experiment 2
Zinc	powdered	powdered
Hydrochloric acid	2 mol·dm^{-3}	2 mol·dm^{-3}
Temperature	25˚C	40˚C

5. FROM THE TABLE ABOVE, write down:

5.1 The independent variable for this investigation.

5.2 ONE controlled variable.

The volume of hydrogen gas produced is measured in each experiment. The graphs below show the results obtained.



6. Which graph, P or Q, represents Experiment 2? Refer to the data given in the table, as well as the shape of the graph, to explain how you arrived at the answer.

7. Give a reason why the rate of hydrogen production slows down towards the end in both experiments.

8. Calculate the mass of zinc used to prepare 0,024 dm^3 of hydrogen of hydrogen at room temperature. Assume that 1 mole of hydrogen gas has a volume of 24,04 dm^3 at room temperature.

Solutions

1. Measuring the volume of a gas produced.

2. Measuring change in mass of reactants.

3. $n = \frac{n}{M}$

$n = \frac{3,25}{65}$

$n = 0,05$ mol

$Zn + 2HC\ell \longrightarrow ZnC\ell_2 + 2H_2$

$n = CV = (2)\left(\frac{30}{1000}\right)$

$n = 0,06$ mol

Therefore the limiting agent is HCℓ

4.1 Conical/Erlenmeyer (flask).

4.2 Measure the volume of gas produced./ Collect the gas produced.

5.1 Temperature (of reactants).

e.g. Worked example 7 (continued)

5.2 Concentration (of HCℓ)

6. **P.**

Experiment 2 has the highest temperature.

The same volume of a gas was produced in a shortest period of time.

OR

Experiment 2 has the highest temperature.

Graph has the steepest slope.

7. The concentration of reactants decreases as the reaction proceeds.

8.

Calculations	Mark Allocation
$n(H_2) = \frac{V}{Vm}$ $n(H_2) = \left(\frac{0,24}{24,01}\right)$ $n(H_2) = 0,01$ mol $n(H_2) = \frac{n}{M}$ $0,01 = \frac{m}{65}$ m = 0,65 g OR 1 mol H_2 gas = 24,04 dm^3 0,01 mol H_2 gas = 0,24 dm^3 65 g Zn = 1 mol 0,65 g = 0,01 mol	• Substitute volume. ✓ • Substitute molar volume. ✓ • 0,01mol ✓ • n(Zn) = $n(H_2)$ ✓ • Substitute 65 $g{\cdot}mol^{-1}$ ✓ • Answer. ✓

Activity 4

81,1 g of nicotine consists of 60,07 g of carbon, 14,01 g of nitrogen and 7,02 g of hydrogen.

Determine the:

1. The empirical formula of nicotine. (13)
2. Molecular formula of nicotine if its molar mass is 162,26g. (4)

[17]

Solutions

1. Determining the percentage composition by molar mass of each element:

$$C = \frac{60,07}{81,1} \times 100 = 74,04\% ✓$$

$$N = \frac{14,01}{81,1} \times 100 = 17,27\% ✓$$

$$H = \frac{7,02}{81,1} \times 100 = 8,65\% ✓$$

Element	g per 100g	$n = \frac{m}{M}$ for 100g	$n = \frac{m}{M}$ for 81,1g	Simplest Ratio
C	74,07	$n = \frac{74,04}{12}$ ✓ $= 6,17$ ✓	$\frac{60,07}{12} = 5$ ✓	5
N	17,28	$n = \frac{17,27}{14}$ ✓ $= 1,23$ ✓	$\frac{14,01}{14} = 1$ ✓	1
H	8,65	$n = \frac{8,65}{1}$ ✓ $= 8,65$ ✓	$\frac{7,02}{1} = 7$ ✓	7

Empirical formula of nicotine is $\mathbf{C_5NH_7}$ (13)

2. Now calculate the molar mass of the substance using empirical formula

$M(C_5NH_7) = 81$ g/mol ✓

$x(81) = 162,2$ ✓

$x = 2$ *(meaning every atom in the empirical formula must be multiplied by 2)* ✓

Molecular formula of nicotine is $C_{10}N_2H_{14}$ ✓ (4)

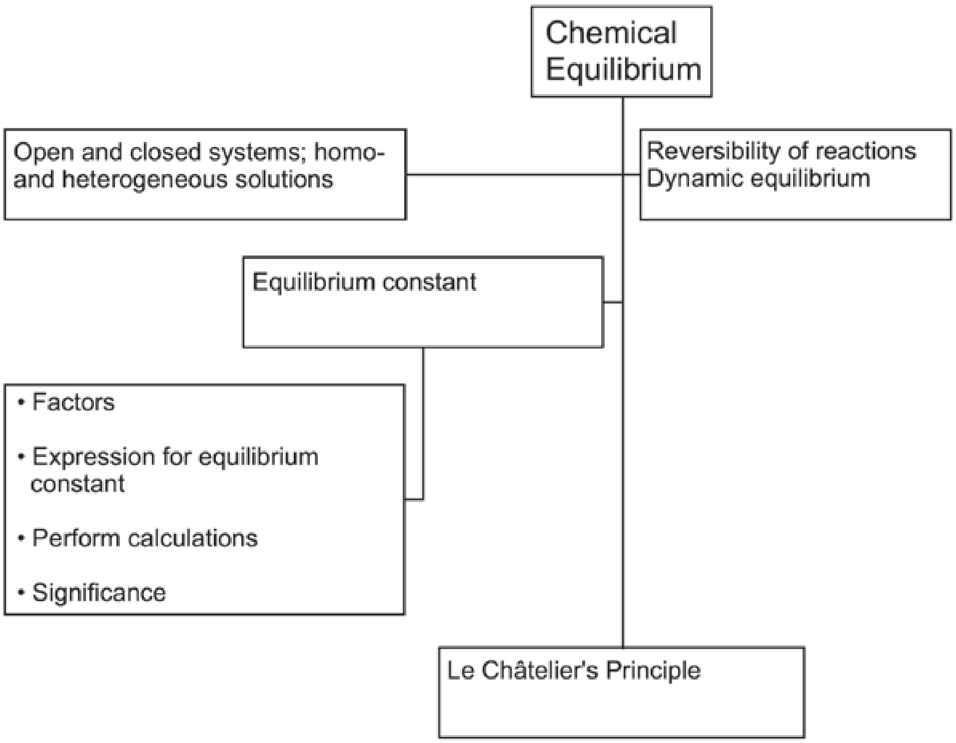
[17]

3 Unit

Chemical equilibrium

When a chemical reaction takes place, the atoms or ions in the reactants form new bonds and new products with different chemical formulas and different chemical properties.

3.1 Summary



3.2 Key concepts

In this section, we will be revising the basic concepts involved in chemical equilibria (plural of equilibrium). In a **chemical** reaction, **chemical equilibrium** is the state in which both reactants and products are present in concentrations which have no further tendency to change with time. Usually, this state results when the forward reaction proceeds (continues) at the same rate as the reverse reaction. **NB.** This does not mean the reaction has stopped; instead it means that it is continuing to react, but the reactants and products are being produced (and re-produced) at a constant rate.

HOMOGENEOUS REACTIONS

- are reactions where all the reactants and products are in the same phase,
- i.e. all are solids, or all are liquids, or all are gases

$$SO_2(g) + O_2(g) \leftrightharpoons SO_3(g)$$

HETEROGENEOUS REACTIONS

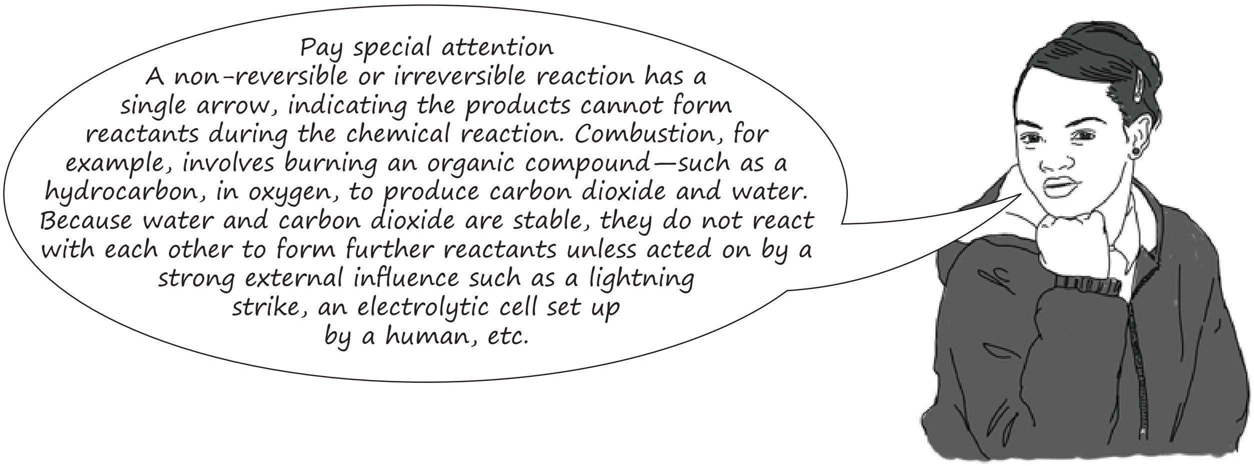
- are reactions where not all species in the reaction vessel are in the same phase.

$$CaCO_3(s) + HC\ell(aq) \rightarrow CaC\ell_2(aq) + CO_2(g) + H_2O(\ell)$$

Most chemical reactions are non-reversible or irreversible – this means that the products cannot change back into the reactants.

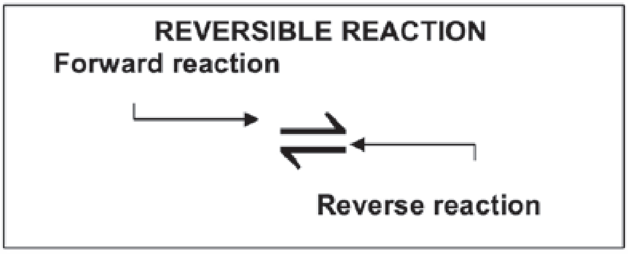
These reactions are essentially like baking. The ingredients, acting as the reactants, are mixed and baked together to form a cake, which acts as the product. This cake cannot be converted back to the reactants (the eggs, flour, etc.), just as the products in an irreversible reaction cannot convert back into the reactants (without e.g. human intervention). An example of an irreversible reaction is combustion. When carbon burns in oxygen to form carbon dioxide, the reaction is said to be **non-reversible**.

$$C(s) + O_2(g) \rightarrow CO_2(g)$$



Some chemical reactions are **reversible.** The products **react with each other** to form the **original reactants** under suitable conditions. (E.g. change in pressure, temperature, reactant concentration, etc.).

$$N_2(g) + 3\ H_2(g) \rightleftharpoons 2\ NH_3(g)$$



hint

A reversible reaction has a **double arrow**

Therefore:

Forward reaction		Reverse reaction
$N_2(g) + 3\ H_2(g) \rightarrow 2\ NH_3(g)$	Reaction	$2\ NH_3(g) \rightarrow N_2(g) + 3\ H_2(g)$
$N_2(g) + 3\ H_2(g)$	Reactants	$2\ NH_3(g)$
$2\ NH_3(g)$	Products	$N_2(g) + 3\ H_2(g)$

NB

DEFINITIONS

- **Open chemical system:** reactants / products can escape from reaction vessel
- **Closed chemical system:** reactants / products cannot escape from reaction vessel
- **Macroscopic changes:** measurable or visible changes e.g. changes in colour, temperature, pressure, volume, concentration
- **Yield:** the amount of product formed during a chemical reaction
- An **open system** continuously interacts with its environment (conditions are not kept constant).
- A **closed system** is isolated from its surroundings (conditions are kept constant)
- A **reversible reaction** occurs when the products can be converted back to reactants
- **Chemical equilibrium** is dynamic when the rate of the forward reaction equals the rate of the reverse reaction
- The **concentration** of a solution or of a gas is the number of moles of substance per unit volume (per dm^3).
- A **dynamic chemical equilibrium** is established in a closed system when the forward and reverse reactions of a reversible chemical reaction take place **at the same time** (simultaneously) and at the **same rate**. The conditions in the system must also remain constant.

$\boxed{c = \frac{n}{V}}$ where $\boxed{n = \frac{m}{M}}$ OR $\boxed{C = \frac{m}{Mv}}$

hint

You need to know the formula, unit and symbols used to calculate the concentration of a solution →

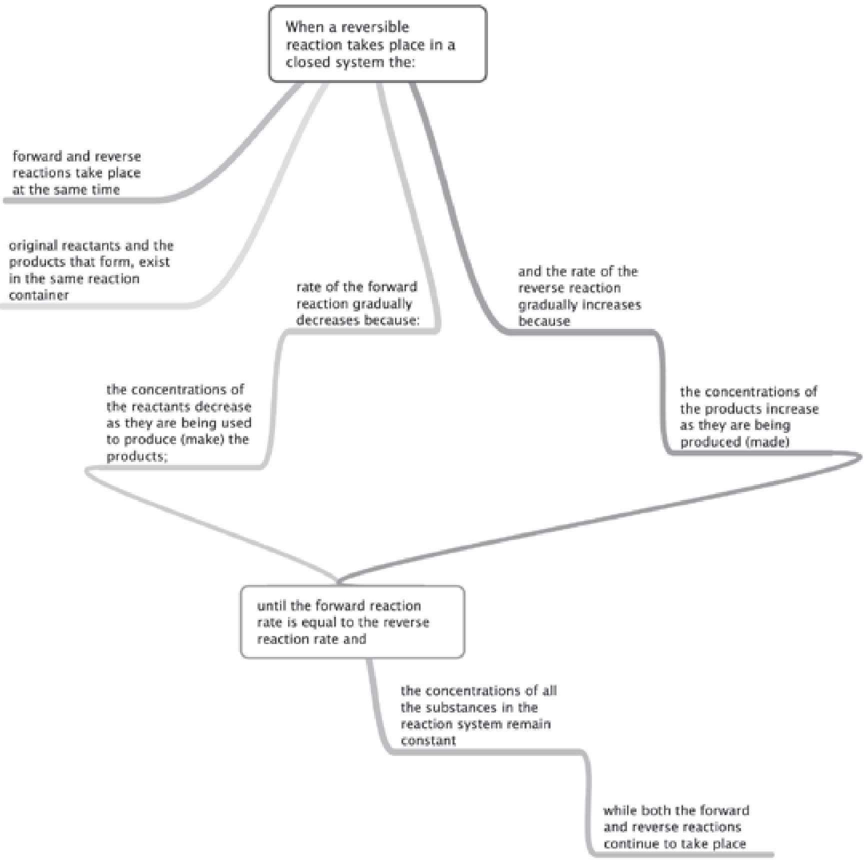
c : concentration ($mol \cdot dm^{-3}$)
V : volume (dm^3)
M : Molar mass ($g \cdot mol^{-1}$)
n : number of moles (mol)
m : mass (g)

NB

You need to understand what a **chemical equilibrium** is and know the conditions needed for a chemical equilibrium.

Chemical equilibrium

- When a chemical system reaches dynamic chemical equilibrium, both the forward and the reverse reactions continue – they do **NOT** stop.
- There are no **macroscopic** (visible with the eye) changes when the system is in equilibrium, but on a **microscopic** (atomic) level, the changes (reactions) continue.
- Neither the reactants nor the products are ever used up in an equilibrium system (incomplete reaction – i.e. "incomplete" in the sense that there are still species of the original/starting species (reactants.))



Activity 1

Write the name of a reaction in which all reactants and products are in the same phase (1)

[1]

Solution

Homogeneous ✓ **[1]**

3.3 Factors that influence chemical equilibrium position

Temperature (T):	Increasing or decreasing the temperature of the equilibrium mixture
Concentration (c):	Adding a substance to or removing a substance from the system at constant volume. This only applies to solutions (aq) and to gases (g).
Pressure (p):	Increasing or decreasing the pressure on an equilibrium mixture (this ONLY applies to gases).

3.4 Le Châtelier's Principle

If a **closed system** is in a state of **dynamic chemical equilibrium**, and one of the factors that influences the equilibrium (temperature, concentration or pressure) is changed:

- the equilibrium position will be disturbed;
- **either** the forward or the reverse reaction will be **favoured**;
- the **applied change** will be **opposed**;
- the reaction rates will **change** and eventually
- a **new equilibrium** will be established
- so that the forward and the reverse reactions again take place at the same rate.

NB

Le Châtelier's Principle states that:

When the equilibrium in a closed system is disturbed, the system will re-instate a new equilibrium by favouring the reaction that will oppose the disturbance.

3.4.1 Applying Le Châtelier's Principle to changes in equilibrium conditions

hint

If any factor changes, we can apply Le Châtelier's Principle to determine which changes will happen to the system in equilibrium (what upsets the balance).

Changing the temperature of the reaction mixture (ΔT)	
Increasing the temperature of the reaction system (i.e. heating it) • favours the reaction that **decreases** the temperature of the system (absorbs heat) • ∴ favours the **endothermic** reaction.	**Decreasing** the temperature of the reaction system (i.e. cooling it) • favours the reaction that **increases** the temperature of the system (releases heat) • ∴ favours the **exothermic** reaction.

Changing the concentration of a solution or gas reactant (Δc)	
Increasing the concentrationof a (g) or (aq) reactant (or product) • favours the reaction that **decreases** the concentration of that substance • ∴ the reaction that **uses** that substance as a **reactant**.	**Decreasing** the concentration of a (g) or (aq) reactant (or product) • favours the reaction that **increases** the concentration of that substance • ∴ the reaction that **makes** that substance as a **product**.

Changing the pressure of a gaseous system (Δp)	
Increasing the pressure (or decreasing the volume) of a gaseous system • favours the reaction that **decreases** the pressure of the system • by decreasing the total number of **gaseous moles** in the system.	**Decreasing** the pressure (or increasing the volume) of a gaseous system • favours the reaction that **increases** the pressure of the system • by increasing the total number of **gaseous moles** in the system.

Steps to follow

Follow these steps to predict the change in a **closed** chemical system in **dynamic** equilibrium:

Check that the reaction:

Step 1: Is reversible ($\rightleftharpoons$) (info given must indicate it is a dynamic equilibrium).

Step 2: **Equation** is **balanced.**

Step 3: Count the number of gaseous (g) **moles** on each side of the $\rightleftharpoons$.

Determine:

Step 4: If the forward reaction is exothermic or endothermic

Step 5: If the reverse reaction is exothermic or endothermic

Step 6: The change (which factor?) disturbs the equilibrium

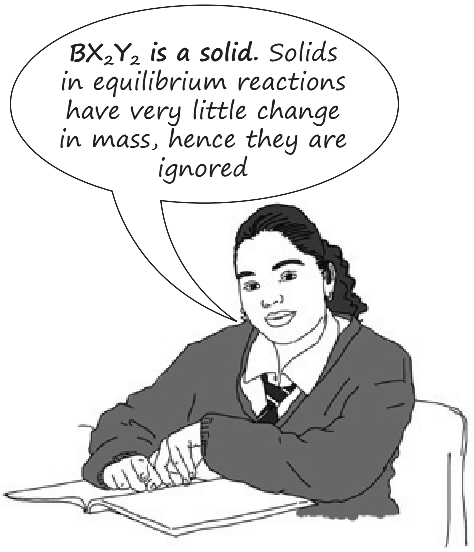
Decide:

Step 7: According to Le Châtelier's Principle, which reaction is favoured (forward or reverse)? (Follow the reasoning in the table above.)

Step 8: How the concentrations of the reactants and products change.

hint

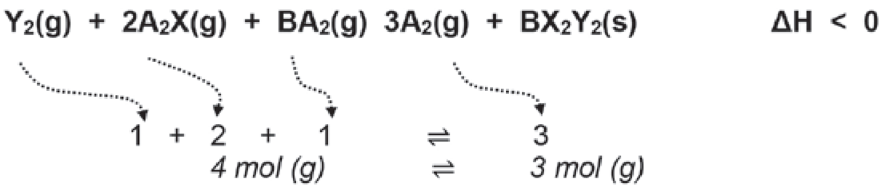
By closed we do not mean a closed container. Rather we mean a closed system where the conditions are kept constant.



Activity 2

Consider the following reversible reaction that is in equilibrium in a closed system (the symbols represent chemicals which are unnamed; if you see symbols like X or Y which aren't on the Periodic Table, it often means you've got to work out what kinds of substances they are).

Step 1, 2 & 3:



$Y_2(g) + 2A_2X(g) + BA_2(g)\ 3A_2(g) + BX_2Y_2(s) \qquad \Delta H < 0$

Step 4/5:

ΔH < 0 - *the forward reaction is exothermic*

- *the reverse reaction is endothermic*

In each of the following cases:

- Explain how the equilibrium will be affected (which reaction will be favoured)
- State how the concentration of the product $A_2(g)$ will change.

CASE 1 **The reaction system is heated.** (3)

[3]

Solution

Case 1.

If the reaction system is heated, the **temperature** of the system **increases.**

According to Le Châtelier's Principle, **increasing** the temperature of the reaction system (i.e. heating it) favours the reaction that will **decrease** the temperature of the system

∴ favours the **endothermic** ✓ reaction but $\Delta H < 0$

∴ the reverse reaction is **endothermic**

∴ the **reverse reaction** is favoured✓

∴ the $3A_2(g) + BX_2Y_2(s)$ reacts faster than it is produced

∴ the concentration of the $A_2(g)$ **decreases.** ✓

(Remember: The opposite is true if the reaction vessel is cooled.)

[3]

hint

You must be able to use Le Châtelier's Principle to **identify** the **factor** that will increase the yield of the products and what **influence** that factor will have on the reaction **AT EQUILIBRIUM**

CASE 2 **Y_2(g) is added to the vessel at constant pressure and temperature** (3)

[3]

Solution

Case 2.
Adding Y_2(g) **increases** the **concentration** of the Y_2(g). ✓

According to Le Châtelier's Principle, **increasing** the concentrationof Y_2(g) favours the reaction that **decreases** the concentration of Y_2(g)

∴ the reaction that **uses** of Y_2(g) as a **reactant**

the **forward reaction** is favoured. ✓

the rate at which A_2(g) and BX_2Y_2(s) is produced, increases

the concentration of the A_2(g) **increases.** ✓

[3]

CASE 3 A_2(g) is removed from the vessel at constant pressure and temperature. (3)

[3]

Solution

Case 3.
Removing A_2(g) **decreases** the **concentration** of the A_2(g). ✓

According to Le Châtelier's Principle, **decreasing** theconcentration of the A_2(g) favours the reaction that **increases** the concentration of the A_2(g);

the reaction that **makes** A_2(g) as a **product**

∴ the **forward reaction** is favoured. ✓

the rate at which A_2(g) and BX_2Y_2(s) is produced, increases

the concentration of the A_2(g) **increases.** ✓ **[3]**

CASE 4 Some of the BX2Y2(s) is removed from the system at constant pressure and temperature. (3)

[3]

Solution

Case 4.
Removing BX_2Y_2(s) has no effect on the **equilibrium** as it is a **solid.** ✓

Removing a solid from an equilibrium system does not disturb the concentration. ✓ (Solids in equilibrium reactions have very little change in mass, hence they are ignored)

The concentration of A_2(g) remain the same. ✓ **[3]**

CASE 5 The pressure on the system is increased (or the volume is decreased) (3)

[3]

There are 4 gaseous moles on the left, and 3 gaseous moles on the right.

Solution

Case 5.

According to Le Châtelier's Principle, **increasing** the **pressure** (or decreasing the volume) of a gaseous system favours the reaction that decreases the pressure of the system by decreasing the total number of gaseous moles in the system. ✓

the **forward reaction** is favoured. ✓

the rate at which $A_2(g)$ and $BX_2Y_2(s)$ is produced, increases

the concentration of the $A_2(g)$ increases. ✓ **[3]**

Activity 3

Say whether the statement is TRUE or FALSE: If the equilibrium constant for the reaction $A_2(g) + B_2(g) \rightleftharpoons 2AB(g)$ is equal to K, then the equilibrium constant for the reverse reaction $2AB(g) \rightleftharpoons A_2(g) + B_2(g)$ is also equal to K. (3)

[3]

Solution

FALSE. ✓ … for the reverse reaction $2AB(g) \rightleftharpoons A_2(g) + B_2(g)$ is equal to $\frac{1}{K}$ ✓✓ OR … less (smaller) than K **[3]**

Activity 4

The industrial preparation of hydrogen gas is represented by the equation below:

$$CH_4(g) + H_2O(g) \rightleftharpoons CO(g) + 3H_2(g) \qquad \Delta H > 0$$

The reaction reaches equilibrium at 1 000 °C in a closed container.

There are various ways to state Le Châtelier's Principle correctly.

1. State Le Châtelier's principle. (2)
2. How will an increase in pressure at 1 000 °C (by decreasing the volume) affect the yield of hydrogen gas? Write down only INCREASES, DECREASES OR NO EFFECT. Explain the answer. (2)
3. Give TWO reasons why high temperatures are used for this reaction. (2)

[6]

Solution

1. When the equilibrium in a closed system is disturbed the system will shift the equilibrium position (OR re-instate a new equilibrium)✓ as to favour the reaction that will oppose OR cancel OR counteract the change OR disturbance. ✓

   OR

   When a stress / change is placed on a system in equilibrium the system shifts the equilibrium (position) OR re-instate a new equilibrium ✓ so as to remove OR cancel OR oppose the stress / change. ✓ (2)

   OR

   When the conditions affecting an equilibrium are changed, the equilibrium (position) shifts in such a way ✓as to oppose the change OR cancel the change. ✓ **(any two)**

2. Decreases ✓ When the pressure is increased, the reverse reaction is favoured.✓

   OR

   The reaction that produced the smaller volume/amount of gas is favoured. ✓

   OR

   4 mol or volumes of gas produces ✓ 2 mol or volumes of gas. ✓ (2) **(any two)**

3. Products form at faster rate. ✓

   Higher yield of products. ✓ (2)

[6]

hint

In physical chemistry, **saturation** is the point at which a solution of a substance can dissolve no more of that substance. Additional amounts of the solute will appear as a separate phase (usually as a precipitate solid). This point of maximum concentration, the saturation point, depends on the temperature and pressure of the solution as well as the chemical nature of the substances involved.

3.4.2 Dynamic chemical equilibrium in solutions

A dynamic chemical equilibrium in a solution:

- is only possible if the solution is **saturated**
- is only affected by **changing** the
  - **concentration** of the ions in the solution or
  - **temperature** of the solution.

The common ion effect

Steps to follow

When a solution is added to a reaction system:

Step 1: Identify the common ion in the solution and the system

Step 2: Explain the effect of the common ion (addition) on the chemical equilibrium.

Solution added to the equilibrium mixture:	Effect on equilibrium mixture: $H^+(aq) + OH^-(aq) \rightleftharpoons H_2O(\ell)$
Hydrochloric acid, $HC\ell(aq)$	• Increases the hydrogen ion concentration, $[H^+]$ or hydronium ion concentration $[H_3O^+]$ • Increases the chloride ion concentration, $[C\ell^-]$ • Decreases the hydroxyl ion concentration $[OH^-]$
Sulphuric acid, $H_2SO_4(aq)$	• Increases the hydrogen ion concentration, $[H^+]$ or hydronium ion concentration $[H_3O^+]$ • Increases the sulphate ion concentration, $[SO_4^{2-}]$ • Decreases the hydroxyl ion concentration $[OH^-]$ because:
Concentrated sulphuric acid, $H_2SO_4(\ell)$	• Extracts water (H_2O) from the system (this is also known as **dehydration**)
A base like $NaOH(aq)$ or $KOH(aq)$	• Increases the hydroxyl ion concentration $[OH^-]$
A solution containing $C\ell(aq)$ ions e.g. $NaC\ell(aq)$	• Increases the chloride ion concentration, $[C\ell^-]$ • Decreases the silver ion concentration in a solution because $Ag^+(aq) + C\ell^-(aq) \rightarrow AgC\ell(s)$

hint

When two different solutions contain the same ion, this ion is called a **common ion**

Worked example 1

Consider the following equilibrium:

$$CoC\ell_4^{2-}(aq) + 6H_2O(\ell) \rightleftharpoons Co(H_2O)_6^{2+}(aq) + 4C\ell^-(aq) \qquad \Delta H < 0$$

blue **purple-pink** **pink**

When cobalt chloride crystals ($CoC\ell_2{\cdot}6H_2O$) are dissolved in ethanol (the solvent) in a flask, a **blue** solution is formed with $CoC\ell_4^{2-}$ ions. By carefully adding water to the blue solution until it just turns **purple-pink** because of the formation of the **pink** $Co(H_2O)_6^{2+}$ ions, the above equilibrium is reached.

Five test tubes each contain a small amount of the above purple-pink equilibrium solution. Describe and explain the colour change observed in each of the following instances:

1. *The solution is cooled down.*

   Becomes pink.

   According to Le Châtelier's Principle, a decrease in temperature favours the exothermic, forward reaction therefore increasing the $[Co(H_2O)_6^{2+}(aq)]$ which is pink.

2. *Water is added to the solution.*

   Becomes pink.

   According to Le Châtelier's Principle, adding H_2O will favour the production of more $Co(H_2O)_6^{2+}(aq)$ ions so that the number of H_2O molecules will decrease, therefore the forward reaction is favoured. The concentration of the $Co(H_2O)_6^{2+}(aq)$ ions which are pink, increases.

e.g. Worked example 1 (continued)

3. *A few NaCℓ crystals are added to the solution.*

   Becomes blue.

   Adding NaCℓ to the equilibrium mixture, increases the [$C\ell^-$] as a result of the common ion ($C\ell^-$) found in the reaction mixture and in the NaCℓ. The reverse reaction which decreases the [$C\ell^-(aq)$], is favoured, thereby increasing the concentration of the $CoC\ell_4^{2-}(aq)$ ions which are blue.

4. *Concentrated sulphuric acid is added to the solution.*

   Becomes blue.

   Concentrated sulphuric acid (H_2SO_4) is a good dehydrating agent therefore it will extract water molecules (H_2O) from the mixture. The reverse reaction that produces H_2O molecules is favoured and at the same time increasing the concentration of the $CoC\ell_4^{2-}(aq)$ ions which are blue.

5. *A few drops of silver nitrate solution are added to the solution.*

   Becomes pink.

   When the silver nitrate solution is added to the mixture, the silver ions, $Ag^+(aq)$ react with the $C\ell^-(aq)$ to form a $AgC\ell(s)$ precipitate, thereby decreasing the [$C\ell^-$]. According to Le Châtelier's Principle, the forward reaction that increases the [$C\ell^-$] ions is favoured. More pink $Co(H_2O)_6^{2+}(aq)$ ions form.

Activity 5

1. The following hypothetical reaction reaches equilibrium in a closed container at a certain temperature:

$X_2(g) + Y_2(g) \rightleftharpoons 2XY(g) \qquad \Delta H < 0$

Which ONE of the following changes will increase the AMOUNT of XY(g)?

A. Decrease in temperature
B. Increase in temperature
C. Increase in pressure
D. Decrease in pressure (2)

2. The equation below represents a chemical reaction at equilibrium in a closed container.

$H_2(g) + I_2(g) \rightleftharpoons 2HI(g) \qquad \Delta H < 0$

Which ONE of the following changes will increase the yield of HI(g) in the above reaction?

A. Increase the temperature
B. Decrease the temperature
C. Increase the pressure by decreasing the volume
D. Decrease the pressure by increasing the volume (2)

3. A chemical reaction reaches equilibrium. Which ONE of the following statements regarding this equilibrium is TRUE?
   - **A.** The concentrations of the individual reactants and products are constant.
   - **B.** The concentrations of the individual reactants and products are equal.
   - **C.** The concentrations of the individual reactants are zero.
   - **C.** The concentrations of the individual products increase until the reaction stops. (2)

4. The reaction represented by the equation below reaches equilibrium.

   $2CrO_2^{4-}(aq) + 2H^+(aq) \rightleftharpoons Cr_2O_2^{7-}(aq) + H_2O(\ell)$

   yellow orange

   Which ONE of the following changes to the reaction mixture will change its colour from yellow to orange?
   - **A.** Add a catalyst.
   - **B.** Add water to the reaction mixture.
   - **C.** Add a few drops of sodium hydroxide solution to the reaction mixture.
   - **D.** Add a few drops of concentrated hydrochloric acid to the reaction mixture. (2)

5. Give one word for the following phrase:
   The stage reached in a reversible chemical reaction when the rate of the forward reaction is equal to the rate of the reverse reaction. (2)

[10]

Solution

1. A ✓✓ (2)
2. B ✓✓ (2)
3. A ✓✓ (2)
4. D ✓✓ (2)
5. (Dynamic/Chemical) equilibrium ✓✓ (2)
[10]

NB

Solids and pure liquids are omitted from the K_c expression as their concentration is [1], as multiplying by 1 has no effect.

3.5 The Equilibrium Constant (K_c) (The Law of Mass Action)

The concentrations of all the compounds (solutions and gases) in a closed system in dynamic chemical equilibrium are related by a mathematical equation. The numerical value of this equation is called the **equilibrium constant (K_c).**

In the hypothetical equation below the equilibrium expression for this reaction is:

$2P + 3R \rightleftharpoons 2S + 4T$

$$K_c = \frac{[S]^2 \times [T]^4}{[P]^2 \times [R]^3}$$

hint

K_c: equilibrium constant (no unit)

[substance]: concentration of reactant or product (in $mol{\cdot}dm^{-3}$)

mol: number of moles of each compound in the balanced reaction equation.

NB

- This is the correct way of writing the K_c expression
- The coefficients are the moles of each reactant and product in the balanced equation
- The product of the concentration of **reactants** (not to be added, but **multiplied**!!), **raised to the power** of the number of moles is the **numerator**
- The product of the concentration of **products** (not to be added, but multiplied!!), **raised to the power** of the number of moles is the **denominator**
- The concentrations used in the Law of Mass Action is the **[reactant]$_{equilibrium}$** and **[product]$_{equilibrium}$** **(NOT initial concentrations!! i.e. the concentrations of reactants and products at equilibrium)**

Activity 6

Write K_c expressions for each of the following reactions:

1. $N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$ (1)

2. $CaCO_3(s) \rightleftharpoons CaO(s) + CO_2(g)$ (1)

3. $P_4(s) + 6C\ell_2(g) \rightleftharpoons 4PC\ell_3(\ell)$ (1)

[3]

Solution

1. $K_c = \frac{[NH_3]^2}{[N_2]^2 \cdot [H_2]^3}$ ✓ (1)

2. $K_c = [CO_2]$ ✓ (1)

3. $K_c = \frac{1}{[C\ell_2]^6}$ ✓ (1)

[3]

3.5.1 Factors that influence the equilibrium constant

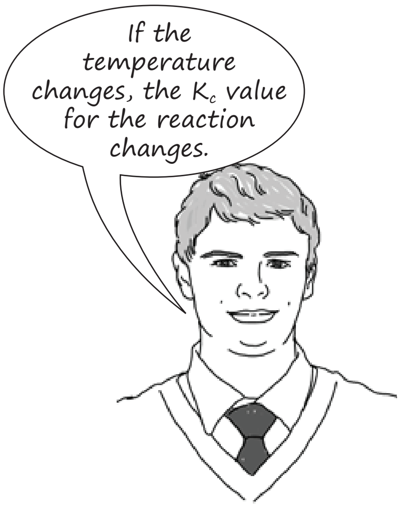
For a closed system in equilibrium:

• Only the concentrations of aqueous solutions (aq) and gases (g) appear in the K_c expression; • Solids (s) and pure liquids (ℓ) are NOT included in the K_c expression.	• The value of K_c **DOES** change if the **temperature** of the system changes.
	The value of K_c **DOES NOT** change if: • the pressure in the system changes; • the concentration of a reactant or product in the system changes; • a catalyst is added to the system.

hint

You need to know the:
- **conditions** and
- **factors**

that play a role in HOW/WHEN K_c changes/does NOT change



a) The effect of a change in temperature on K_c

K_c for a specific reaction is **constant** at a **specific temperature.**

If the change in the temperature of a closed equilibrium system:

*favours the **forward** reaction:*

- more products form;
- **[products] increases**;
- [reactants] decreases and
- K_c **increases**

*favours the **reverse** reaction:*

- more reactants form;
- **[products] decreases**;
- [reactants] increases and
- K_c **decreases**

3.5.2 The meaning of K_c-values

The significance of the K_c value is important in industrial processes. The economic viability of an industrial process in the chemical industry depends on the manufacturing costs, the product yield (amount of product produced), and the retail cost. These factors determine the profit a company would make.

K_c values are used to determine if the possible yield at a specific temperature is low or high.

NB

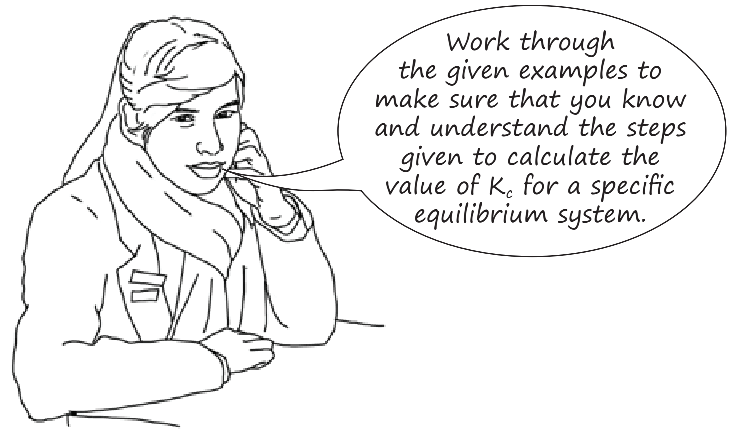
You must understand the meaning of K_c.

The value of K_c is directly linked to the **yield** of the reaction.

If K_c is small ($K_c < 1$) the:	**If K_c is large ($K_c > 1$) the:**
• equilibrium concentrations of the products are relatively **low** compared to those of the reactants • **product yield** is **low** • industrial process is not economically viable.	• equilibrium concentrations of the products are relatively **high** compared to those of the reactants • **product yield** is **high** • industrial process may be economically viable.

3.5.3 Calculating the value of K_c for a closed system in dynamic equilibrium

There are THREE types of calculations that you may be asked to perform. They will be covered in the following pages.



i) Type 1: The initial amount (mol) of each reactant is given

Worked example 2

1. Consider the following balanced reaction for the formation of sulphur trioxide, in the second step of the Contact Process:

$$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$$

Exactly **8 mol SO_2** and 10 mol **O_2** are sealed in a **500 cm^3** reaction vessel which is initially empty. The compounds react to produce SO_3. **At equilibrium**, the vessel contains **6 mol SO_3**.

1.1 Calculate the equilibrium concentrations of each of the compounds in the reaction vessel.

Solution

The Contact

Process is a three step process in the manufacturing of sulphuric acid.

Step 1:
Always start by drawing a table with a column for the descriptions and a column for each of the reactants and products. Fill in the formulas of the reactants and products and the number of moles of each in the balanced reaction equation in the top line. The table should always consist of 5 rows with names as indicated:

Reactants Products

balanced equation	$2SO_2(g)$	$O_2(g)$	$2 SO_3(g)$
initial mol			
mol used or produced			
final mol at equilibrium			
final [ ] at equilibrium $c = \frac{n}{V}$			

hint

- Use a **table** (as indicated) to show each of the calculation steps when calculating the **number of mol** of each compound at equilibrium.
- **DO NOT** use abbreviations such as **I, C and E** in your table.
- Clearly indicate if you work with mol or concentration of each substance at equilibrium in the table.

Worked example 2 (continued)

Reactants

Products

balanced equation	$2SO_2(g)$	$O_2(g)$	$2\ SO_3(g)$
initial mol			
mol used or produced			
final mol at equilibrium			
final [ ] at equilibrium $c = \frac{n}{V}$			

Step 2:
Now fill in all the values given in the question. If only reactants were added at the beginning of the reaction, the initial mol of the products is zero.

balanced equation	$2SO_2(g)$	$O_2(g)$	$2SO_3(g)$
initial mol	**8**	**10**	**0**
mol used / produced			
final mol at equilibrium			**6**
final [ ] at equilibrium	$c = \frac{n}{V} = \frac{n}{0,5}$	$c = \frac{n}{V} = \frac{n}{0,5}$	$c = \frac{n}{V} = \frac{n}{0,5}$

Step 3:

Find the column with 2 values. Complete the mol used or produced line for this compound.

balanced equation	$2SO_2(g)$	$O_2(g)$	$2SO_3(g)$
initial mol	8	10	0
mol used / produced			**6**
final mol at equilibrium			6
final [ ] at equilibrium	$c = \frac{n}{V} = \frac{n}{0,5}$	$c = \frac{n}{V} = \frac{n}{0,5}$	$c = \frac{n}{V} = \frac{n}{0,5}$

Step 4:
Compare the ratio of moles according to which the reactants react and to which the products are produced, according to the balanced reaction equation: $SO_2 : O_2 : SO_3 = 2 : 1 : 2$

Consider the actual mol used or produced for the compound which is ***known****.*

We have just calculated that **6** *mol* SO_3 *has been produced.*

This means that the ratio of $SO_2 : O_2 : SO_3 = 2 : 1 : 2$ *(balanced equation)* $= 6 : 3 : 6$

Worked example 2 (continued)

Fill in these values.

balanced equation	**2**SO_2(g)	**1** O_2(g)	**2**SO_3(g)
initial mol	8	10	0
mol used / produced	**6**	**3**	**6**
final mol at equilibrium			6
final [ ] at equilibrium	$c = \frac{n}{V} = \frac{n}{0,5}$	$c = \frac{n}{V} = \frac{n}{0,5}$	$c = \frac{n}{V} = \frac{n}{0,5}$

Step 5:
For the reactants: initial mol – mol used = final mol at equilibrium.
For the products: initial mol + mol produced = final mol at equilibrium.

balanced equation	2SO_2(g)	O_2(g)	2SO_3(g)
initial mol	8	10	0
mol used / produced	6	3	6
final mol at equilibrium	**8 – 6 = 2**	**10 – 3 = 7**	**6**
final [ ] at equilibrium	$c = \frac{n}{V} = \frac{n}{0,5}$	$c = \frac{n}{V} = \frac{n}{0,5}$	$\frac{6}{0,5} = 12$

Step 6:
Substitute the final mol values in the last line, and calculate the final concentrations.

These are the answers to Question 1.1 above.

balanced equation	2SO_2(g)	O_2(g)	2SO_3(g)
initial mol	8	10	0
mol used / produced	6	3	6
final mol at equilibrium	2	7	6
final [ ] at equilibrium	$\frac{2}{0,5} = 4$	$\frac{7}{0,5} = 14$	12

∴ at equilibrium:

$[SO_2\,(g)] = 4\ mol{\cdot}dm^{-3}$ and $[O_2\,(g)] = 14\ mol{\cdot}dm^{-3}$ and $[SO_3\,(g)] = 12\ mol{\cdot}dm^{-3}$

Worked example 3

1.2 Write an expression for the equilibrium constant for the forward reaction and calculate K_c for the forward reaction at this temperature.

Solution

1. $K_c = \frac{[SO_3]^2}{[SO_2]^2{\cdot}[O_2]} = \frac{12^2}{4^2.14} = 0,64$

ii) Type 2: The initial amount (mol) of one reactant and the concentration of a reactant or product are given

e.g. Worked example 4

2 mol of $NO_2(g)$ and an **unknown amount of $N_2O_4(g)$** are sealed in a **2 dm^3 container**, that is fitted with a plunger, at a certain temperature. The following reaction takes place:

$$2NO_2(g) \rightleftharpoons N_2O_4(g)$$

At equilibrium it is found that the **NO_2 concentration is 0,4 $mol \cdot dm^{-3}$**. The equilibrium constant (K_c) at this temperature is **2**.

1. Calculate the initial amount (in mol) of $N_2O_4(g)$ that was sealed in the container.

Solution

Step 1:
Draw the table as before. Fill in the formulas of the reactants and products and the number of moles of each in the balanced reaction equation in the top line.

*Now fill in all the values given in the question. If only reactants were added at the beginning of the reaction, the initial mol of the products is zero. When the initial amount (mol) of a reactant or product is NOT zero and the value is not given (in this case the amount of N_2O_4) is **not given**, let this amount equal x. Write the statement regarding 'x' down, "Let .... be x".*

Let the initial amount of N_2O_4 in the reaction vessel be x.

balanced equation	**2 NO_2**	**N_2O_4**
initial mol	2	
mol used / produced		
final mol at equilibrium		
final [ ] at equilibrium $c = \frac{n}{V}$	0,4	

Step 2:
Use the concentration given and the formula for concentration ($c = \frac{n}{V}$) to calculate the number of moles of NO_2 in the equilibrium mixture. The volume of the container (2 dm^3) was given. Show the calculation and substitute the calculated value in the table.

$$\boxed{c = \frac{n}{V}} \therefore \boxed{0,4 = \frac{n}{2} \therefore n = (2)(0,4) = 0,8 \text{ mol}}$$

Step 3:
*Find the column with Find the column with **2** values. Complete the mol used or produced line for this compound.*

2 mol NO_2 initially – ? mol NO_2 used = 0,8 mol
$\therefore$ mol NO_2 initial = 1,2 mol

Worked example 4 (continued)

Step 4:
From the balanced equation ratio 2 : 1 determine the ratio of the moles used and produced. Therefore 2 : 1 becomes 1,2 (as calculated in Step 3): 0,6

Step 5:
For the reactants: initial mol – mol used = final mol at equilibrium.
For the products: initial mol + mol produced = final mol at equilibrium.

Step 6:
Substitute the final mol values into the last line, and calculate the final concentration of the N_2O_4*.*

	$2NO_2$	**N_2O_4**
balanced equation	2	
initial mol	1,2 ***(Step 3)***	0,6 ***(Step 4)***
mol used / produced	0,8 ***(Step 2)***	+ 0,6 ***(Step 5)***
final mol at equilibrium	0,4	$\boxed{\left(\frac{x+0,6}{2}\right)}$ ***(Step 6)***

Step 7:

Write the expression for K_c *and substitute all the known values – remember that the value of* K_c *was given. Solve for* x*.*

$$K_c = \frac{[N_2O_4]}{[NO_2]^2} \quad \therefore 2 = \frac{\left(\frac{x+0,6}{2}\right)}{0,4^2}$$
$$\therefore (2)(0,4^2) = \frac{x+0,6}{2}$$
$$\therefore x = 0,4 \text{ mol}$$

The plunger is now pushed into the container and the volume of the container ***decreases.***

2. How will this change influence the amount of nitrogen dioxide at equilibrium? Only write down **increases**, **decreases** or **remains the same**.

Solution

Decreases

3. Use Le Châtelier's principle to explain your answer to Question 2.2.

Solution

When the volume of the container decreases, the pressure increases. According to Le Châtelier's Principle the reaction that decreases the pressure will be favoured ∴ the (forward) reaction that produces fewer gas moles, 2 mol (g) $\rightleftharpoons$ 1 mol (g), is favoured.

iii) Type 3: The initial mass of a reactant and the value of K_c are given and the mass of the reactant that remains unreacted, is asked

Activity 7

The thermal decomposition of calcium carbonate ($CaCO_3$) is an example of a heterogeneous equilibrium. The decomposition that takes place in a closed container can be represented by the following equation:

$$CaCO_3(s) \rightleftharpoons CaO(s) + CO_2(g)$$

Initially **5 g of $CaCO_3$(s)** is placed in a closed **500 cm^3 container** and then heated. Equilibrium is reached at 900 °C.

1. Why is the above decomposition referred to as a **heterogeneous equilibrium**? (1)
2. Calculate the mass of unreacted $CaCO_3$(s) that remains in the container at equilibrium if **K_c for the reaction is 0,0108 at 900 °C**. (19)
3. It is found that the value of **K_c increases** when the container is heated. Is the forward reaction **exothermic** or **endothermic**? Use Le Châtelier's principle to explain your answer. (5)
4. The volume of the container is now **decreased** to 250 cm^3 while the temperature is kept constant.

   How will each of the following be affected? Give a reason for your answer.

   3.4.1 The value of K_c.

   3.4.2 The number of mol $CaCO_3$(s) present in the equilibrium mixture. (10)

   3.4.3 The concentration of CO_2(g) at the new equilibrium.
5. **More** $CaCO_3$(s) is now added to the equilibrium mixture in the 500 cm^3 container.

   How will this change influence the number of moles of CO_2(g) in the equilibrium mixture? Give a reason for your answer. (2)

[37]

hint

Refer back to the definition of a heterogeneous equilibrium

Solutions

1. Reactants and products are in different **phases.** ✓ (1)
2. This answer takes six steps. Answers for questions 3.3 to 3.5 appear below these steps.

Step 1:

Convert the mass of the reactant to moles. ONLY moles may be used in the table.

$M(CaCO_3) = 40 + 12 + 3(16) = 100\ g{\cdot}mol^{-1}$ ✓

$n = \frac{m}{M} = \frac{5}{100} = 0{,}05\ mol$ ✓

Solutions to Activity 7 (continued)

Step 2:
Write the expression for K_c and substitute all the known values – remember that the value of K_c was given.

$K_c = [CO_2]$ ✓
$0{,}0108 = [CO_2]$
$\therefore [CO_2] = 0{,}0108\ mol{\cdot}dm^{-3}$ ✓

Step 3:
Use the calculated $CO_2(g)$ concentration and the formula for concentration ($c = \frac{n}{V}$) to calculate the number of moles of CO_2 in the equilibrium mixture. The volume of the container (500 cm^3) was given. Convert the volume to dm^3. Show all working.

$$\boxed{c = \frac{n}{V}} \therefore \boxed{0{,}0108 = \frac{n}{0{,}5} \therefore n = (0{,}5)(0{,}0108) = 0{,}0054\ mol\ CO_2}$$

✓ ✓

Step 4:
*Find the column with **2** values. Complete the mol used or produced line for this compound. (0 mol CO_2 initially + produced mol CO_2 = 0,0054 mol* ✓ *$\therefore$ mol CO_2 produced = 0,0054 mol)* ✓

Step 5:
*From the balanced equation **ratio 1 : 1 : 1** determine the ratio of the moles used and produced. Therefore 1 : 1 : 1 becomes 0,0054 (from Step 3): **0,0054 : 0,0054*** ✓

Step 6: ✓
For the reactant $CaCO_3$ ... initial mol – mol used = final mol at equilibrium
$\therefore$ 0,05 mol – 0,0054 = final mol at equilibrium = 0,0046 mol ✓ ✓

balanced equation	**$CaCO_3$**	**CaO**	**CO_2**	
initial mol	0,05 ***(Step 1)***	0 ***(Given)***	0 ***(Given)***	✓
mol used / produced	0,0054 ***(Step 5)***	0,0054 ***(Step 5)***	0,0054 ***(Step 4)***	✓
final mol at equilibrium	0,05 – 0,0054 = 0,0046 ***(Step 6)***	0,0054 ***(Step 3)***	0,0054 ***(Step 3)***	✓
Equilibrium concentration ($mol{\cdot}dm^{-3}$) $c = \frac{n}{V}$	not asked	not asked	$\frac{n}{V} = \frac{n}{0{,}5}$ = 0,0108 ***(Step 2)***	✓

$\therefore$ 0,0046 mol $CaCO_3$ remains unreacted at equilibrium

$M(CaCO_3) = 40 + 12 + 3(16) = 100\ g{\cdot}mol^{-1}$
✓

$$\boxed{n = \frac{m}{M}} \therefore \boxed{0{,}0046 = \frac{m}{100} \therefore m = (0{,}0046)(10) = 0{,}46\ g}$$ ✓

$\therefore$ 0,46g $CaCO_3$ remains unreacted. ✓ (19)

hint

- Convert cm^3 to dm^3:
- 500 cm^3 = 500 ÷ 1000 = 0,5 dm^3 .
  Note: cm^3 = mL, dm^3 = L.
  It's probably easier to remember e.g. that if 500 cm^3 = 500 mL, it's the same as 0,5 L = 0.5 dm^3
- Convert mass to mol using the formula: $n = \frac{m}{M}$

hint

- Mass was asked, so convert the mol calculated to mass
- $n = \frac{m}{M}$

Solutions to Activity 7 (continued)

3. Endothermic. ✓

K_c increases ∴ the forward reaction or reaction to the right is favoured. ✓ ✓

According to Le Châtelier's principle, an increase in temperature will favour the endothermic reaction ✓ the forward reaction or reaction to the right must be endothermic. ✓ (5)

4.1 Remains the same. ✓ Only temperature ✓ affects the value of K_c.

4.2 Increases. ✓

Decreasing the volume increases the pressure. ✓ According to Le Châtelier's Principle, when the pressure is increased, the reaction which decreases the pressure by producing fewer moles of gas products, is favoured. ✓

As 0 mol (g) ∴ 1 mol (g), the reverse reaction is favoured. ✓

4.3 Remains the same. ✓

$K_c = [CO_2]$. The temperature remains constant ✓ ∴ K_c remains constant ∴ the concentration ✓ of CO_2 will remain constant. ✓ (10)

5. Remains the same. Adding a solid does not affect the equilibrium, it does not change the concentration of a reagent. ✓✓ (2)

[37]

Activity 8

The equation below represents an equilibrium reaction in a sealed $1 dm^3$ container.

$$NO_2(g) + NO(g) \rightleftharpoons N_2O(g) + O_2(g) \qquad \Delta H > 0$$

Equilibrium was reached at a certain temperature and the value of **K_c was 3,93.** The concentration (in $mol \cdot dm^{-3}$) of each **reactant and product** in the container at equilibrium was:

$[NO_2] = 0,06\ mol \cdot dm^{-3}$
$[NO] = 0,29\ mol \cdot dm^{-3}$
$[N_2O] = 0,18\ mol \cdot dm^{-3}$
$[O_2] = 0,38\ mol \cdot dm^{-3}$

One of the conditions affecting the equilibrium is changed and a new equilibrium is established. At the new equilibrium, the concentration of the $NO_2(g)$ is $0,12 mol \cdot dm^{-3}$.

1. Calculate the K_c value at the new equilibrium. (11)
2. Which condition, concentration or temperature, was changed? (1)
3. Give an explanation for the answer to Question 4.2. (1)

[13]

NB

- When Δ**H > 0** it means the reaction to the right (the forward reaction) is **endothermic**
- When Δ**H < 0** the forward reaction is **exothermic**

hint

These are the **initial** concentrations – **before** the new equilibrium is established. $V = 1\ dm^3$ (given)

∴ the values of the initial concentrations are equal to the initial number of moles.
$c = \frac{n}{V}$ and $c = \frac{n}{1}$
∴ $n = c(1)$

Solutions

1. $NO_2(g) + NO(g) + \text{Energy} \rightleftharpoons N_2O(g) + O_2(g)$

$\Delta [NO_2] = [NO_2]_{final} \overset{✓}{-} [NO_2]_{initial} = (0{,}12 - 0{,}06) = 0{,}06 \overset{✓}{\text{mol}}\ NO_2$ is **formed.**

but NO_2 is the **product** of the **reverse reaction**

∴ the reverse reaction was favoured. ✓

From the balanced reaction equation, **1** NO_2 : **1** NO : **1** N_2O : **1** O_2

∴ 0,06 mol N_2O + 0,06 mol O_2 → 0,06 mol NO_2 + 0,06 mol NO ✓

So at equilibrium:

	NO_2	NO	N_2O	O_2	
Initial number of moles (mol)	0,06 *(Given)*	0,29 *(Given)*	0,18 *(Given)*	0,38 *(Given)*	✓
Number of moles used / formed (mol)	+0,06 *(Step 4)*	+0,06 *(Step 5)*	−0,06 *(Step 5)*	−0,06 *(Step 5)*	✓
Number of moles at equilibrium (mol)	0,12 *(Step 3)*	0,35 *(Step 6)*	0,12 *(Step 6)*	0,32 *(Step 6)*	✓
Equilibrium concentration (mol·dm⁻³)	$\frac{n}{1} = 0{,}12$ *(Step 2)*	$\frac{0{,}35}{1} = 0{,}35$ *(Step 7)*	$\frac{0{,}12}{1} = 0{,}12$ *(Step 7)*	$\frac{0{,}32}{1} = 0{,}32$ *(Step 7)*	✓

$K_c = \frac{[N_2O][O_2]}{[NO_2][NO]} = \frac{(0{,}12)(0{,}32)}{(0{,}12)(0{,}35)} \overset{✓}{\underset{✓}{=}} 0{,}91$ ✓ (11)

2. Temperature. ✓ (1)

3. K_c was initially 3,93 (given) now it is 0,91. If the K_c value changed, the temperature must have changed – only a change in temperature can change the value of K_c. ✓ (1)

[13]

Activity 9

Consider the following reaction equation for the production of ammonia in the Haber process.

$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g) \qquad \Delta H < 0$$

In **each** of the following cases:

a) State how K_c changes and
b) Briefly explain your answer.

1. The concentration of the nitrogen gas is increased. (1)
2. The pressure in the reaction system is decreased. (1)
3. FeO is added to the reaction system. (1)
4. The reaction system is heated. (5)

[8]

NB

The **Haber Process** is the name of the chemical process to manufacture NH_3

Solutions

1. Remains constant because... ✓ (1)
2. ... K_c is only affected by a change in temperature. ✓ (1)
3. K_c Decreases ✓ (1)
4. Heating the reaction system favours the endothermic, reverse reaction ✓ which decreases the temperature ✓ of the system ∴ the concentration of the forward product, $[NH_3]$ ✓ decreases while the concentrations of the forward reactants, $[N_2]$ and $[H_2]$ increase ✓ ∴ K_c decreases. ✓ (5)

[8]

Activity 10

1. The reaction represented by the equation below reaches equilibrium.

$$\mathbf{Co(H_2O)_6^{2+}(aq) + 4C\ell^-(aq) \rightleftharpoons CoC\ell_4^{2-}(aq) + 6H_2O(\ell) \quad \Delta H > 0}$$

pink **blue**

Which ONE of the following changes to the reaction mixture will changes its colour from blue to pink?

A. Add a catalyst
B. Place the reaction mixture in a container with hot water.
C. Add a few drops of concentrated hydrochloric acid to the reaction mixture.
D. Add water to the reaction mixture. (2)

[2]

Solution

1. D ✓✓ **[2]**

3.6 Interpretation of graphs for chemical systems in dynamic equilibrium

Dynamic equilibrium in a chemical system can be represented graphically by a graph of:

- **reaction rate** versus time
- **amount** of each reagent (number of moles / mass / volume)
- **concentration** of each reagent (in mol·dm^{-3}) versus time.

For each of these graphs:

- **time** is the **independent variable** and is therefore placed on the **horizontal axis** and
- either the **concentration, amount** or the **reaction rate** is measured and is therefore the **dependent variable** which is placed on the **vertical axis.**

Worked example 5

Equal amounts of $SO_2(g)$ and $O_2(g)$ react in a sealed container and reach equilibrium:

$$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g) \qquad \Delta H < 0$$

Key to all graphs:
Reaction Rate:
Forward reaction: ——————
Reverse reaction: - - - - - - -
Concentration or amount of mol:
$[O_2]$ ——————
$[SO_2]$ ....
$[SO_3]$ — · — · —

PAY SPECIAL ATTENTION:
We use **square brackets [ ]** to indicate the **concentration** of a substance

Steps to follow

Step 1: We need to **interpret** each part of the graph for each reactant and product, step by step as the reaction proceeds and

Step 2: **identify** what **happens** if there is a change in the rate/ concentration of each substance, which is visible by a change in the shape of the graph.

(i) When the reaction initially starts:

Initially

- The forward reaction rate is high because the [reactants] is initially high and
- The reverse reaction rate is zero as there are no products to react in the reverse reaction.

hint

Graphs coincide: this means the graphs lie on top of each other

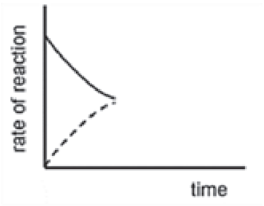
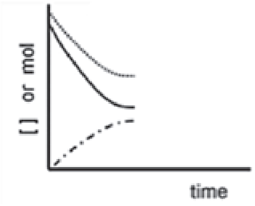
Worked example 5 (continued)

As the reaction takes place the

- concentrations of the reactants, $[SO_2]$ and $[O_2]$ decrease
- concentration of the forward product, $[SO_3]$ increases as

forward reaction rate > the reverse reaction rate.

The **forward** reaction **rate** gradually **decreases** and the **reverse** reaction **rate** gradually increases.

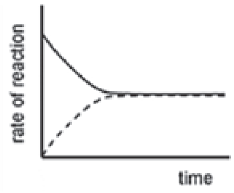
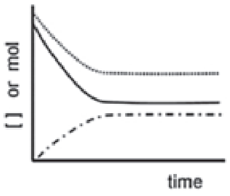
Reaction rate vs. time	Concentration (or mol) vs. time
	

(ii) The reaction reaches a state of dynamic chemical equilibrium

The forward and reverse reactions take place at the:

- **same time** and
- **same rate.**

The concentrations of the reactants and of the products remain constant.

Reaction rate vs. time	Concentration (or mol) vs. time
The lines **coincide** and are **horizontal**. 	The lines on the graph are all **horizontal**. The concentrations are not necessarily equal, so the lines do **not coincide**. 

(iii) O_2(g) is added to the system.

Adding O_2 (g) to the system **increases** the **concentration** of the O_2(g). O_2(g) is a reactant in the **forward reaction**, therefore the rate of the **forward** reaction immediately shows a **sharp increase.**

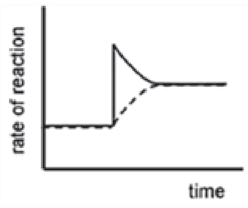
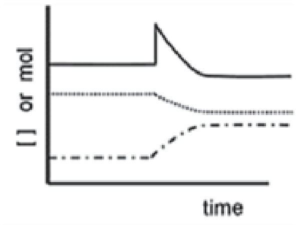
According to Le **Châtelier's Principle**:

- the reaction that opposes the change and decreases the concentration of the O_2(g) is favoured so the
  - forward reaction is favoured
  - concentrations of the SO_2(g) and O_2(g) (forward reactants) decrease
  - concentration of the SO_3(g) (forward product) increases.

Worked example 5 (continued)

The rate of the

- forward reaction decreases as the [O_2] and [SO_2] decrease and
- reverse reaction increases as the [SO_3] increases
- until a new dynamic equilibrium is established when the
    - forward and reverse reaction rates are again equal and
    - [O_2] and [SO_2] as well as the [SO_3] again remain constant.

Reaction rate vs. time	Concentration (or mol) vs. time
Increasing the **concentration** of the **forward reactant (O_2)** causes a **sharp rise** in the **forward reaction rate**. 	**Increasing** the **concentration** of the **O_2(g)** causes a **sharp rise** in its **concentration**. 

(iv) SO_3(g) is removed from the system.

Removing SO_3(g) to the system **decreases** the **concentration** of the SO_3(g). SO_3(g) is a reactant in the **reverse reaction**, therefore the rate of the **reverse** reaction immediately shows a **sharp decrease**.

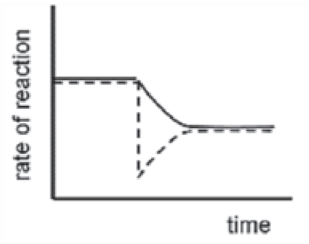
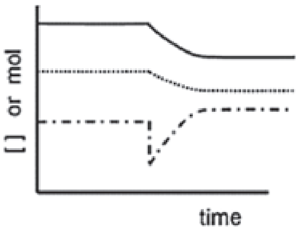
According to **Le Châtelier's Principle**:

- the reaction that opposes the change and increases the concentration of the SO_3(g) is favoured so the
- forward reaction is favoured
- concentrations of the SO_2(g) and O_2(g) (forward reactants) decrease
- concentration of the SO_3(g) (forward product) increases.

The **rate** of the

- forward reaction decreases as the [O_2] and [SO_2] decrease
- reverse reaction increases as the [SO_3] increases
- until a new dynamic equilibrium is established when the
    - forward and reverse reaction rates are again equal
    - [O_2] and [SO_2] as well as the [SO_3] again remain constant.

Worked example 5 (continued)

Reaction rate vs. time	Concentration (or mol) vs. time
Decreasing the **concentration** of the **reverse reactant (SO_3)** causes a **sharp drop** in the **reverse reaction rate**. 	**Decreasing** the **concentration** of the **reverse reactant (SO_3)** causes a **sharp drop in its concentration.** 

(v) **The temperature of the equilibrium mixture is increased.**

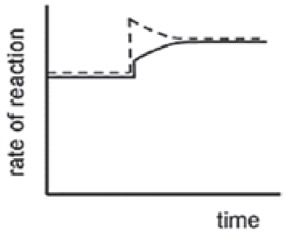
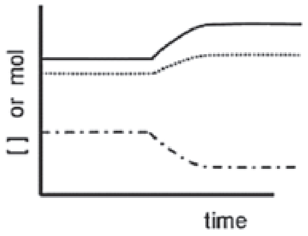
The heat of reaction is negative ($\Delta H < 0$) so the
- forward reaction is exothermic
- reverse reaction is endothermic.

Increasing the temperature of the system **increases both** the forward and the reverse **reaction rates.** The **rate** of the **endothermic reaction** always **increases the most** if the system's **temperature increases**, so for this reaction, the **reverse** reaction rate increases the most.

According to **Le Châtelier's Principle**:
- The reaction that opposes the change and decreases the temperature of the equilibrium system, is favoured so
  - the **endothermic reaction is favoured** and therefore the
  - reverse reaction is favoured and the
  - concentration of the $SO_3(g)$ (reverse reactant) decreases and the
  - concentrations of the $SO_2(g)$ and $O_2(g)$ (reverse products) increase and

Worked example 5 (continued)

The **rate** of the
- reverse reaction that was initially increased, decreases as the [SO_3] decreases and
- forward reaction increases as the [O_2] and [SO_2] increase
- until a new dynamic equilibrium is established when the
  - forward and reverse reaction rates are again equal and
  - [O_2] and [SO_2] as well as the [SO_3] again remain constant.

Reaction rate vs. time	Concentration (or mol) vs. time
Both reaction **rates initially increase** due to the **increase** in **temperature.**  The rate of the **endothermic** reaction **increases most** when an equilibrium system is heated. In this case the endothermic reaction is the reverse reaction.	A **change** in **temperature** does **not** cause any **sharp increases** or **decreases** in **concentration**. (There are no vertical lines on the graph.) 

(vi) The temperature of the equilibrium mixture is decreased.

The heat of reaction is negative ($\Delta H < 0$) so the
- forward reaction is exothermic
- reverse reaction is endothermic.

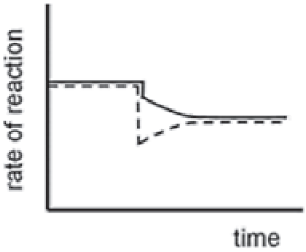
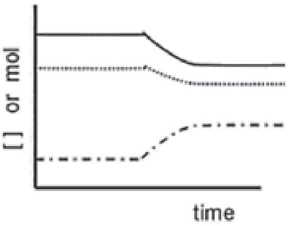
Decreasing the temperature of the system **decreases both** the forward and the reverse **reaction rates**. The **rate** of the **endothermic reaction** always **decreases the most** if the system's **temperature decreases**, so for this reaction, the **reverse** reaction rate decreases the most.

According to **Le Châtelier's Principle**:
- the reaction that opposes the change and increases the temperature of the equilibrium system, is favoured so the
  - **exothermic reaction is favoured** and therefore
  - **forward** reaction is favoured
  - concentrations of the SO_2(g) and O_2(g) (forward reactants) decrease and
  - concentration of the SO_3(g) (forward product) increases and

e.g. Worked example 5 (continued)

The **rate** of the

- forward reaction decreases as the [O_2] and [SO_2] decrease
- reverse reaction increases as the [SO_3] increases
- until a new dynamic equilibrium is established when
  - the forward and reverse reaction rates are again equal and
  - the [O_2] and [SO_2] as well as the [SO_3] again remain constant.

Reaction rate vs. time	Concentration (or mol) vs. time
Both reaction **rates initially decrease** due to the **decrease** in **temperature**.  The rate of the **endothermic** reaction **decreases most** when an equilibrium system is cooled. In this case the endothermic reaction is the reverse reaction.	A **change** in **temperature** does **not** cause any **sharp increases** or **decreases** in concentration. (There are no vertical lines on the graph.) 

hint

This applies to gases only.

(vii) The pressure of the equilibrium mixture is increased

From the balanced reaction equation, the number of gaseous moles is:

$2SO_2(g) + 1O_2(g) \rightleftharpoons 2SO_3(g)$

$2 + 1 = 3$ mol(g) $\rightleftharpoons$ 2 mol (g)

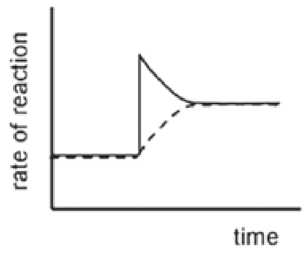
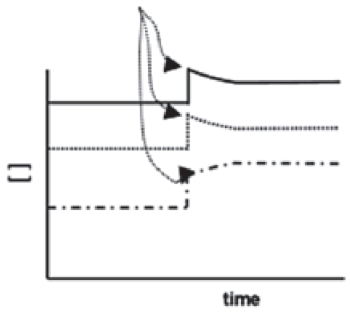
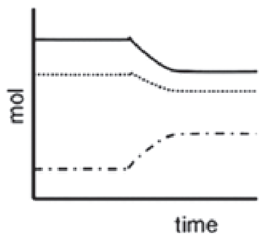
According to **Le Châtelier's Principle**:

- the reaction that opposes the change and decreases the pressure in the equilibrium system, is favoured so
  - the reaction that produces the **least moles of gas is favoured**
  - therefore the **forward** reaction is favoured and
  - the concentrations of the $SO_2(g)$ and $O_2(g)$ (forward reactants) decrease and
  - the concentration of the $SO_3(g)$ (forward product) increases and

Worked example 5 (continued)

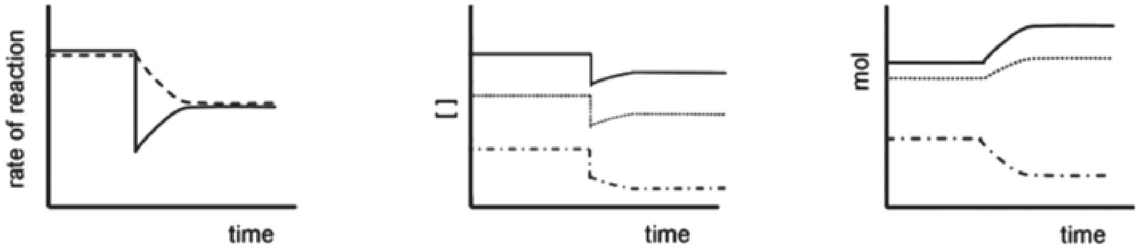
The rate of the

- forward reaction decreases as the [O_2] and [SO_2] decrease
- reverse reaction increases as the [SO_3] increases
- until a new dynamic equilibrium is established when
  - the forward and reverse reaction rates are again equal and
  - the [O_2] and [SO_2] as well as the [SO_3] again remain constant.

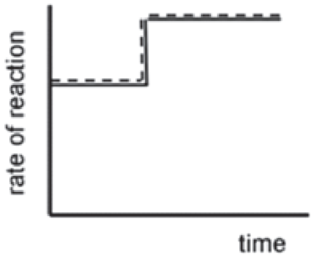
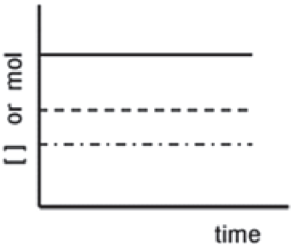
Reaction rate vs. time	Concentration vs. time
Increasing the **pressure** in the system **favours** the **forward** reaction and its **rate increases** sharply.  	When the **pressure** in the system **increases**, the **volume decreases** and the **concentration** is **inversely proportional** to the **volume** ($c = \frac{n}{V} \therefore\ c \propto \frac{1}{V}$) so the concentrations of all the gases in the system initially show a **sharp increase.**  Thereafter the concentrations change as predicted by Le Châtelier's Principle.
	Amount (mol) vs. time
	When the **pressure** in the system **increases**, there is no immediate **change** in the moles of each substance present, so there are **no vertical lines** on the mol vs. time graph.  The amounts (moles) change gradually as predicted by Le Châtelier's Principle.

Worked example 5 (continued)

(viii) The pressure of the equilibrium mixture is decreased (the volume is increased). The same reasoning is applied as in the previous example and the graphs are as follows:



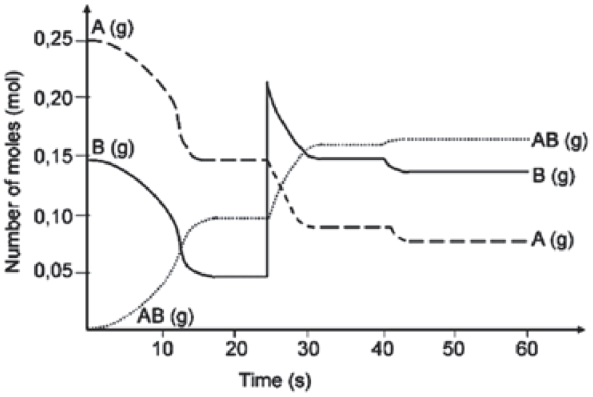
(ix) The addition of a suitable catalyst

The addition of a catalyst has no effect on the equilibrium of the system.	
Reaction rate vs. time	**Concentration vs. time**
Adding a catalyst **increases the rate** of the **forward** and the **reverse** reactions **equally.**  ↑ Addition of the catalyst	Adding a catalyst **does not disturb the equilibrium**, so the [O_2], [SO_2] and [SO_3] remain **constant.**  ↑ Addition of the catalyst

Activity 11

0,25 mol of A and 0,15 mol of B are introduced into a 1 dm^3 vessel. A and B react and reach an equilibrium which can be represented by the following equation:

$$A(g) + B(g) \rightleftharpoons AB(g) \qquad \Delta H < 0$$



hint

Make use of the **graph** to read off the values

The graph shows the number of moles of A(g), B(g) and AB(g) vs time, under varying conditions.

1. What are the concentrations of A(g), B(g) and AB(g) at t = 20 s? (3)
2. How can we be sure that the system has reached equilibrium at t = 20 s? (1)
3. Give an explanation for the change that occurs at t = 25 s. (1)
4. Explain the change in concentrations of A(g) and B(g) between t = 25 s and t = 35 s. (3)
5. How does the equilibrium constant at t = 35 s compare with the equilibrium constant at t = 25 s? (No calculation is required.) (1)
6. Assuming that the volume was kept constant, what was done at t = 40 s that produced the change as shown? Explain your answer. (5)
7. Do any reactions occur during the interval t = 30 s and t = 40 s? Briefly explain your answer. (4)

[18]

Solutions

1. [A] = 0,15 mol·dm^{-3} ✓ [B] = 0,05 mol·dm^{-3} ✓ [AB] = 0,1 mol·dm^{-3} ✓ (3)
2. The number of mol of A, B and AB **remains constant** from 16 s to 25 s. ✓ (1)
3. The amount of B is increased by adding B to the system, thus **increasing** the **[B]**. ✓ (1)
4. With the addition of B, [B] increases and the **forward reaction is favoured** ✓ according to Le Châtelier's principle, so that some of B reacts with A to form more AB. Hence the [A] and [B] ✓ decrease and [AB] increases. ✓ (3)
5. **K$_c$** remains **constant** provided the **temperature** remains **constant.** ✓ (1)
6. The **temperature** was **lowered.** ✓ It was not a concentration change, because there are no peaks at 25 s ✓**.** Therefore it must be a temperature change. From the graph, it can be seen that the forward reaction was favoured ✓ because there is an increase in the number of moles of AB, and a decrease in the number of moles of A and B when establishing the **new equilibrium.** ✓ According to the information given, the forward reaction is exothermic. ✓ According to Le Châtelier's Principle, a decrease in temperature favours the exothermic reaction. (5)
7. Yes, but since equilibrium has been reached, ✓ the forward and reverse reactions take place at the **same time** ✓ and at the **same** ✓ **rate**, so that **no changes** occur in the concentrations of A, B or AB. ✓ (4)

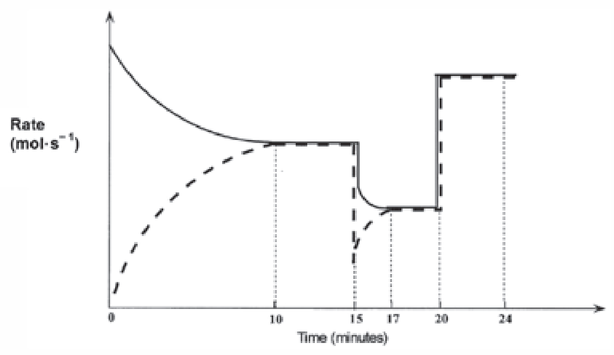
[18]

Activity 12

Nitrogen and oxygen gases react in a sealed container according to the following equation:

$$O_2(g) + N_2(g) \rightleftharpoons 2NO(g)$$

After the reaction reaches equilibrium, certain changes are made. The following graph of rate of reaction versus time represents the situation.



1. Write the equation for the reaction represented by the dashed line on this graph. (2)

2. What is represented by the section of the graph between the 10th and 15th minute? Explain your answer. (2)

3. A temperature change takes place at t = 15 minutes.

3.1 Was the temperature increased or decreased at t = 15 minutes? (1)

3.2 Explain whether the forward reaction is exothermic or endothermic. (3)

3.3 What effect does this temperature change have on the equilibrium constant (K_c)? Explain your answer. (3)

4. A pressure change is introduced at t = 20 minutes.

4.1 Was the pressure increased or decreased? (3)

4.2 Explain how this change in pressure affects the amounts of each gas at equilibrium. (2)

[16]

Solutions

1. $2NO(g) \rightarrow N_2(g) + O_2(g)$ ✓✓ (2)

2. The system is in equilibrium ✓ because the rates of the forward and reverse reactions are equal. ✓ (2)

3.1 Decreased. ✓ (1)

3.2 The rates of both the forward and the reverse reactions decrease ✓, but the rate of the reverse reaction decreases more. ✓ The rate of the endothermic reaction will always decrease the most when a reaction mixture is cooled. Thus the reverse reaction is endothermic. That means that the forward reaction must be exothermic and was favoured by the decrease in temperature. ✓

$$O_2(g) + N_2(g) \rightleftharpoons 2NO(g) + \text{Energy}$$ (3)

3.3 Increases. ✓

Since $K_c = \frac{[NO]^2}{[N_2][O_2]}$ (3)

and the forward reaction is favoured ✓ which causes an increase in [NO], the value of K_c increases. ✓ (3)

4.1 Increased. ✓ The pressure is probably caused by a volume decrease. This results in the concentrations ($c = \frac{n}{V}$) of the reactants, as well as the products, to increase ✓, which in turn causes an equal increase in the forward and reverse reaction rates. ✓ (3)

4.2 The amount (n) of reactants and products does not change, ✓ since **2 moles** of gaseous reactant molecules $\rightleftharpoons$ **2 moles** of gaseous product molecules. ✓ (2)

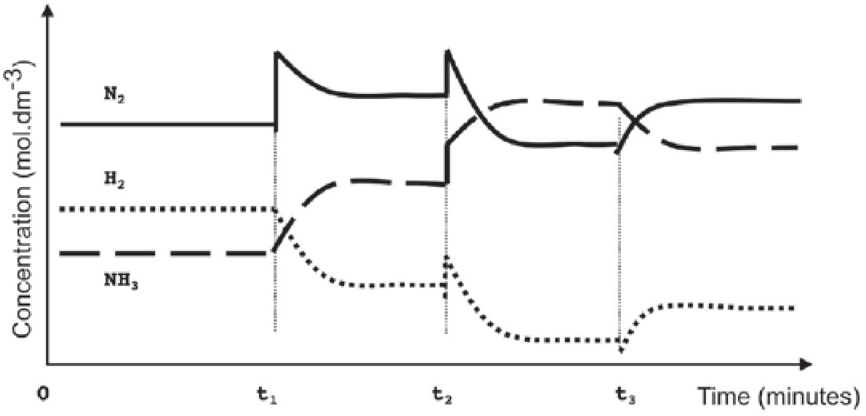
[16]

Activity 13

A fertiliser company produces ammonia on a large scale at a temperature of 450 °C. The balanced equation below represents the reaction that takes place in a sealed container.

$$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g) \qquad \Delta H < 0$$

To meet an increased demand for fertiliser, the management of the company instructs their engineer to make the necessary adjustments to increase the yield of ammonia. In a trial run on a small scale in the laboratory, the engineer makes adjustments to the TEMPERATURE, PRESSURE and CONCENTRATION of the equilibrium mixture. The graphs below represent the results obtained.



1. Identify the changes made to the equilibrium mixture at each of the following times:
   - **1.1** t_1 (2)
   - **1.2** t_2 (2)
   - **1.3** t_3 (2)
2. At which of the above time(s) did the change made to the reaction mixture lead to a higher yield of ammonia? Write down only $\mathbf{t_1}$ and/or $\mathbf{t_2}$ and/or $\mathbf{t_3}$ (2)
3. The engineer now injects 5 mol N_2 and 5 mol H_2 into a 5 dm^3 sealed empty container. Equilibrium is reached at 450 °C. Upon analysis of the equilibrium mixture, he finds that the mass of NH_3 is 20,4 g. Calculate the value of the equilibrium constant (K_c) at 450 °C (9)

[17]

Solutions

1.

1.1 The concentration of nitrogen ✓ is increased ✓ / More Nitrogen ✓ added ✓ **(any two)** (2)

1.2 The pressure ✓ on the system is increased ✓ (2)

1.3 The temperature ✓ is increased ✓ (2)

2. t_1 ✓and t_2 ✓ (2)

3.

PAY SPECIAL ATTENTION:

This is how marks are allocated to the answer of this K_c calculation:

- Use of $n = \frac{m}{M}$ ✓
- $n(NH_3)$ at equilibrium = 1,2 mol ✓
- Using ratio $n(N_2) : n(H_2) : n(NH_3) = 1 : 3 : 2$ ✓
- $n(N_2)$ at equilibrium (initial - change) ✓
- $n(H_2)$ at equilibrium (initial - change) ✓
- divide by volume (calculation of concentration) ✓
- K_c expression ✓
- Substitution into K_c expression ✓
- Final answer ✓ (9)

$n(NH_3) = \frac{m}{M} = \frac{20,4}{17}$ ✓= 1,2 mol ✓

	SO_2	O_2	SO_3
Molar ratio	1	3	2
Initial quantity (mol)	5	5	0
Change (mol)	0,6	1,8	1,2
Quantity at equilibrium	4,4	3,2	1,2
Concentration ($mol \cdot dm^{-3}$)	0,88	0,64	0,24

$$K_c = \frac{[NH_3]^2}{[N_2][H_2]^3} = \frac{(0,24)^2}{(0,88)(0,64)^3} = 0,25$$

[17]

Activity 14

2 mol of $NO_2(g)$ and an unknown amount of $N_2O_4(g)$ are sealed in a 2 dm^3 container, that is fitted with a plunger, at a certain temperature. The following reaction takes place:

$$2NO_2(g) \rightleftharpoons N_2O_4(g)$$

At equilibrium it is found that the NO_2 concentration is 0,4 $mol{\cdot}dm^{-3}$. The equilibrium constant at this temperature is 2.

1. Calculate the initial amount (in mol) of $N_2O_4(g)$ that was sealed in the container. (8)

The plunger is now pushed into the container causing the pressure of the enclosed gas to increase by decreasing the volume

2. How will this change influence the amount of nitrogen dioxide at equilibrium? Only write down INCREASES, DECREASES or REMAINS THE SAME. (1)
3. Use Le Châtelier's principle to explain your answer to QUESTION 2.1.2. (2)

[11]

Solutions

1.

	$2NO_2$	N_2O_4
Initial number of mole (mol)	2	x
Number of moles used/formed (mol)	–1,2✓	+0,6 ✓
Number of moles at equilibrium(mol)	0,8✓	x + 0,6 ✓
Equilibrium concentration ($mol{\cdot}dm^{-3}$)	0,4	$\frac{(x + 0,6)}{2}$ ✓

$$K_c = \frac{[N_2O_4]}{[NO_2]^2} ✓$$

$$2 ✓ = \frac{(x + 0,6)\ \ 2}{(0,4)^2}$$

$$x = 0,04 \text{ mol} ✓$$

(8)

hint Remember, if you struggle to see how this calculation worked, please revise the "subject of formula" section at the beginning of this book.

2. Decreases ✓ (1)

3. When the pressure is increased the system will try to decrease the pressure. ✓
The forward reaction (2 mol to 1 mol) is favoured. ✓ (2)

[11]

3.7 Applications of equilibrium principles in the chemical industry

- Many industrial processes involve reversible chemical reactions that reach equilibrium.
- Two factors that are important from an economic point of view are the **yield** (**amount of products** produced relative to the amount of reactants) and the **reaction rate** (rate at which the products are formed).

hint

The success of chemical processes in both the laboratory and the industry depends on:

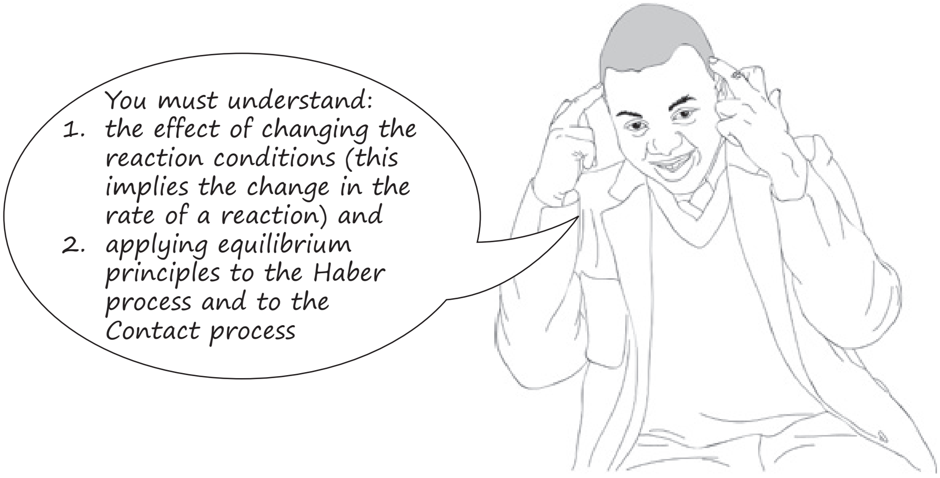
- the **amount of product** that is produced and
- how **cost effective** this production is.

NB

REMEMBER

Standard atmospheric pressure (1 atm) is the atmospheric pressure at sea level.

1 atm = 101,3 kPa
= 101 325 Pa (pascal)



Haber Process		Step 2 of the Contact Process
Nitrogen, $N_2(g)$ Hydrogen, $H_2(g)$	**Reactants**	Sulphur dioxide, $SO_2(g)$ Oxygen, $O_2(g)$
• $N_2(g)$: fractional distillation of liquid air • $H_2(g)$: steam reforming of methane (CH_4) from natural gas	**Source of reactants**	• S (s) : sulphur • O_2 (g) : fractional distillation of liquid air • $S(s) + O_2(g) \rightarrow SO_2(g)$
Ammonia, $NH_3(g)$	**Products**	Sulphur trioxide, $SO_3(g)$
$N_2(g) + 3H_2(g) \rightleftharpoons 2NH_3(g)$	**Reaction equation**	$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g)$
4 mol (g) : 2 mol (g)	**Gas mol ratio**	3 mol (g) : 2 mol (g)
$\Delta H < 0$ ∴ forward reaction is exothermic	**Heat of reaction (Enthalpy)**	$\Delta H < 0$ ∴ forward reaction is exothermic
• Increasing the temperature • Increasing the concentrations of the forward reactants N_2 and H_2 • Adding a suitable catalyst	**Increase the reaction rate by**	• Increasing the temperature • Increasing the concentrations of the forward reactants SO_2 and O_2 • Adding a suitable catalyst
• Decreasing the temperature • (favours the forward exothermic reaction) • Increasing the concentrations of the forward reactants N_2 and H_2 • Increasing the pressure • (favours the forward reaction that produces less gas moles)	**Increase the yield by**	• Decreasing the temperature • (favours the forward exothermic reaction) • Increasing the concentrations of the forward reactants SO_2 and O_2 • Increasing the pressure • (favours the forward reaction that produces less gas moles)
Temperature: approx. 450 °C Pressure: approx. 200 atm	**Optimal Reaction conditions**	Temperature: approx. 450 °C Pressure: approx. 1 – 2 atm
Fe (iron) OR FeO (iron(II)oxide)	**Catalyst**	V_2O_5 (vanadium pentoxide)

NB

- When the reaction system is in a state of dynamic equilibrium, **high temperatures** will **increase the reaction rates** BUT will **decrease the yield** of the products. Both the forward reactions are **exothermic**, therefore high temperature will, according to Le Châtelier's Principle, favour the reverse endothermic reactions. This makes the reactions economically less viable!
- Temperatures of ± 450 °C are maintained in both the Haber and Contact processes.
- Industrial processes at **high pressures** require powerful compressors and strong reaction vessels which are very **expensive**. This makes the reactions economically less viable! Industrial plants that operate at high pressures also pose **safety risks** for the workers.
- It is therefore necessary to find a compromise between the **reaction rates**, the **yield**, and the **higher costs**.
- A pressure of 200 times that of atmospheric pressure is maintained in the Haber process to ensure that the yield is high enough.
- The yield of SO_3 in the Contact Process is however more than 90% at a pressure of 1 atm and therefore it is economically viable to keep the reaction at atmospheric pressure. It is unnecessary to maintain higher pressures and this saves unnecessary costs.

Activity 15

Name the industrial process for the production of ammonia (1)

[1]

Solution

Haber (Bosch) process ✓ **[1]**

Activity 16

Sulphuric acid is an important substance used in the manufacture of fertilisers. The equation below represents one of the steps in the industrial preparation of sulphuric acid.

$$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g) \qquad \Delta H < 0$$

1. Write down the name of the process used to prepare sulphuric acid in industry. (1)
2. Write down the NAME or FORMULA of the catalyst used in the process in question (1)
3. Is the forward reaction exothermic or endothermic? Give a reason for the answer.

   The reaction reaches equilibrium at a certain temperature in a 2 dm^3 closed container.

   On analysis of the equilibrium mixture, it is found that 0,6 mol of $SO_2(g)$, 0,5 mol of $O_2(g)$ and 0,4 mol of $SO_3(g)$ are present in the container. (1)
4. List THREE changes that can be made to this equilibrium to increase the yield of $SO_3(g)$ (3)
5. The temperature is NOW increased and the reaction is allowed to reach equilibrium for the second time at the new temperature. On analysis of this new equilibrium mixture, it is found that 0,2 mol of $SO_3(g)$ is present in the container. Calculate the equilibrium constant for this reaction at the new temperature. (8)

[14]

Solutions

1. Contact process ✓ (1)
2. V_2O_5 (vanadium pentoxide) ✓ (1)
3. Exothermic $\Delta H < 0$ ✓ (1)
4. Any three: ✓✓✓
   Decrease temperature
   Increase pressure
   Increase concentration of both/any one of the reactants
   Remove SO_3 continuously (3)
5.

	SO_2	O_2	SO_3
Molar ratio	2	1	2
Initial quantity (mol)	0,6	0,5	0,4
Change (mol)	0,2	0,1	0,2
Quantity at equilibrium	0,8	0,6	0,2
Concentration ($mol \cdot dm^{-3}$)	0,4	0,3	0,1

$$K_c = \frac{[SO_3]^2}{[SO_2]^2[O_2]} = \frac{(0,1)^2}{(0,4)^2(0,3)} = 0,21$$

(8)

NB

This how marks are allocated to the answer of this K_c calculation:

- Change in $n(SO_3) = 0,2$ mol ✓
- Ratio $n(SO_2) : n(O_2) : n(SO_3) = 2 : 1 : 2$ ✓
- $n(SO_2)$ at equilibrium = initial + change ✓
- $n(O_2)$ at equilibrium = initial + change ✓
- divide three equilibrium amounts by 2 (calculation of concentration) ✓
- K_c expression ✓
- Substitution into K_c expression ✓
- Final answer ✓ (8)

[**14**]

Activity 17

The reaction below represents the catalysed step in the contact process:

$$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g) \qquad \Delta H < 0$$

The reaction takes place in a closed container and reaches equilibrium at 427 °C. How will a HIGHER temperature affect each of the following? Write down only INCREASES, DECREASES or REMAINS THE SAME.

1. The rate of production of $SO_3(g)$ (2)
2. The yield of $SO_3(g)$ (2)
3. The reaction is investigated on a small scale in the laboratory. Initially 4 mol of $SO_2(g)$ and an unknown mass, x, of $O_2(g)$ are sealed in a 2 dm^{-3} flask and allowed to reach equilibrium at a certain temperature.
   At equilibrium it is found that the concentration of $SO_3(g)$ present in the flask is 1,5 $mol{\cdot}dm^{-3}$.
   Calculate the mass of $O_2(g)$ initially present in the flask if the equilibrium constant (K_c) at this temperature is 4,5. (8)

[12]

Solutions

1. Increases ✓✓ (2)
2. Decreases ✓✓ (2)
3.

	SO_2	O_2	SO_3
Molar ratio	2	1	2
Initial quantity (mol)	4	$\frac{x}{32}$ ✓✓	0
Change (mol)	3	1,5	3 ratio✓
Quantity at equilibrium	1	$\frac{x}{32} - 1,5$ ✓	3 ✓
Concentration ($mol{\cdot}dm^{-3}$) ($C = \frac{n}{V}$)	$C = \frac{n}{V} = \frac{1}{2} = 0,5$	$\frac{(x - 48)}{64}$	$\frac{3}{2} = 1,5$ (divide by 2) ✓

$$K_c = \frac{[SO_3]2}{[SO_2]^2[O_2]} \quad ✓ \qquad \therefore 4,5 = \frac{(1,5)^2}{(0,5)^2\,\frac{(x-48)}{64}}$$

$\therefore x = 176$ g ✓ (8)

[12]

hint

Remember, if you struggle to see how this calculation worked, please revise the “subject of formula” section at the beginning of this book.

4 Unit

Acids and bases

4.1 Summary

Acid	(**Arrhenius theory**): is a substance that produces hydrogen ions (H^+) / hydronium ions (H_3O^+) when it dissolves in water (**Brønsted-Lowry theory**): is a proton (H^+ ion) donor.
Strong acid	Ionises completely in water to form a high concentration of H_3O^+ ions. Examples of strong acids are hydrochloric acid ($HC\ell$), sulphuric acid (H_2SO_4) and nitric acid (HNO_3).
Weak acid	Ionises incompletely in water to form a low concentration of H_3O^+ ions. Examples of weak acids are ethanoic acid (CH_3COOH) and oxalic acid $(COOH)_2$.
Concentrated acid	Concentrated acids contain a large amount (number of moles) of acid in proportion to the volume of water.
Diluted acid	Dilute acids contain a small amount (number of moles) of acid in proportion to the volume of water.
Base	(**Arrhenius theory**): is a substance that produces hydroxide ions (OH^-) when it dissolves in water. (**Brønsted-Lowry theory**): is a proton (H^+ ion) acceptor.
Strong base	Dissociates (breaks up) completely in water to form a high concentration of OH^- ions. Examples of strong bases are sodium hydroxide ($NaOH$) and potassium hydroxide (KOH).
Weak base	Dissociates/ionises incompletely in water to form a low concentration of OH^- ions. Examples of weak bases are ammonia (NH_3), calcium carbonate ($CaCO_3$), potassium carbonate (K_2CO_3) , and sodium hydrogen carbonate ($NaHCO_3$).
Concentrated base	Concentrated bases contain a large amount (number of moles) of base in proportion to the volume of water.
Diluted base	Dilute bases contain a small amount (number of moles) of base in proportion to the volume of water.
Equivalence point	is the point at which the acid / **base** has completely reacted with the base/**acid**.
End point	is the point where the indicator changes colour.
Ionisation	a process that takes place when a covalent compound reacts with water to form new ions OR Breaking up of a molecule into charged components (ions). In acid-base reactions this usually means dissolving in water.

Dissociation	a process that take place when an ionic compound dissolves in water allowing the ions in the compound to separate. The same as ionisation.
Hydrolysis	ionisation of a salt in water, or, more generally, splitting a molecule by reacting it with water (e.g. in organic chemistry).
Ampholyte (Amphiprotic)	is a substance that can act either as an acid or a base. example: Water (H_2O)

Activity 1

1. An Arrhenius acid is a substance that
   - **A.** Accept a proton
   - **B.** Donates a proton
   - **C.** Produces H^+ in an aqueous solution
   - **D.** Produces OH^- in an aqueous solution (2)

2. Which of the following is an example of the strong base
   - **A.** $CaCO_3$
   - **B.** KOH
   - **C.** K_2CO
   - **D.** $NaHCO_3$ (2)

3. An aqueous solution that contains more hydronium ions than hydroxyl ions is a(an)
   - **A.** Acidic solution
   - **B.** Neutral solution
   - **C.** Basic solution
   - **D.** Standardised solution (2)

4. A solution that has a large amount of dissolved substances in proportion to the volume of water
   - **A.** Strong solution
   - **B.** Weak solution
   - **C.** Concentrated solution
   - **D.** Diluted solution (2)

[8]

Solutions

1. D✓✓ **2.** B✓✓ **3.** A✓✓ **4.** C✓✓ [8]

NOTE:

- You must know the Arrhenius and the Brønsted-Lowry definitions for acids and bases, BUT we will **ALWAYS use the Brønsted-Lowry** theory for all further discussions of acids and bases.

4.2 Properties of acids and bases

	ACIDS	BASES
PROPERTIES	• Have a sour taste; • Influence the colour of indictors; • Are electrolytes in solution; • Increase the H^+-ion concentration in a solution; • Decrease the OH^--ion concentration in a solution; • Decrease the pH of a solution.	• Have a bitter taste and feel soapy; • Influence the colour of indictors; • Are electrolytes in solution; • Decrease the H^+-ion (or H_3O^+-ion) concentration in a solution; • Increase the OH^--ion concentration in a solution; • Increase the pH of a solution.
ACID-BASE THEORIES	**ARRHENIUS**	
	• An **acid** releases $\mathbf{H^+}$/ $\mathbf{H_3O^+}$ -ions/ in **aqueous solutions.** • $HC\ell \rightarrow \mathbf{H^+} + C\ell^-$ • $HC\ell + H_2O \rightarrow \mathbf{H_3O^+} + C\ell^-$	• A base releases OH^- -ions in aqueous solutions. • $NaOH \rightarrow Na^+ + \mathbf{OH^-}$
	BRØNSTED-LOWRY	
	• An acid is a **proton donor.** • $\mathbf{HC\ell} + H_2O \rightarrow H_3O^+ + C\ell^-$ • $\mathbf{NH_4^+} + H_2O \rightarrow H_3O^+ + NH_3$	• A base is a **proton acceptor.** • $\mathbf{OH^-} + H^+ \rightarrow H_2O$ • $\mathbf{NH_3} + H_2O \rightarrow OH^- + NH_4^+$
REACTIONS WITH WATER	• **Ionise** in water to produce hydronium ions E.g. $HC\ell + H_2O \rightarrow H_3O^+ + C\ell^-$	• Ionic bases like NaOH **dissociate** in water to form hydroxyl ions. NaOH(s) ⟶ Na+(aq) + $C\ell^-$(aq) • Ammonia (NH_3) ionises in water to form hydroxyl ions $NH_3 + H_2O \rightarrow OH^- + NH_4^+$

Activity 2

1. Which of the following is the property of an acid
   - **A.** Decreases H_3O^+ ion concentration in solution
   - **B.** Decreases OH^- ion concentration in solution
   - **C.** Increases OH^- ion concentration in solution
   - **D.** Increases the pH of a solution (2)

[2]

Solution

1. B✓✓ **[2]**

4.3 Common acids

	ACID	FORMULA	STRONG / WEAK		EXAMPLES & USES
STRONGEST	Hydrochloric acid	$HC\ell$	Strong	Ionises almost completely in water	• Stomach acid (to digest food) Used • in swimming pools to control the pH (acidity) of the water; • to clean metals for soldering.
	Sulphuric acid	H_2SO_4	Strong		Used • to produce fertilisers; • to produce phosphoric acid; • as dehydrating agent; • as car battery acid and • in gold extraction.
	Nitric acid	HNO_3	Strong		Used • to produce fertilisers and • to produce explosives.
INCREASING STRENGTH	Oxalic acid	$(COOH)_2$	Weak	Ionises partially in water	Used • to remove rust and stains and • as bleach.
	Phosphoric acid	H_3PO_4	Weak		Used • to add taste to gaseous cold drinks; • in dental cement and • to produce fertilisers like superphosphates.
WEAKEST	Ethanoic acid	CH_3COOH	Weak		Vinegar • Used • to flavour food; • to produce plastics; • to neutralise hair relaxers and • to treat jellyfish stings.
	Carbonic acid	H_2CO_3	Weak		Used • to make gaseous cold drinks.

hint

Strong acid: **$HC\ell$; H_2SO_4; HNO_3**

Weak acid: **CH_3COOH; $(COOH)_2$**

Strong base: **$NaOH$; KOH; $Mg(OH)_2$**

Weak base: **NH_3; $NaHCO_3$; $CaCO_3$**

4.4 Common bases

	BASE	FORMULA	STRONG / WEAK		EXAMPLES & USES
	Sodium hydroxide (Caustic soda)	$NaOH$	Strong	Dissociates completely in water	Used • in the production of soap and • as drain cleaner and • to relax the curl in human hair.
STRONGEST	Potassium hydroxide (Caustic potash)	KOH	Strong		Used • in the production of soap; • in the production of biodiesels and • as electrolytes in cells.
	Magnesium hydroxide	$Mg(OH)_2$	Strong		Used • in antacids (Milk of Magnesia); • in laxatives and • to neutralise acidic waste water.
INCREASING STRENGTH	Calcium hydroxide (Slaked lime)	$Ca(OH)_2$	Strong		Used • to clarify water by removing particles from the water; • to neutralise acidic water so that water pipes are not damaged and • to neutralise acidic soil.
	Sodium carbonate (Washing soda)	Na_2CO_3	Weak	Dissociates / Ionises partially in water	Used • to manufacture glass and • to soften water or laundry.
WEAKEST	Calcium carbonate (Limestone)	$CaCO_3$	Weak		Found in marble and sea shells. Used • in the production of cement; • in chalk to write with; • as an antacid.
	Ammonia	NH_3	Weak		Used • to produce nitric acid; • to produce fertilizers and • in cleaning materials.
	Sodium bicarbonate (Baking soda)	$NaHCO_3$	Weak		Used • in baking to let dough rise

4.5 Mono- and polyprotic acids

Acids can be classified according to the number of protons (H^+) that they can donate.

NB: Monoprotic acids have only one proton (H^+) to donate**. Polyprotic** acids can donate two or three protons. The protons are donated in steps as shown in the examples in the table below**.**

Monoprotic acids	**Polyprotic acids**	
Can only donate only one proton (H^+)	Can donate more than one proton (H^+)	
	Diprotic acids	**Triprotic acids**
	Can donate 2 protons (H^+).	Can donate 3 protons (H+).
$\mathbf{H}C\ell$, $\mathbf{H}NO_3$, $CH_3COO\mathbf{H}$	$\mathbf{H_2}SO_4$, $\mathbf{H_2}CO_3$	$\mathbf{H_3}PO_4$
E.g. $\mathbf{H}C\ell \rightarrow \mathbf{H}^+ + C\ell^-$	E.g. $\mathbf{H}_2SO_4 \rightarrow \mathbf{H}^+ + HSO_4^-$ $HSO_4- \rightarrow \mathbf{H}^+ + SO_4^{2-}$	E.g. $\mathbf{H}_3PO_4 \rightarrow \mathbf{H}^+ + H_2PO_4^-$ $\mathbf{H}_2PO_4^- \rightarrow \mathbf{H}^+ + HPO_4^{2-}$ $HPO_4^{2-} \rightarrow \mathbf{H}^+ + PO_4^{3-}$

4.6 Conjugate acid-base pairs

4.6.1 Acid-base reactions

hint

"Conjugate" is from Latin, it means literally "yoked together" or to be a couple.

Acid-base reactions take place **simultaneously**. The acid donates a proton to the base, while the base accepts the proton from the acid.

NB

DEFINITION

An **acid-base (protolytic) reaction** is a reaction in which a **proton (H^+) is transferred**

4.6.2 Conjugate acids and bases

CONJUGATE ACIDS
• When an **acid donates a proton (H^+)**, a conjugate base is produced. • The acid and its conjugate base are called a **conjugate acid-base pair.**
acid $\rightleftharpoons$ H^+ + ***conjugate base***
Examples: $HC\ell \rightleftharpoons H^+ + \mathbf{C\ell^-}$ acid ***conjugate base*** $H_2SO_4 \rightleftharpoons H^+ + \mathbf{HSO_4^-}$ acid ***conjugate base***

CONJUGATE BASES
• When a **base receives a proton (H^+)**, a ***conjugate acid*** is produced. • The base and its conjugate acid are called a **conjugate acid-base pair**.
base + H^+ $\rightleftharpoons$ ***conjugate acid***
Examples: $OH- + H^+ \rightleftharpoons \mathbf{H_2O}$ base ***conjugate acid*** $HSO_4^- + H^+ \rightleftharpoons \mathbf{H_2SO_4}$ base ***conjugate acid***

Activity 3

1. In the reaction: $H_2SO_4(aq) + H_2O(\ell) \rightleftharpoons HSO_4^-(aq) + H_3O^+(aq)$, the Brønsted-Lowry bases are:

A H_2O and H_3O^+

B H_2SO_4 and H_3O^+

C HSO_4^- and H_3O^+

D H_2O and HSO_4^- (2)

[2]

Solution

1. D ✓✓ **[2]**

Activity 4

Find the conjugate bases and conjugate acids.

Acid	Conjugate base
$HC\ell$	
HNO_3	
H_2SO_4	
HSO_4^-	
H_3PO_4	
$H_2PO_4^-$	
HPO_4^{2-}	
H_2CO_3	
HCO_3^-	
CH_3COOH	
$(COOH)_2$	
H_2O	
NH_4^+	
H_3O^+	

Base	Conjugate acid
$C\ell^-$	
NO_3^-	
HSO_4^-	
SO_4^{2-}	
$H_2PO_4^-$	
HPO_4^{2-}	
PO_4^{3-}	
HCO_3^-	
CO_3^{2-}	
SO_4^{2-}	
HSO_4^-	
OH^-	
NH_3	
H_2O	

[28]

Note that some of these are marked in BOLD. That is because they are "**amphiprotic**". We will see what this means later on.

Solution

1. Check your answers

Acid	Conjugate base
$HC\ell$	$C\ell^-$ ✓
HNO_3	NO_3^- ✓
H_2SO_4	**HSO_4^-** ✓
HSO_4^-	SO_4^{2-} ✓
H_3PO_4	$H_2PO_4^-$ ✓
$H_2PO_4^-$	**HPO_4^{2-}** ✓
HPO_4^{2-}	PO_4^{3-} ✓
H_2CO_3	**HCO_3^-** ✓
HCO_3^-	CO_3^{2-} ✓
CH_3COOH	CH_3COO^- ✓
$(COOH)_2$	$C_2O_4H^-$ ✓
H_2O	OH^- ✓
NH_4^+	NH_3 ✓
H_3O^+	**H_2O** ✓

Base	Conjugate acid
$C\ell^-$	$HC\ell$ ✓
NO_3^-	HNO_3 ✓
HSO_4^-	H_2SO_4 ✓
SO_4^{2-}	**HSO_4^-** ✓
$H_2PO_4^-$	H_3PO_4 ✓
HPO_4^{2-}	**$H_2PO_4^-$** ✓
PO_4^{3-}	HPO_4^{2-} ✓
HCO_3^-	H_2CO_3 ✓
CO_3^{2-}	**HCO_3^-** ✓
SO_4^{2-}	**HSO^-** ✓
HSO_4^-	H_2SO_4 ✓
OH^-	**H_2O** ✓
NH_3	NH_4^+ ✓
H_2O	H_3O^+ ✓

[28]

Steps to follow when identifying conjugates

1. Find the **acid** on the **left** hand side of the arrow. Label it **acid$_1$.**
2. Find the **conjugate base** of this acid on the **right** hand side of the arrow. Label it **base$_1$.**
3. Draw a **bracket** to show that these two form an **acid-base conjugate pair**.
4. Find the **base** on the **left** hand side of the arrow. Label it **base$_2$.**
5. Find the **conjugate acid** of this base on the **right** hand side of the arrow. Label it **acid$_2$.**
6. Draw a **bracket** to show that these two form an **acid-base conjugate pair**.

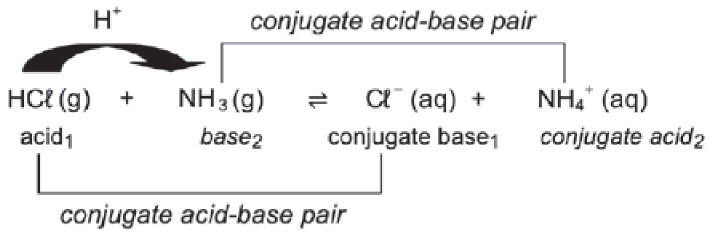
Worked example 1

For each of the following reactions, indicate the acid-base conjugate pairs.

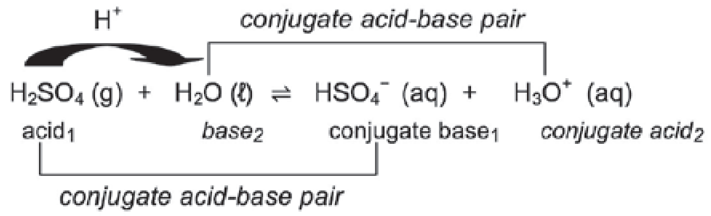
1. $HC\ell(g) + NH_3(g) \rightleftharpoons C\ell^-(aq) + NH_4^+(aq)$
2. $H_2SO_4(g) + H_2O(\ell) \rightleftharpoons HSO_4^-(aq) + H_3O^+(aq)$
3. $H_3PO_4(g) + OH^-(aq) \rightleftharpoons H_2PO_4^-(aq) + H_2O(\ell)$

Solutions

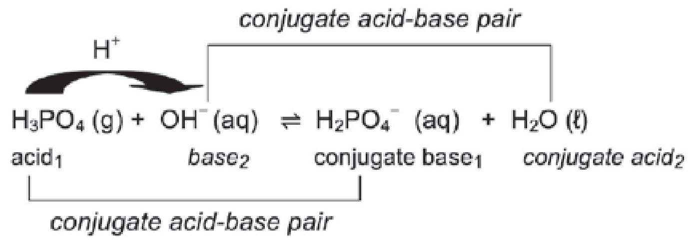
1.



2.



3.



4.7 Ampholyte (amphiprotic) substance

NB

Ampholyte is a substance that can act as either a base or acid.

An ampholyte:

- acts as a **base** in the presence of an **acid** and
- acts as an **acid** in the presence of a **base.**

Example:

Water (H_2O) is an ampholyte:

Water as an acid
$H_2O(\ell)$ + $NH_3(g)$ $\leftrightharpoons$ **$OH^-(aq)$** + $NH_4^+(aq)$
acid$_1$ base$_2$ conjugate base$_1$ *conjugate acid$_2$*

Water as a base
$HC\ell(g)$ + **H_2O (g)** $\leftrightharpoons$ $C\ell^-(aq)$ + **$H_3O^+(aq)$**
acid$_1$ base$_2$ conjugate base$_1$ *conjugate acid$_2$*

Example:

Show that hydrogen sulphate ion **(HSO_4^-)** is an ampholyte.

The hydrogen sulphate ion **(HSO_4^-)** donates a proton when it acts as **an acid**
$HSO_4^-(aq) \leftrightharpoons$ **$H^+(aq)$** + $SO_4^{2-}(aq)$
acid conjugate base

The hydrogen sulphate ion **(HSO_4^-)** accepts a proton when it acts as **a base**
$HSO_4^-(aq)$ + **$H^+(aq)$** $\leftrightharpoons$ $H_2SO_4(aq)$
base conjugate acid

Activity 5

In the acid-base equilibrium formed by adding HSO_4^- and OH^- the acids are:

A HSO_4^- and H_2SO_4
B HSO_4^- and H_2O
C SO_4^{2-} and H_2SO^-
D SO_4^{2-} and H_2O (2)

Which of the following is amphiprotic in water?

A SO_2
B SO_3^{2-}
C HSO_3^-
D H_2SO_3 (2)

[4]

Solutions

1. B✓✓ **2.** C✓✓ **[4]**

4.8 Salt hydrolysis

A salt is formed in the reaction between an acid and a base. When an ionic salt dissolves in water, the ions in the salt dissociate. These ions react with the water and new ions form.

NB: **Hydrolysis** occurs when a salt (a compound made of a metal + non-metal portion) reacts with water. Hydrolysis, more generally, is the splitting of any compound by reacting it with water. In this chapter, we only deal with the hydrolysis of salts. (Salt is not just what you have on your table; that is just one type of salt, specifically NaCℓ. Any metal combined with any non-metal is a salt).

Worked example 2

To determine whether the solutions of each of the following salts are:

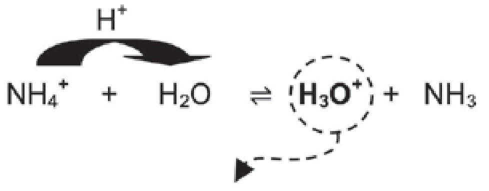
1. acidic or basic, and
   the pH of each solution is above or below 7?
   a. $NH_4NO_3(aq)$ (2) **b.** $K_2SO_4(aq)$ (2)

Solutions

1a:

$$NH_4NO_3(s) \overset{H_2O}{\rightleftharpoons} NH_4^+(aq) + NO_3^-(aq)$$

NO_3^- is a spectator ion
∴ consider only NH_4^+



$$NH_4^+ + H_2O \rightleftharpoons H_3O^+ + NH_3$$

The solution is acidic (due to H_3O^+) ✓
pH < 7 ✓

1b:

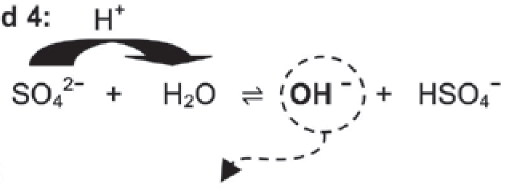
Step1.

$$K_2SO_4(s) \overset{H_2O}{\rightleftharpoons} 2K^+(aq) + SO_4^{2-}(aq)$$

Step 2.

K^+ is a spectator ion
∴ consider only SO_4^{2-}

Steps 3 and 4:



$$SO_4^{2-} + H_2O \rightleftharpoons OH^- + HSO_4^-$$

Step 5:

The solution is basic (due to OH^-) ✓
pH > 7✓

In summary:

Remember that acids and bases react with each other to form new compounds:

acid + base → salt + water

We can determine whether the salt solution is basic or acidic by comparing the strengths of the reacting acids and bases.

- A salt formed between a strong acid and a weak base is an **acidic salt**, for example $NH_4C\ell$.
- When a salt reacts with water to form **hydronium** ions **(H_3O^+)**, the solution is acidic **($pH < 7$)**.
- A salt formed between a weak acid and a strong base is a **basic salt**, for example $NaCH_3COO$.
- When a salt reacts with water to form **hydroxyl** ions (OH^-), the solution is basic **($pH > 7$)**.
- **Neutral salt** is formed when a strong acid and a strong base are neutralized in the reaction.

To determine the approximate pH of salts in salt hydrolysis

H_2O forms H_3O^+	H_2O forms OH^-
• H_2O acts as a base; • it receives a proton (H^+) and • H_3O^+ ions form so • the **solution is acidic** and • $pH < 7$	• H_2O acts as an acid; • it donates a proton (H^+) and • OH^- ions form so • the **solution is basic** and • $pH > 7$
Hydrolysis reaction: ion + $H_2O \rightleftharpoons$ **H_3O^+** + molecule / ion	Hydrolysis reaction: ion + $H_2O \rightleftharpoons$ **OH^-** + molecule / ion

REMEMBER:

- When water reacts with a salt to form hydronium ions **(H_3O^+)**, the solution is acidic **($pH < 7$)**.
- When a salt reacts with water to form hydroxyl ions **(OH^-)**, the solution is basic **($pH > 7$)**.
- The ions that don't react are called **spectator ions**.
  - Positive spectator ions: cations from Groups I and II e.g. K^+ and Mg^{2+}
  - Negative spectator ions e.g. SO_4^{2-}; $C\ell^-$; NO_3^-.

Salt of		Nature of solution	pH in an aqueous solution	Example
Acid	Base			
Strong	Strong	Neutral	pH = 7	$NaC\ell(aq)$ ($HC\ell$ + $NaOH$)
Weak	Weak	Neutral	pH = 7	$CH_3COONH_4(aq)$ (CH_3COOH + NH_3)
Strong	Weak	Acidic	pH < 7	$NH_4C\ell(aq)$ ($HC\ell$ + NH_3)
Weak	Strong	Basic	pH > 7	$CH_3COONa(aq)$ (CH_3COOH + $NaOH$)

Step by step

Step 1: Write down the formula of the acid and of the base that reacted to form the salt.
Step 2: Write down whether the acid is strong or weak.
Step 3: Write down whether the base is strong or weak.
Step 4: Is the salt solution acidic or basic?

Worked example 3

Determine whether each of the following salt solutions are acidic, basic or neutral.

a) $Na_2SO_4(aq)$ **b)** $NH_4NO_3(aq)$

Solution

	Acid	+	Base	Acid	+	Base
a)	Acid	+	Base	Acid	+	Base
	$H_2\mathbf{SO_4}$	+	NaOH	$HN\mathbf{O_3}$	+	$\mathbf{NH_3}$
	Strong		Strong	Strong	+	Weak
	∴ neutral solution			∴ acidic solution		

4.9 Acid-base indicators

DEFINITION

An indicator is a substance that changes colour in the presence of an acid or a base.

Indicators:

- can be used to determine whether a solution is acidic or basic;
- are weak acids that are in equilibrium with their conjugate bases (or vice versa) and
- have complex structures and formulae which will simply be represented as **HIn** (**H** followed by **In** for "indicator").

Indicator in equilibrium

$$\mathbf{HIn} \rightleftharpoons \mathbf{H^+} + \mathbf{In^-}$$

colour 1 *colour 2*

Indicator in acid	Indicator in base
• The high $[H^+]$ of the acid will disturb the indicator equilibrium. • According to Le Châtelier's Principle, the reverse reaction, which lowers the $[H^+]$, will be favoured. • More HIn is produced and the indicator will exhibit colour **1**.	• The low $[H^+]$ of the base will disturb the indicator equilibrium. • According to Le Châtelier's principle the forward reaction, which increases the $[H^+]$, will be favoured. • More In^- is produced and the indicator will exhibit (show) colour **2**.

Worked example 4

Bromothymol blue is an acid-base indicator. The colours it exhibits (shows) can be represented as follows:

$$\underset{\text{yellow}}{\mathbf{HIn}} \rightleftharpoons \mathbf{H^+} + \underset{\text{blue}}{\mathbf{In^-}}$$

A test tube contains a solution to which a drop of bromothymol blue has been added. The solution appears blue.

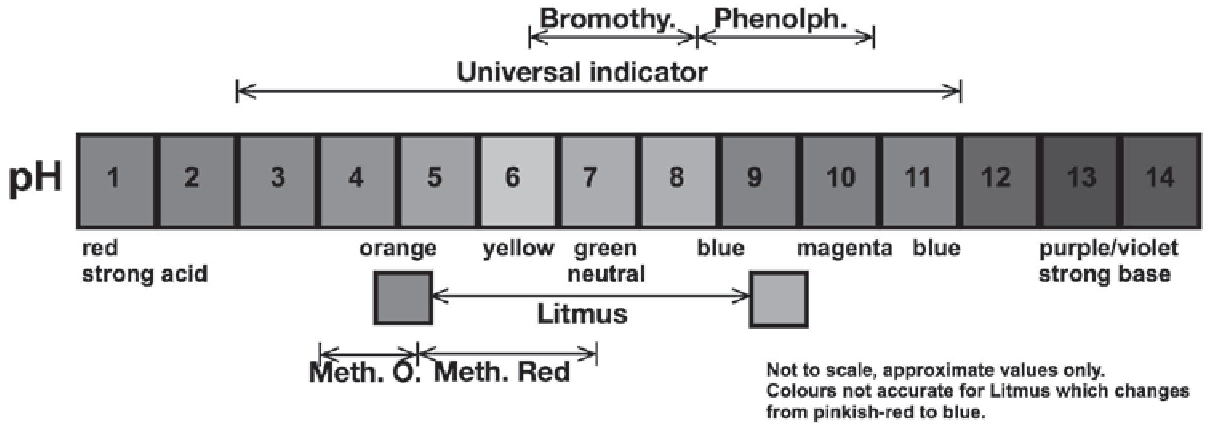
a) What will you observe if a few drops of concentrated hydrochloric acid are added to the test tube?
b) Explain your answer.

Solutions

a) The colour of the solution changes from blue to yellow.
b) Adding hydrochloric acid increases the concentration of the H^+ ions in solution. According to Le Châtelier's Principle the reverse reaction that opposes this change and decreases the $[H^+]$, will be favoured. Therefore the [HIn] increases and the colour changes to blue.

The most common indicators that are used in laboratories are:

INDICATOR	pH RANGE	COLOUR CHANGE
methyl orange	3,1 – 4,4	red to orange to yellow
methyl red	4,2 – 6,2	red to yellow
litmus	4,5 – 8,3	red to blue
bromothymol blue	6,0 – 7,8	yellow to blue
phenolphthalein	8.3 – 10	pink-purple (magenta) in range, colourless outside range
universal	3-11	red (3 and below); 3-6 orange/yellow; 7 green; 8-11 blue; 11 and above, violet.



Not to scale, approximate values only.
Colours not accurate for Litmus which changes from pinkish-red to blue.

Choose the most suitable indicator for a particular titration. If you do not have Universal Indicator available, you should follow these steps:

Step by step – universal indicator

Step 1:	Identify the strength of the acid and the base (pH range maximum and minimum)
Step 2:	Draw a **bracket** to show the strength of the identified acid and base (shown as a line with arrowheads above)
Step 3:	Note or mark the mid point (centre) of the bracket (or line as shown above)
Step 4:	Use the indicator table to choose the indicator that shows the range of pH around the mid point (centre) of that bracket/line.
RESULT:	You now have selected the appropriate indicator to use.

Worked example 5

	Which one of the indicators given below will be the most suitable to be used in the titration of ethanoic acid against sodium hydroxide?		
		INDICATOR	pH COLOUR CHANGE RANGE
	A	bromothymol blue	6,0 – 7,8
	B	phenolphthalein	8,3 – 10
	C	methyl orange	3,1 – 4,4
	D	methyl red	4,2 – 6,2

Solution

Consult the table at Sections (3) and (4) above. We see Ethanoic Acid has a pH of about 2,4 (1M solution), and NaOH has a pH of about 14. The mid-point between 2,4 and 14 is about 5,8, so any indicator which changes from indicating acid to base around 5,8 would do. Answer: D; methyl red.

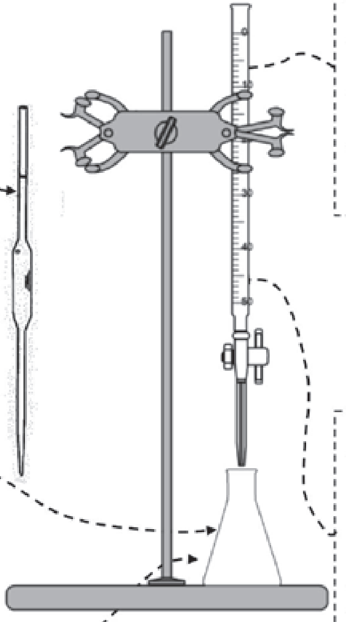
4.10 Acid-base titrations (volumetric analysis)

Titrations are used to experimentally determine the concentration of an unknown acid or base. When the titration results are used to determine the concentration of the unknown solution it is called a **volumetric analysis.**

a) Method and apparatus for an acid-base titration

STEP 1

- Wash the **conical flask** with distilled water.
- Using a **pipette,** transfer some of the base (usually 25 cm^3) to the conical flask.
- Add a few drops of suitable **indicator.**
- Swirl the flask carefully during the titration.



STEP 2

Place a **white tile or paper** under the flask so that the colour changes of the indicator are clearly visible.

STEP 3

- Rinse the **burette** with some of the acid solution.
- Using a funnel carefully fill the burette with acid.
- Take the initial reading on the burette.

STEP 4

- Slowly add the acid from the burette to the base in the flask until the colour of the indicator just changes colour. This is the **end point** of the titration.
- Take the final reading on the burette.
- Determine the volume of acid that was added to the base.

4.11 Preparing a standard solution

DEFINITION

A **standard solution** has a known concentration which remains constant for a period of time.

Standard solutions are often used in laboratories and it is important to know how to prepare a standard solution.

CONCENTRATION ($c = \frac{n}{V}$)

CONCENTRATED SOLUTION

Greater number of moles of substance per unit volume.

$$c = \frac{n_{solute}}{V_1}$$

$$\xrightarrow{+\ H_2O(\ell)}$$

$$n_{diluted} = n_{concentrated}$$

DILUTE SOLUTION

Smaller number of moles of substance per unit volume.

$$c = \frac{n_{solute}}{V_1 + V_{water\ added}} = \frac{n_{solute}}{V_2}$$

Worked example 6

1 cm^3 = 1 mℓ ; 1 dm^3 = 1 ℓ

Aim: To prepare a 200 cm^3 NaOH standard solution with a concentration of 0,5 $mol \cdot dm^{-3}$.

Step 1: Calculate the mass of NaOH pellets required. M(NaOH) = 40 + 16 + 1 = 40 $g \cdot mol^{-1}$

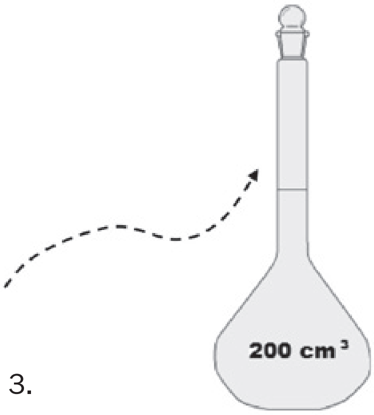
Step 2: Use an electronic scale (balance) to measure off ± 4,4 g NaOH.

NOTE:
A specific mass of NaOH(s) can't always be measured because it consists of pellets (not a fine powder).

Step 3: Note the **exact** mass of NaOH on the scale.

Step 4: Transfer the NaOH pellets to a volumetric flask. Add ± 100 cm^3 of distilled water to the flask and seal it with a stopper. Shake the flask carefully until all the solute (NaOH) has dissolved.

Step 5: Slowly fill the flask to the calibration mark on the neck of the flask.

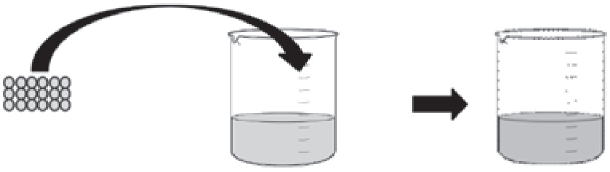


Step 6: Now calculate the **exact** concentration of the prepared solution – use the mass that was noted on the scale in Step 3.

$n = \frac{m}{M} = \frac{4,1}{40} = 0,103$ mol and $c = \frac{n}{V} = \frac{0,103}{0,3} = 0,52\ mol \cdot dm^{-3}$

∴ a standard NaOH(aq) solution of concentration 0,52 $mol \cdot dm^{-3}$ has been prepared.

Solute:	**Solvent:**	**Solution:**
The substance (usually a solid) that is dissolved in the solvent.	The substance (usually distilled water) in which the solute is dissolved.	The mixture of the solute and the solvent.



4.12 Dilution of solutions

We sometimes need to dilute a solution so that we can use it in a laboratory. We do this by taking a small amount of the solution and adding distilled water to it.

When diluting a solution, we need to know:

- the exact amount of distilled water that needs to added as well as
- the exact concentration of the dilute solution.

In symbols:
$c_1V_1 = c_2V_2$

c_1	:	concentration 1	(mol·dm^{-3})
V_1	:	volume 1	(dm^{-3})
c_2	:	concentration 2	(mol·dm^{-3})
V_2	:	volume 2	(dm^{-3})

Worked example 7

Solution 1 has a concentration of 0,2 mol·dm^{-3}. Exactly 150 cm^3 of solution A is transferred to a beaker 2 and 250 cm^3 of distilled water is added to the beaker. Calculate the concentration of the diluted solution.

Solution

$$\begin{aligned} c_1V_1 &= c_2V_2 \\ (0{,}2)(0{,}15) &= c_2(0{,}4) \\ c_2 &= \frac{(0{,}2)(0{,}15)}{0{,}4} \\ &= 0{,}075\ \text{mol·dm}^{-3} \end{aligned}$$

- The volume of the final solution (V_2) is:
  $V_2 = V_1 + V_{water}$
  $= 150 + 250 = 400$ cm^3
- 400 cm^3
  $= 400 \div 1000 = 0{,}4$ dm^3
- convert to dm^3

4.13 Acid-base titration calculations

In symbols:
$\frac{n_a}{n_b} = \frac{c_aV_a}{c_bV_b}$

$c = \frac{n}{V}$

where OR $c = \frac{m}{MV}$

$n = \frac{m}{M}$

n	mol	(mol)
c	concentration	($mol \cdot dm^{-3}$)
V	volume	(dm^{-3})
a	acid	
b	base	

Worked example 8

During a titration 20 cm^3 diluted H_2SO_4 precisely neutralises 25 cm^3 of a NaOH solution. If the concentration of the H_2SO_4 solution is 0,5 $mol \cdot dm^{-3}$, calculate the concentration of the NaOH.

Solution

First write down the balanced reaction.

$\mathit{1}\ H_2SO_4(aq) + \mathbf{2}\ NaOH(aq) \rightarrow Na_2SO_4(aq) + H_2O(\ell)$

Find the mol ratio of acid : base: $H_2SO_4 : NaOH = 1 : 2$

$$\frac{n_a}{n_b} = \frac{c_aV_a}{c_bV_b}$$

$$\frac{1}{2} = \frac{(0,5)(20)}{c_b\ (25)}$$

$$1 \cdot c_b\ (25) = (0,5)(20)(2)$$

$$c_b = 0,8\ mol \cdot dm^{-3}$$

$n_a = \mathit{1}$
$n_b = \mathit{2}$
$V_a = 20\ cm^3$
$V_b = 25\ cm^3$
$c_a = 0,5\ mol \cdot dm^{-3}$
$c_b = ?$

Worked example 9

TITRATION CALCULATIONS

Eight grams (8,0 g) of sodium hydroxide are dissolved in 350 cm^3 of distilled water. 15 cm^3 of this solution neutralises 20 cm^3 of a sulphuric acid solution. The balanced equation for this reaction is:

$$2NaOH(aq) + H_2SO_4(aq) \rightarrow Na_2SO_4(aq) + 2H_2O(\ell)$$

Calculate the concentration of the sulphuric acid solution.

Solution

STEP 1

$c = \frac{m}{MV}$ **OR** $n = \frac{m}{M}$

$c = \frac{8}{(40 \times 0{,}35)}$ $n = \frac{8}{40} = 0{,}2$ mol NaOH

$c = 0{,}57\ mol{\cdot}dm^{-3}$ $c = \frac{n}{V}$

$c = \frac{0{,}2}{0{,}35}$

$c = 0{,}5\ mol{\cdot}dm^{-3}$

Solution

STEP 1

$c = \frac{m}{MV}$ **OR** $n = \frac{m}{M}$

$c = \frac{8}{(40 \times 0{,}35)}$ $n = \frac{8}{40} = 0{,}2$ mol NaOH

$c = 0{,}57\ mol{\cdot}dm^{-3}$ $c = \frac{n}{V}$

$c = \frac{0{,}2}{0{,}35}$

$c = 0{,}5\ mol{\cdot}dm^{-3}$

STEP 2

$$\frac{n_a}{n_b} = \frac{c_aV_a}{c_bV_b}$$

From the balanced equation **2** n(NaOH) : 1 n(H_2SO_4)

$\frac{1}{2} = (c_a \times 0{,}02)$

$(0{,}57 \times 0{,}025)$

$c_a = 0{,}36\ mol{\cdot}dm^{-3}$

e.g. Worked example 10

The titration of oxalic acid with sodium hydroxide

Part 1:

Aim: To prepare a 250 cm^3 of oxalic acid standard solution with a concentration of 0,08 $mol·dm^{-3}$

Solutions

Step 1

- Measure between 2,5 and 2,7 g of pure oxalic acid hydrate crystals $(COOH)_2 \cdot 2H_2O$ into the glass beaker and weigh again.
- Add 30-60 cm^3 of distilled water to the glass beaker and dissolve the crystals.
- Transfer the solution into a clean 250 cm^3 volumetric flask.
- Rinse the beaker with 15-20 cm^3 of distilled water and pour this solution into the volumetric flask and repeat. This will ensure that all of the oxalic acid is transferred into the volumetric flask.
- Fill the volumetric flask to within about 2 cm of the mark and allow it to sit for a minute. This will allow any water clinging to the edges of the neck to drain into the flask. Using an eyedropper, fill the flask to the calibrated mark with water.
- Stopper (close) the flask and mix the solution by repeated inversion (turning upside-down) and swirling. This requires about 30 inversions and takes close to 1 minute.

Step 2

- Calculate the exact concentration of the oxalic acid solution using the mass of acid used and the volume of the volumetric flask and record the concentration of your solution on the bottle.

If you have used the following

Mass oxalic acid crystals	2,6 g
Final volume solution	250,0 cm^3

Using the above information to calculate the number of moles and concentration of oxalic acid crystals.

Part 2:

Procedure to perform (to do) a titration of sodium hydroxide with oxalic acid.

Aim: use a standard solution of oxalic acid to determine the concentration of sodium hydroxide

$$H_2C_2O_4(aq) + 2\,NaOH(aq) \rightarrow 2\,H_2O(\ell) + Na_2C_2O_4(aq)$$

Solutions

- Measure exact 25,00 cm^3 of the oxalic acid standard solution ($c = 0{,}084\ mol·dm^{-3}$) into a flask and add few drops of phenolphthalein.
- In this titration the oxalic acid solution is acidic and therefore phenolphthalein will be **colourless**.

e.g. Worked example 10 (continued)

- The sodium hydroxide solution will be added drop wise (drop by drop) from a burette into the flask containing the oxalic acid and indicator.
- As the sodium hydroxide is added to the flask it will react with the oxalic acid and be neutralized.
- At the point where all of the oxalic acid is reacted, the next drop of sodium hydroxide will make the entire solution basic and it will turn **pink**. At this point you have completed the titration.

Results (If the following data and results were obtained after at least three trials)

Volume oxalic acid solution	25,00 cm^3
Volume sodium hydroxide to titrate	19,43 cm^3

Mole of sodium hydroxide reacted:

$$\frac{n_a}{n_b} = \frac{c_aV_a}{c_bV_b}$$

First write down the balanced reaction.

$$\mathbf{1}\ H_2C_2O_4(aq) + \mathbf{2}\ NaOH(aq) \rightarrow 2\ H_2O(\ell) + Na_2C_2O_4(aq)$$

Find the mol ratio of acid : base ... ratio of $H_2C_2O_4$: NaOH = **1** : **2**

$$\frac{n_a}{n_b} = \frac{c_aV_a}{c_bV_b}$$

$$\frac{1}{2} = \frac{(0{,}084)(25)}{c_b\,(25)}$$

$1 \cdot c_b\,(19{,}43) = (0{,}084)(25)(2)$

$c_b = 0{,}216\ \text{mol}\cdot\text{dm}^{-3}$

$n_a = \mathbf{1}$
$n_b = \mathbf{2}$
$V_a = 20\ \text{cm}^3$
$V_b = 25\ \text{cm}^3$
$c_a = 0{,}5\ \text{mol}\cdot\text{dm}^{-3}$
$c_b = ?$

Part 3:

In order to determine the concentration of acetic acid in the vinegar solution you will titrate it with the standardized sodium hydroxide solution. The equation for this reaction is

$$\mathbf{1}\ CH_3COOH(aq) + \mathbf{1}\ NaOH(aq) \rightarrow H_2O(\ell) + CH_3COONa(aq)$$

The following data was obtained during titration

Data

Volume vinegar solution	25,00 cm^3
Volume sodium hydroxide titrated	22,84 cm^3

Calculations for determining concentration of acetic acid in vinegar

First write down the balanced reaction.

$$\mathbf{1}\ CH_3COOH(aq) + \mathbf{1}\ NaOH(aq) \rightarrow H_2O(\ell) + CH_3COONa(aq)$$

Find the mol ratio of acid : base ... CH_3COOH : NaOH = **1** : **1**

Worked example 10 (continued)

From a balanced equation **2** n(NaOH) : **1** n(H_2SO_4)

$$\frac{n_a}{n_b} = \frac{c_aV_a}{c_bV_b}$$

$$\frac{1}{1} = \frac{(c_a)(25)}{(0{,}216)(22{,}84)}$$

$$1\cdot(0{,}216)\,(22{,}84) = c_a\,(25)(2)$$

$$c_a = 0{,}197\ \text{mol}\cdot\text{dm}^{-3}$$

n_a = **1**
n_b = **1**
V_a = 25 cm^3
V_b = 22,84 cm^3
c_b = 0,216 mol·dm^{-3}
c_a = ?

In order to get the best precision possible, you should repeat each titration until you get 3 trials that are within 1% of each other.

4.14 The Equilibrium Constant (K_c) (The Law of Mass Action)

The concentrations of all the compounds (solutions and gases) in a closed system in dynamic chemical equilibrium are related by a mathematical equation. The numerical value of this equation is called the **equilibrium constant (K_c).**

NB

Solids and pure liquids are omitted from the K_c expression as their concentration is [1], as multiplying by 1 has no effect.

In the hypothetical equation below the equilibrium expression for this reaction is:

$2P + 3R \rightleftharpoons 2S + 4T$

$$K_c = \frac{[S]^2 \times [T]^4}{[P]^2 \times [R]^3}$$

hint

K_c: equilibrium constant (no unit)

[substance]: concentration of reactant or product (in mol·dm^{-3})

mol: number of moles of each compound in the balanced reaction equation.

NB

- This is the correct way of writing the K_c expression
- The coefficients are the moles of each reactant and product in the balanced equation
- The product of the concentration of **reactants** (not to be added, but **multiplied**!!), **raised to the power** of the number of moles is the **numerator**
- The product of the concentration of **products** (not to be added, but multiplied!!), **raised to the power** of the number of moles is the **denominator**
- The concentrations used in the Law of Mass Action is the **$[\text{reactant}]_{\text{equilibrium}}$** and **$[\text{product}]_{\text{equilibrium}}$ (NOT initial concentrations!! i.e. the concentrations of reactants and products at equilibrium)**

4.15 K_a and K_b values

Since the ionisation of a weak acid is an equilibrium, a chemical equation and an equilibrium constant expression can be written as follows. Remember that square brackets means "concentration", or moles per dm³.

$$HA + H_2O \rightleftharpoons H_3O^+ + A^- \qquad K_a = \frac{[H_3O^+][A^-]}{[HA]}$$

The equilibrium constant for the ionisation of an acid is called the *acid ionisation constant (K_a)*.

A similar expression can be written for bases:

$$A + H_2O \rightleftharpoons HA^+ + OH^- \quad Kb = \frac{[OH^-][HA^+]}{[A^-]}$$

The equilibrium constant for the ionisation of a base is called the *base ionisation constant (K_b)*

NB

An acid or base's strength refers to its degree of ionisation. **A strong acid will completely ionise in water while a weak acid will only partially ionise.** Since there are different degrees of ionisation, there are different levels of weakness. Fortunately, there is a simple quantitative way of expressing this.

ACIDS	BASES
Ionisation of acid (HA): $HA + H_2O \rightleftharpoons H_3O^+ + A^-$	Ionisation of base (B): $B + H_2O \rightleftharpoons OH^- + BH^+ (aq)$
$K_a = \frac{[H_3O^+][A^-]}{[HA]}$	$K_b = \frac{[OH^-][BH^+]}{[B]}$ (NB: here we substituted in values from the line above!)
Strong acid ⟶ high K_a-value (>1) Weak acid ⟶ low K_a-value (<1)	Strong base ⟶ high K_b-value (>1) Weak base ⟶ low K_b-value (<1)

Examples:

$HC\ell(g) + H_2O(\ell) \rightleftharpoons H_3O^+(aq) + C\ell^-(aq)$	$NH_3(g) + H_2O(\ell) \rightleftharpoons OH^-(aq) + NH4^+(aq)$
	Dissociation of base: $NaOH (s) \xrightarrow{H_2O(\ell)} Na^+ (aq) + OH^- (aq)$ $K_b = [Na^+][OH^-]$

Activity 6

Do you think a strong acid will have larger or smaller K_a value? Explain your answer. (3)

[3]

Solution

The strong acid will have a larger K_a value. ✓

A strong acid is a better proton donor, resulting in more products. ✓ Since the concentration of the products is in the numerator of the **K_a**expression, the stronger the acid, the larger the **K_a**. ✓ [3]

Activity 7

Choose the strongest base in the list below by comparing their K_b values.

	Base	K_b	
A	Ammonia, NH_3	$1,8 \times 10^{-5}$	
B	Hydroxylamine, $HONH_2$	$9,1 \times 10^{-9}$	
C	Ethylamine, $C_2H_5NH_2$	$4,3 \times 10^{-4}$	(2)

[2]

Solution

C ✓✓ [The larger the K_b, the stronger the base] **[2]**

4.16 The relationship between K_a and K_b for a substance

We know that the strength of a conjugate base is inversely proportional to the strength of the conjugate acid; i.e. weak acids produce strong conjugate bases, and vice versa.

ACID	CONJUGATE BASE
$HA(aq) + H_2O(\ell) \rightleftharpoons H_3O^+(aq) + A^-(aq)$	$A^-(aq) + H_2O(\ell) \rightleftharpoons HA(aq) + OH^-(aq)$
$K_a = \frac{[H_3O^+][A^-]}{[HA]}$	$K_b = \frac{[OH^-][HA^+]}{[A^-]}$
Then follows:	
$K_aK_b = \frac{[H_3O^+][A^-]}{[HA]} \times \frac{[HA][OH^-]}{[A^-]} = [H_3O^+][OH^-]$	
But:	
$[H_3O^+][OH^-] = K_w = 1 \times 10^{-14}$	

NB

You are aware that the pH scale runs from 1 to 14... now look at the values above again.

4.17 Auto-ionisation of water

Water is an ampholyte and can react as an acid (donates a H^+) or a base (accepts a H^+).

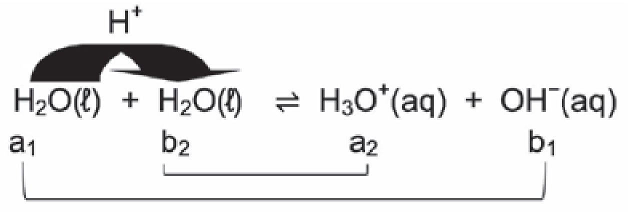
Two water molecules can undergo **autoprotolysis** or **auto-ionisation.** One water molecule can act as an acid and donate a H^+ to the other water molecule, the base.

An acid : $H_2O \rightleftharpoons H^+ + OH^-$

A base : $H_2O + H^+ \rightleftharpoons H_3O^+$

- Water is a weak acid and a weak base.
- Low % auto-ionisation occurs.
- Pure water is a weak electrical conductor.

Net reaction showing the conjugate acid-base pairs:



4.18 Equilibrium constant for water (K_w)

From the acid-base reaction for water the equilibrium expression for water can be written.

$$H_2O(\ell) + H_2O(\ell) \rightleftharpoons H_3O^+(aq) + OH^-(aq)$$

$K_c = [H_3O^+][OH^-]$

$K_w = [H_3O^+][OH^-]$

K_w : equilibrium constant for water

At 25°C:
$K_w = 1 \times 10^{-14}$

Water has a low percentage of ionisation with a low concentration of products. The K_w-value will be low.

Due to the symbol H^+ often being used instead of H_3O^+, the ionisation constant (ion product) for water can also be written as:

$$K_w = [H^+][OH^-]$$

Therefore:
Ion product for water $K_w = [H_3O^+][OH^-] = [H^+][OH^-] = 1 \times 10^{-14}$ at 25 °C

4.19 The pH scale

We know $K_w = [H_3O^+][OH^-] = [H^+][OH^-] = 1 \times 10^{-14}$

therefore $[H_3O^+] = [OH^-] = 10^{-7}$ or $[H^+] = [OH^-] = 10^{-7}$

Acid solution	Neutral solution	Base solution
$[H_3O^+] > [OH^-]$ OR $[H^+] > [OH^-]$	$[H_3O^+] = [OH^-]$ OR $[H^+] = [OH^-]$	$[H_3O^+] < [OH^-]$ OR $[H^+] < [OH^-]$
$[H_3O^+] > 10^{-7}$ mol·dm^{-3}	$[H_3O^+] = 10^{-7}$ mol·dm^{-3}	$[H_3O^+] < 10^{-7}$ mol·dm^{-3}

e.g. Worked example 11

Determine whether the following solutions are acidic, basic or neutral:

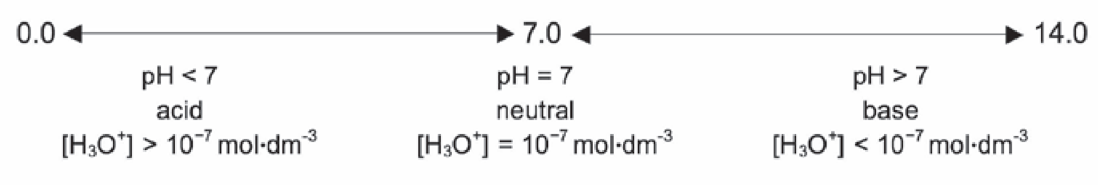
A solution with	
$[H_3O^+] = 10^{-3}$ mol·dm^{-3}	1. A solution with $[H_3O^+] = 10^{-3}$ mol·dm^{-3} 10^{-3} mol·dm^{-3} > 10^{-7} mol·dm^{-3} ∴ Solution is acidic
$[H_3O^+] = 10^{-12}$ mol·dm^{-3}	2. A solution with $[H_3O^+] = 10^{-12}$ mol·dm^{-3} 10^{-12} mol·dm^{-3} < 10^{-7} mol·dm^{-3} ∴ Solution is basic
$[OH^-] = 10^{-7}$ mol·dm^{-3}	3. A solution with $[OH^-] = 10^{-7}$ mol·dm^{-3} $[H_3O^+][OH^-] = 10^{-14}$ ∴ $[H_3O^+](10^{-7}) = 10^{-14}$ ∴ $[H_3O^+] = 10^{-14} \div 10^{-7} = 10^{-7}$ ∴ Solution is neutral
$[OH^-] = 10^{-4}$ mol·dm^{-3}	4. A solution with $[OH^-] = 10^{-4}$ mol·dm^{-3} $[H_3O^+][OH^-] = 10^{-14}$ ∴ $[H_3O^+](10^{-4}) = 10^{-14}$ ∴ $[H_3O^+] = 10^{-14} \div 10^{-4} = 10^{-10}$ 10^{-10} mol·dm^{-3} < 10^{-7} mol·dm^{-3} ∴ Solution is basic

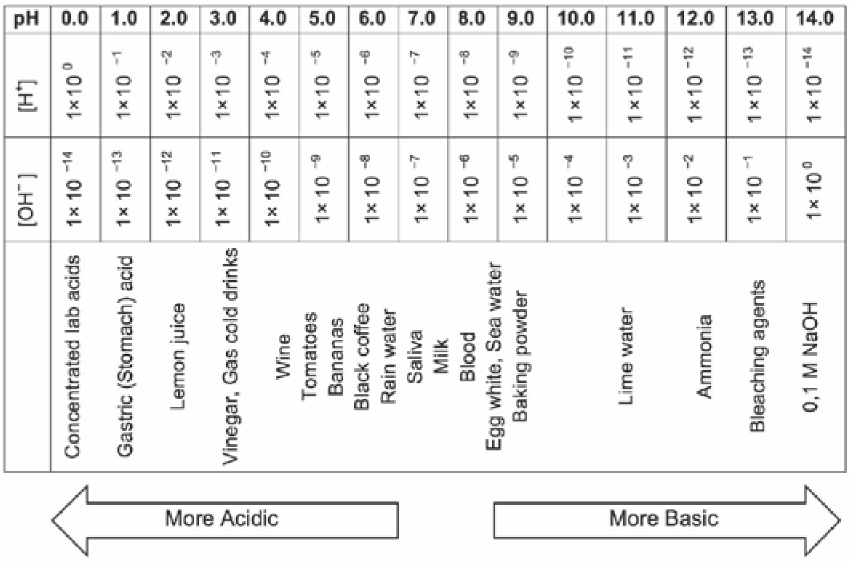
NB

DEFINITION

pH of a solution is the **negative logarithm** of the **hydronium ion concentration** in a solution.
pH = log $[H_3O^+]$

It is complicated to continually refer to the hydronium ion concentration. The pH scale is therefore used as a simplified method of indicating the degree of acidity of a solution.





pH	0.0	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0
$[H^+]$	1×10^{0}	1×10^{-1}	1×10^{-2}	1×10^{-3}	1×10^{-4}	1×10^{-5}	1×10^{-6}	1×10^{-7}	1×10^{-8}	1×10^{-9}	1×10^{-10}	1×10^{-11}	1×10^{-12}	1×10^{-13}	1×10^{-14}
$[OH^-]$	1×10^{-14}	1×10^{-13}	1×10^{-12}	1×10^{-11}	1×10^{-10}	1×10^{-9}	1×10^{-8}	1×10^{-7}	1×10^{-6}	1×10^{-5}	1×10^{-4}	1×10^{-3}	1×10^{-2}	1×10^{-1}	1×10^{0}
	Concentrated lab acids	Gastric (Stomach) acid	Lemon juice	Vinegar, Gas cold drinks	Wine	Tomatoes Bananas	Black coffee Rain water	Saliva Milk	Blood Egg white, Sea water	Baking powder		Lime water	Ammonia	Bleaching agents	0,1 M NaOH

More Acidic

More Basic

4.20 pH Calculations for strong acids and bases

To calculate the pH of a strong acid or base, these steps should be followed:

Acid	Step	Base
0,1 mol·dm^{-3} of HCℓ solution	For example:	0,5 mol·dm^{-3} of NaOH solution
Write down the ionisation reaction for the acid. $HC\ell + H_2O \rightleftharpoons \mathbf{1}\ H_3O^+ + C\ell^-$	1	Write down the dissociation reaction for the base. $\mathbf{1NaOH(s)} \rightleftharpoons Na^+(aq)^+OH^-(aq)$
Find the mol ratio of acid to hydronium ions **1** mol HCℓ : **1** mol H_3O^+	2	Find the mol ratio of base to hydroxyl ions **1** mol NaOH : **1** mol OH^-
Determine the $[H_3O^+]$ $[HC\ell] = 0,1$ mol·dm^{-3} $\therefore\ [H_3O^+] = 0,1$ mol·dm^{-3}	3	Determine the $[OH^-]$ $[NaOH] = 0,5$ mol·dm^{-3} $\therefore\ [OH^-] = \mathbf{1}(0,5) = 0,5$ mol·dm^{-3}
No step 4 for acids	4	Determine the $[H_3O^+]$ $[H_3O^+][OH^-] = 10^{-14}$ $\therefore [H_3O^+](0,5) = 10^{-14}$ $\therefore [H_3O^+] = 10^{-14} \div 0,5 = 2 \times 10^{-14}$
Calculate the pH $pH = -\log [H_3O^+]$ $= -\log 0,1$ $= 1$	5	Calculate the pH $pH = -\log [H_3O^+]$ $= -\log (2 \times 10^{-14})$ $= 13,7$

Worked example 12

Calculate the pH of a H_2SO_4 solution of concentration 0,6 mol·dm^{-3}.

Solutions

Step 1: $\mathbf{1}\ H_2SO_4(g) + 2\ H_2O(\ell) \rightleftharpoons \mathbf{2}\ H_3O^+(aq) + SO_4^{2-}(aq)$

Step 2: **1** mol HCℓ : **2** mol H_3O^+

Step 3: $[H_2SO_4] = 0,6$ mol·dm^{-3} $\therefore\ [H_3O^+] = \mathbf{2}(0,6) = 1,2$ mol·dm^{-3}

Step 4:

$$\begin{aligned} pH &= -\log [H_3O^+] \\ &= -\log 1,2 \\ &= 0,08 \end{aligned}$$

4.21 Summary: Strong and weak acids and bases

Acids ionise in water to form ions:

Examples:

$$HC\ell(g) + H_2O(\ell) \rightleftharpoons H_3O^+(aq) + C\ell^-(aq)$$

$$CH_3COOH(g) + H_2O(\ell) \rightleftharpoons H_3O^+(aq) + CH_3COO^-(aq)$$

REMEMBER:

The electrical conductivity of any electrolyte is determined by the number of ions in solution. The greater the ion concentration, the higher the conductivity.

Reaction rate is determined by the concentration of a reactant. The higher the concentration of the ions in a solution, the higher the rate of reaction.

STRONG AND WEAK ACIDS	
Strong acids	**Weak acids**
• High % ionisation • Donate many protons (H^+) • High [H_3O^+] or [H^+] • Low pH • Good electric conductors • High reaction rates	• Low % ionisation • Donate few protons (H^+) • Low [H_3O^+] or [H^+] • Relatively low pH • Poor electric conductors • Low reaction rates
Examples: $HC\ell$ (hydrochloric acid) H_2SO_4 (sulphuric acid) HNO_3 (nitric acid)	***Examples:*** CH_3COOH (acetic acid) $(COOH)_2$ (oxalic acid) $C_6H_8O_7$ (citric acid) H_2CO_3 (carbonic acid)
Strong acid $\leftrightharpoons$ weak conjugate base + H^+ $HC\ell \leftrightharpoons C\ell^- + H^+$	Weak acid $\leftrightharpoons$ strong conjugate base + H^+ $CH_3COOH \leftrightharpoons CH_3COO^- + H^+$

Bases like:

- NaOH are ionic and dissociate in water while
- NH_3 consists of covalent molecules which ionise in water forming NH_4^+.

STRONG AND WEAK BASES	
Strong bases	**Weak bases**
• High % dissociation • Accept many protons (H^+) • High [OH^-] • Very high pH	• Low % dissociation or ionisation • Accept few protons (H^+) • Low [OH^-] • Relatively high pH
NaOH Sodium hydroxide KOH Potassium hydroxide	NH_3 Ammonia $CaCO_3$ Calcium carbonate
strong base + $H^+ \leftrightharpoons$ weak conjugate acid $OH^- + H^+ \leftrightharpoons$ H2O	weak base + $H^+ \leftrightharpoons$ strong conjugate acid $NH_3 + H^+ \leftrightharpoons NH_4^+$

REMEMBER:

The pH of an acid is dependent on the relative concentrations of the H_3O^+ and OH^- ions in the solution.

In general:

pH 1 - 2 : strong acid

pH 3 - 6 : weak acid

pH 12 - 14 : strong base

pH 8 - 11 : weak base

pH 7 : neutral

4.22 Summary: Concentrated and dilute acids and bases

Concentration of an acid or a base is an indication of the number of moles of solute per unit volume. Both strong and weak acids and bases can be either concentrated or diluted.

Examples:

1 mol·dm^{-3} $HC\ell$(aq) : **concentrated** solution of a *strong acid*
0,01 mol·dm^{-3} $HC\ell$(aq) : **diluted** solution of a *strong acid*
1 mol·dm^{-3} CH_3COOH(aq) : **concentrated** solution of a *weak acid*
0,01 mol·dm^{-3} CH_3COOH(aq) : **diluted** solution of a *weak acid*
1 mol·dm^{-3} $NaOH(aq)$: **concentrated** solution of a *strong base*
0,01 mol·dm^{-3} $NaOH(aq)$: **diluted** solution of a *strong base*
1 mol·dm^{-3} $NH_3(aq)$: **concentrated** solution of a *weak base*
0,01 mol·dm^{-3} $NH_3(aq)$: **diluted** solution of a *weak base*

Activity 8

1. A standard solution is a solution …

A. at 25 °C
B of an acid or a base
C of which the volume is known
D of which the concentration is known (2)

2. Consider the following ionisation equilibrium:

$$H_2O(\ell) \rightleftharpoons H^+(aq) + OH^-(aq)$$

The ionisation constant of water (K_w) in the above reaction increases from 1×10^{-14} at 25 °C to $9{,}6 \times 10^{-14}$ at 60 °C. Which one of the following statements is therefore correct

A $[H^+] > [OH^-]$ at 60 °C
B The ionisation reaction is exothermic
C The pH increases with an increase in temperature
D The pH decreases with an increase in temperature (2)

3. Consider the reaction:

$$CH_3COOH(g) + H_2O(\ell) \rightleftharpoons H_3O^+(aq) + CH_3COO^-(aq)$$

The ionisation constant for this reaction at 25 °C is $1{,}8 \times 10^{-5}$. The equilibrium constant for this reaction at 60 °C, is $3{,}6 \times 10^{-7}$. From this information we can deduce that forward reaction … (Explain your choice).

A is endothermic
B is exothermic
C is a redox reaction
D is a precipitation reaction (2)

4. Two beakers, A and B, contain solutions of the same concentration with a pH of 2 and 4,5 respectively. Which of the following combinations is correct?

	Beaker A	**Beaker B**
A	Weak Acid	Strong Acid
B	Strong Acid	Weak Acid
C	Strong base	Weak base
D	Weak base	Strong base

(2)

5. Andile rinses the apparatus before starting an acid-base titration experiment. Which rinsing method is likely to cause inaccurate results?

A The Erlenmeyer (conical) flask is rinsed with distilled water
B The burette is rinsed with the acids it is to be filled with
C The pipette is rinsed with the base it is to be used for
D The volumetric (measuring) flask, which is used to make up the standard solution of the base, is rinsed with distilled water. (2)

6. If base **X** is titrated against acid **Y**, the pH of the solution at the end point is 8. The base **X** and acid **Y** are respectively:

	X	**Y**
A	NaOH	CH_3COOH
B	Na_2CO_3	$HC\ell$
C	NaOH	H_2SO_4
D	Na_2CO_3	CH_3COOH

(2)

[12]

Solutions

1. D ✓✓ (2)

2. D
At 60˚C: $[H^+] = [OH^-] = \sqrt{9,6 \times 10^{-14}} = 3,1 \times 10^{-7}$ mol·dm^{-3} ✓
pH = $-\log[H^+] = -\log(3,1 \times 10^{-7}) = 6,5$ ✓ (2)

3. B✓ ✓ K_c at 25°C is greater than K_c at 60°C
$K_c = [CH_3COO^-][H_3O^+]$. If the mixture is heated, the K_c decreases (2)

4. B✓✓ Beaker A has a low pH which indicates that it contains more H^+, therefore it has ionised completely. Whilst beaker B has a high pH which indicates few H^+ ions, thus it has partially ionised. (2)

5. A✓✓ The Erlenmeyer (conical) flask must be rinsed with distilled water. Only the number of moles of base which was measured in the pipette must be neutralised. (2)

6. A✓✓ (2)

[12]

Activity 9

1. Write down:
   1.1 The meaning of the term diprotic acid. (2)
   1.2 The formula of a diprotic acid. (1)

2. Magnesium hydroxide ($Mg(OH)_2$) is often used as medicine to relieve an upset stomach. The pH of the $HC\ell(aq)$ in a person's stomach is 1.
   2.1 Calculate the concentration of the hydrochloric acid in the person's stomach. (3)
   2.2 Will the pH in the stomach **INCREASE**, **DECREASE** or **STAY THE SAME** after taking in a dose of $Mg(OH)_2$? (2)
   2.3 A person takes in a dose of $Mg(OH)_2$. Write down the balanced equation for the reaction that takes place in the stomach. (3)

3. A textbook states that calcium sulphate ($CaSO_4$) is slightly soluble in water.

   Two learners decided to test the dam water from a local municipality for calcium sulphate. They took a 0,5 dm^3 sample of the dam water and treated it with sodium carbonate solution to precipitate the calcium ions present according to the following equation:

$$CaSO_4(aq) + Na_2CO_3(aq) \rightarrow Na_2SO_4(aq) + CaCO_3(s)$$

   The precipitate is then dissolved in 30 cm^3 of 0,1 $mol{\cdot}dm^{-3}$ $HC\ell$ solution which converts the precipitate to aqueous calcium chloride, water and carbon dioxide according to the following equation:

$$CaCO_3 + 2HC\ell \rightarrow CaC\ell_2 + CO_2 + H_2O$$

   The $HC\ell$ was in excess. They neutralised the excess $HC\ell$ by adding 15,8 cm^3 of a 0,1 $mol{\cdot}dm^{-3}$ NaOH solution. The equation for the reaction is:

$$HC\ell + NaOH \rightarrow NaC\ell + H_2O$$

   Calculate the mass of calcium sulphate that was present in the sample of dam water.

(10)

[21]

Solutions

1. An acid that can <u>release</u>/*donate*✓ two protons (H^+)✓ (2)

2. H_2SO_4✓ (H_2S ; H_2SO_3 ; H_2CO_3 ; $(COOH)_2$) (1)

2.1 pH = $-\log [H_3O^+] = 1$✓

$\therefore [H_3O^+] = 10^{-1} = 0{,}1$ ✓

$\therefore [HC\ell] = 0{,}1\ \text{mol·dm}^{-3}$✓ (3)

2.2 INCREASE ✓✓ (2)

2.3 $Mg(OH)_2(s) + 2HC\ell(aq) \rightarrow MgC\ell_2(aq) + 2H_2O(\ell)$ (3)

✓ ✓ ✓

3.

$\frac{n_a}{n_b} = \frac{c_aV_a}{c_bV_b}$ ✓ $n_a = n_b = 1$

$n(CaCO_3) = 0{,}5 \times n(HC\ell)$ ✓

$= 0{,}5 \times 1{,}42 \times 10^{-3}$ ✓

$= 7{,}1 \times 10^{-4}$ mol ✓

$V = c_bV_b = 0{,}1 \times 15{,}8 \times 1 = 15{,}8\ \text{cm}^3$

$\therefore n(CaSO_4) = 0{,}5 \times n(HC\ell)$ ✓

$= 0{,}5 \times 1{,}42 \times 10^{-3}$

$= 7{,}1 \times 10^{-4}$ mol

$\therefore m(CaSO_4) = nM$ ✓

$= 7{,}1 \times 10^{-4} \times 136$ ✓

$= 0{,}097$ g ✓ (10)

$V_{HC\ell\ (\text{reacted with NaOH})} = 15{,}8\ \text{cm}^3$

$V_{HC\ell\ (\text{reacted with } CaCO_3)} = 30 - 15{,}8\ \text{cm}^3$ ✓

$= 14{,}2\ \text{cm}^3$

$\therefore n_{HC\ell\ (\text{reacted with } CaCO_3)} = 0{,}0142 \times 0{,}1$

$= 1{,}42 \times 10^{-3}$mol ✓

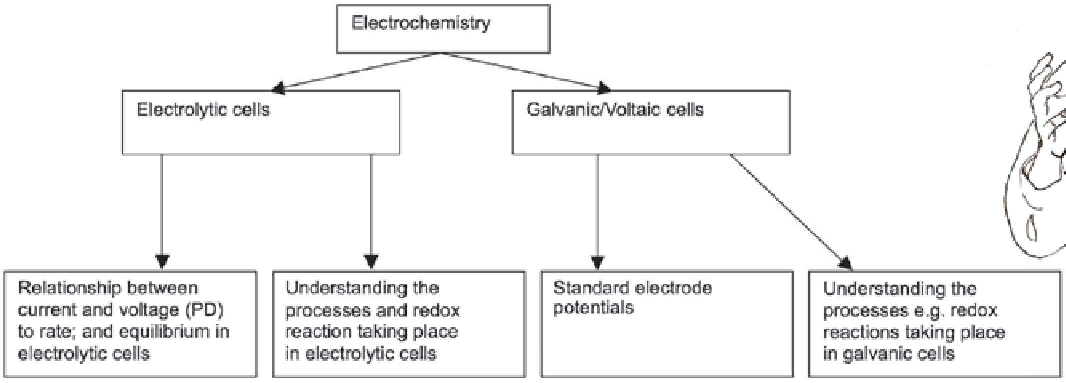
[21]

Unit 5

Electrochemistry

Electrochemistry refers to chemical reactions during which chemical energy is converted to electric energy, or electric energy is converted to chemical energy. During these chemical reactions oxidation and reduction take place. These are called redox reactions.

5.1 Summary



Redox (reduction - oxidation) reactions:

- Electron transfers take place.
- can be represented by two half-reactions:
  - an oxidation half-reaction and
  - a reduction half-reaction.

5.2 Key concepts: Definitions and terminology

NB

Electrolysis is the chemical process in which electrical energy is converted to chemical energy.

Electrolysis is the process where electrical energy is used to produce a chemical change.

REMEMBER

You must remember these basic **definitions** for electrochemistry:

- Galvanic cells
- Reduction
- Anode
- Electrolysis
- Electrolytic cells
- Oxidising agent
- Cathode
- Oxidation
- Reducing agent
- Electrolyte

A galvanic cell is a cell in which chemical energy is converted into electrical energy.

An electrolytic cell is a cell in which electrical energy is converted into chemical energy.

NB

REMEMBER

We define oxidation and reduction in terms of electron (e^-) transfer

RED CAT:

REDuction – **CAT**hode

AN OX :

ANode - **OX**idation

Oxidation	Reduction
Oxidation is the loss of electrons by a substance (i.e. by an atom, a molecule or an ion).	**Reduction** is the gain of electrons by a substance (i.e. by an atom, a molecule or an ion).
Learn: ***LEO*** for *Loss of Electrons is Oxidation.*	***Learn:*** ***GER*** for *Gain of Electrons is Reduction.* (because gaining electrons is gaining minuses, so reducing)
A substance that is oxidised (i.e. loses electrons) is called a **reducing agent.**	A substance that is reduced (i.e. gains electrons) is called an **oxidising agent**.
The **oxidation number** of a compound that is **oxidised, increases** (becomes less negative, or becomes more positive).	The **oxidation number** of a compound that is **reduced**, decreases (becomes more negative, or becomes less positive).

The **anode (–)** is the electrode where **oxidation (+)** takes place

The **cathode (+)** is the electrode where **reduction (–)** takes place.

The **electrodes**:

- conduct electricity
- are placed in electrolytes which are solutions consisting of ions.

The **electrolyte** is the **solution/liquid/dissolved substance** that **conducts electricity through the movement of ions.**

Activity 1

Give one word for the following statements:

1. The chemical process when an electric current is passed through an ionic compound in solution or in molten state. (1)
2. An ionic solution that conducts electricity. (1)
3. The reactant that donates electrons during a redox reaction. (1)
4. The electrode in an electrochemical cell where reduction takes place. (1)
5. **TRUE OR FALSE?** The reactions $C(s) + O_2(g) \rightarrow CO_2(g)$ and $2KC\ell O_3(s) \rightarrow 2KC\ell(s) + 3O_2(g)$ are examples of redox reactions. (1)
6. The electrode in an electrochemical cell where oxidation occurs. (1)
7. A substance that shows a decrease in oxidation number during chemical reactions. (1)

8. Which of the following substances can be used as an electrolyte?
   A. Mercury
   B. Molten copper
   C. Sugar dissolved in distilled water
   D. Table salt dissolved in distilled water. (1)

[8]

Solutions

1. Electrolysis✓ (1)
2. Electrolyte✓ (1)
3. Reducing agent✓ (1)
4. Cathode✓ (1)
5. TRUE statement✓ (1)
6. Anode✓ (1)
7. Oxidising agent✓ (1)
8. D✓ (1)

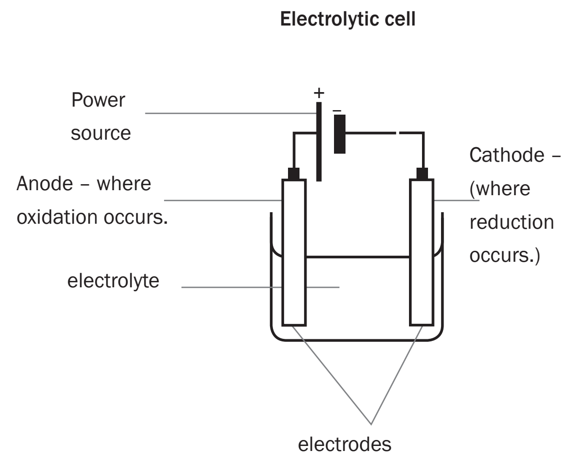
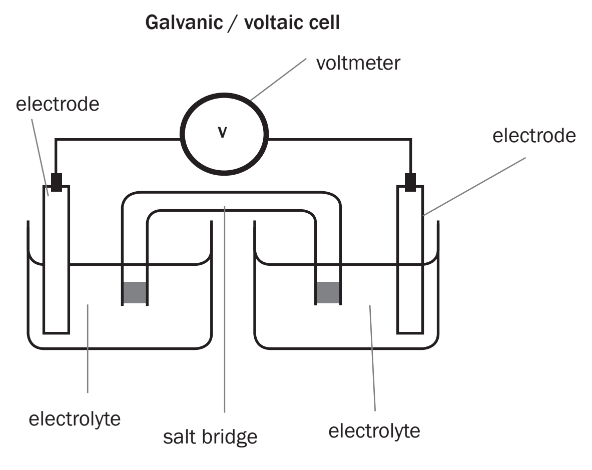
[8]

5.3 Electrochemical cells

Electrochemical cells allow conversion between electrical and chemical energy.

There are two types of electrochemical cells:

- Galvanic (voltaic) cells
- Electrolytic cells.

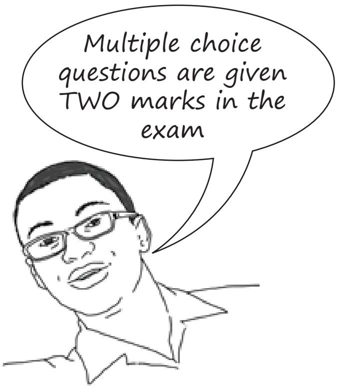
Electrolytic cell	Galvanic / voltaic cell
	
Electric energy → chemical energy	Chemical energy → electric energy
No salt bridge	Salt bridge
Non-spontaneous redox reactions	Spontaneous redox reactions
Endothermic reaction	Exothermic reaction
Positive electrode → anode → oxidation	Negative electrode → anode → oxidation
Negative electrode → cathode → reduction	Positive electrode → cathode → reduction
emf is always negative	emf is always positive

Activity 2

Give ONE word for the following statements:

1. The electrode in a galvanic cell at which reduction occurs. (1)
2. Anode in an electrolytic cell. (1)
3. The type of electrochemical cell in which electrical energy is converted to chemical energy. (1)
4. **TRUE** or **FALSE**?
   An electrolytic cell converts mechanical energy to electrical energy. (1)
5. Which ONE of the following half-reactions occurs at the cathode during the electrolysis of an aqueous $CuC\ell_2$ solution?
   A. $C\ell_2 + 2e^- \rightarrow 2C\ell^-$
   B. $Cu^+ + e^- \rightarrow Cu$
   C. $2C\ell^- \rightarrow C\ell_2 + 2e^-$
   D. $Cu^{2+} + 2e^- \rightarrow Cu$ (2)
6. The gain of electrons by a substance in a chemical reaction is known as …
   A. Oxidation
   B. Reduction
   C. Electrolysis
   D. Oxidation and reduction (2)

[8]

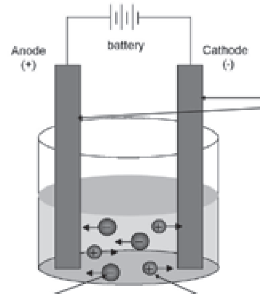


Solutions

1. Cathode✓ (1)
2. Positive electrode✓ (1)
3. Electrolytic✓ (1)
4. This statement is FALSE. This cell converts electrical energy to chemical energy.✓ (1)
5. D ✓✓ (2)
6. B ✓✓ (2)

[8]

5.4 Electrolytic cells



Electrodes are made from unreactive substances (platinum, Pt or graphite, C) and are placed in the same ionic solution or molten ionic compound

The electrons flow in the **external circuit** from the negative pole of the battery to the cathode (–)

Negative ions (anions) move (migrate) to the anode where they are oxidised

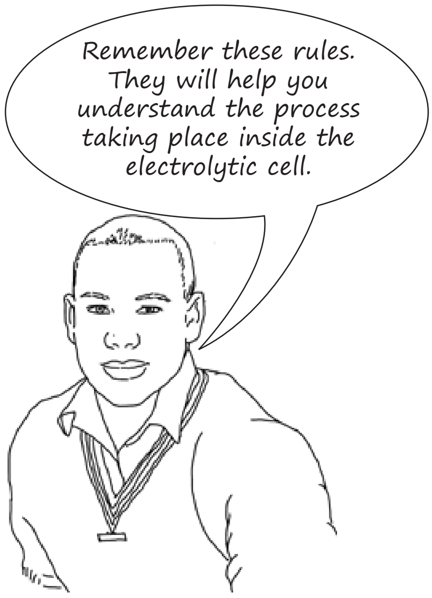
Positive ions (cations) move (migrate to the cathode where they are reduced

a) Electrolysis of molten ionic compounds:

- The negative ions migrate (move) to the anode where they are **oxidised.**
- The positive ions migrate to the cathode where they are **reduced.**

b) Electrolysis of ionic solutions:

The ***anions*** *(negative ions)* from the ionic compound **and** the hydroxyl ions (OH^-) from the water migrate to the anode (positive electrode). The anions from the ionic compound compete with the hydroxide ions (OH^-) from the solution, to be oxidised.



Rules:

If the ionic compound contains:

- **halide** ions (**$C\ell^-$**; **Br^-** or **I^-**), the halide ion will be oxidised and **NOT** the hydroxide ion. The product will therefore be the corresponding **halogen.**
- **sulphate** (**SO_4^{2-}**) or nitrate (**NO_3^-**) ions, the hydroxide ion (OH^-) will be oxidised to produce oxygen, **$O_2(g)$**.

The ***cations*** *(positive ions)* from the ionic compound and the H^+ ions from the water migrate to the **cathode** (negative electrode). The cations from the ionic compound compete with the H^+ ions to be reduced.

Rules:

If the ionic compound contains:

- **cations** of metals with a **positive electrode potential**, these cations will be reduced to form the corresponding **metal** e.g. Cu. See the table on electrode potentials provided in introduction to this book.
- **cations** of metals with a **negative electrode potential** (e.g. Zn^{2+}), the H^+ ions will be reduced to form **hydrogen, $H_2(g)$.** See the table on electrode potentials provided in this book.

NB

Remember to indicate the charge on the ion

Worked example 1

1. Explain how the electrolysis of a copper (II) chloride solution $CuC\ell_2(aq)$ takes place.

Solution

1. **The anions** $C\ell^-$ and OH^- migrate to the positive anode. The $C\ell^-$ ions are **oxidised.**

oxidation half-reaction: $2C\ell^-(aq) \rightarrow C\ell_2(g) + 2e^-$

The cations (Cu^{2+} and H^+) migrate to the cathode. The Cu^{2+} ions are reduced.

reduction half-reaction: $Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$

The net reaction: $Cu^{2+}(aq) + 2C\ell^-(aq) \rightarrow Cu(s) + C\ell_2(g)$

The solution is initially blue due to the presence of the Cu^{2+} ions, but as they are reduced to Cu(s), the solution turns colourless and red-brown Cu(s) is deposited on the cathode.

Worked example 2

2. Predict the products of the electrolysis of a copper (II) sulphate solution $CuSO_4(aq)$

Solution

2.
- **At the anode:** $O_2(g)$
- **At the cathode:** Cu(s)

Worked example 3

3. Predict the products of the electrolysis of a zinc chloride solution $ZnC\ell_2(aq)$

Solution

3.
- **At the anode:** $C\ell_2(g)$
- **At the cathode:** Zn(s)

c) Electrolysis of water:

Water is a **weak electrolyte** (weak electric conductor). A small amount of dilute sulphuric acid (H_2SO_4) is added to water to increase its conductivity. When an electric current is passed through the acidified water, oxidation and reduction reactions take place.

At the anode:

oxidation half-reaction: $2H_2O \rightarrow O_2(g) + 4H^+ + 4e^-$ $E^0 = +1{,}23\ V$

At the cathode:

reduction half-reaction: $2H^+ + 2e^- \rightarrow H_2(g)$ $E^0 = 0{,}00\ V$

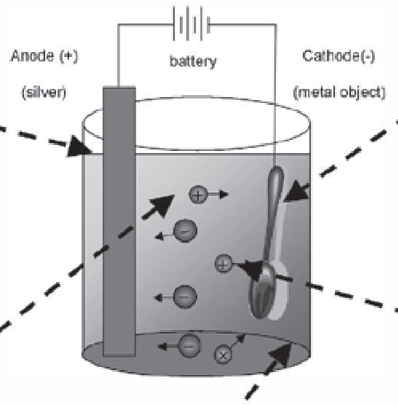
The net reaction: $\mathbf{2H_2O(\ell) \rightarrow 2H_2(g) + O_2(g)}$

5.5 Application of electrolysis

- Electroplating
- Production of chemicals e.g. chlorine gas, hydrogen gas and sodium hydroxide (membrane cell, chlor-alkali industry)
- Extraction of metals e.g. aluminium
- Refining (purifying) of metals e.g. copper.

a) Electroplating

Electroplating is the process of putting a metallic coating on an object using electrolytic reactions.



The positive anode (which is oxidised) is made of the metal used to cover the object e.g. silver (Ag).

The cations that are produced at the anode migrate through the electrolyte towards the cathode (the object that needs to be electroplated).

The object that must be electroplated acts as the cathode (reduction takes place), and is connected to the negative terminal of the electrical supply.

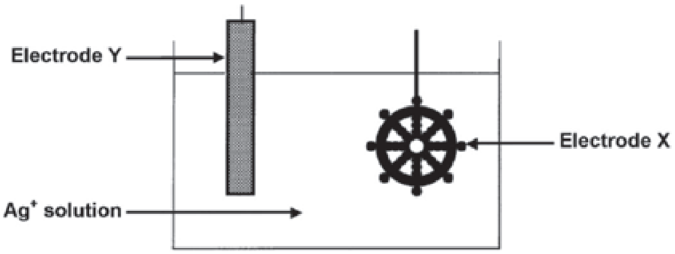
At the cathode, the metal cations from the solution are reduced to form the solid metal which then forms a layer on the object being electroplated.

Electrodes are suspended in a bath containing a solution **(electrolyte)** of a suitable salt of the metal with which it is supposed to be plated.
The concentration of the ions in the solution remains constant, as they are produced (by the oxidation half-reaction at the anode) at the **same rate** as they are used (during the reduction half-reaction at the cathode).

Electroplating is used to protect metals that oxidise easily, by covering them with a thin layer of a metal that does not oxidise easily e.g. chromium, silver or gold. A relatively cheap metal is covered by an expensive metal. Silver is used to cover cutlery — it is too expensive to make a spoon of pure silver, and it is too weak to use — while chromium can be used to cover car parts like bumpers.

Worked example 4

An attractive silver appearance can be created by electroplating artefacts (objects) made from cheaper metals, such as nickel, with silver. The simplified diagram here represents an arrangement that can be used to electroplate a nickel artefact with silver.



1. Which electrode (cathode or anode) does the nickel artefact represent?
2. Name the metal represented by electrode Y.
3. Write down the half-reaction responsible for the change that occurs at the surface of the artefact.
4. Give a reason why the concentration of the electrolyte remains constant during electroplating.
5. In industry some plastic articles are sometimes electroplated. Explain why plastic must be coated with graphite before electroplating.
6. Give a reason why, from a business point of view, it is not advisable to plate platinum with silver.

Solutions

1. Cathode
2. Silver
3. $Ag^+ + e^- \rightarrow Ag$
4. The rate of oxidation of silver at the anode is equal to the rate of reduction of silver ions at the cathode.
5. Plastic is a non-conductor. It must be covered with a conducting layer so that it can act as the cathode. Graphite is a conductor.
6. Platinum is expensive and is more durable than other metals. You would normally electroplate a cheap metal with an expensive, durable metal and not the other way round.

Activity 3

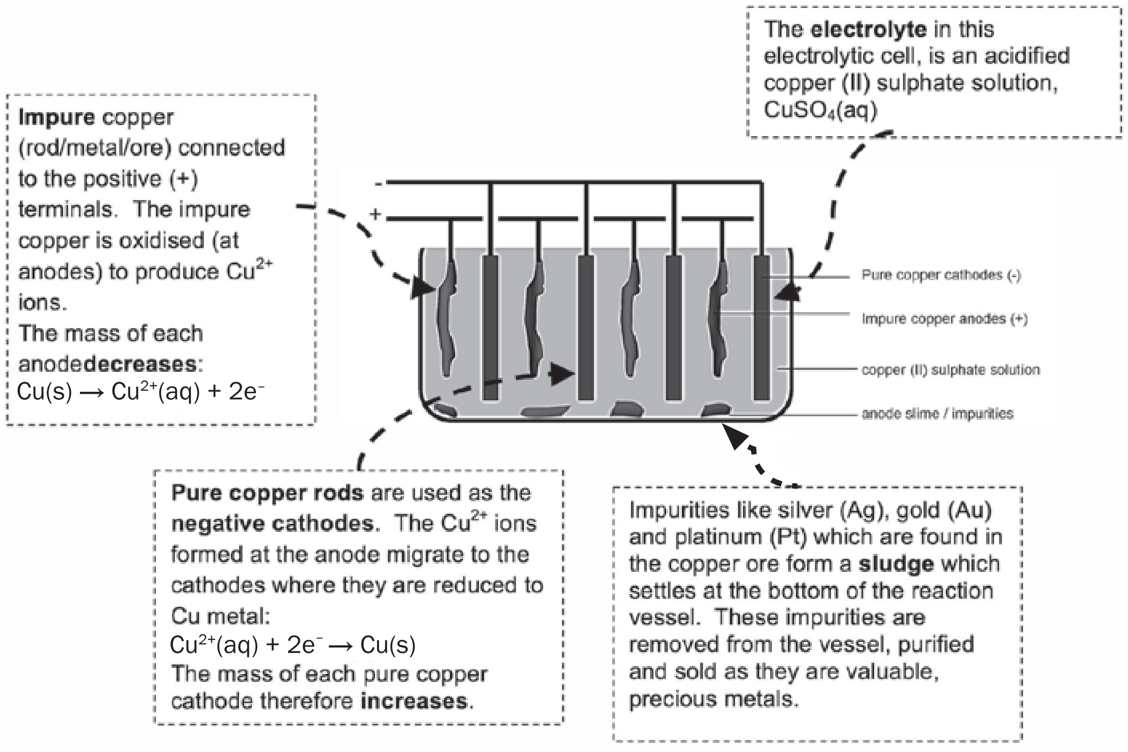
1. TRUE or FALSE? During electroplating of a steel teaspoon with silver, the teaspoon is the cathode and the electrolyte is a solution of any soluble compound [2]

Solution

1. FALSE. ✓… the electrolyte is a solution of a soluble silver compound. ✓ [2]

b) Refining of copper

Copper which is mined is impure and the copper ore can be refined as follows by means of electrolysis:



The **electrolyte** in this electrolytic cell, is an acidified copper (II) sulphate solution, $CuSO_4(aq)$

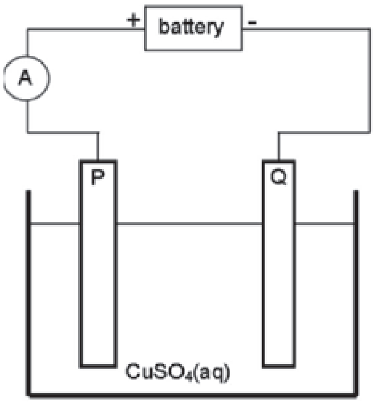
Impure copper (rod/metal/ore) connected to the positive (+) terminals. The impure copper is oxidised (at anodes) to produce Cu^{2+} ions.
The mass of each anode**decreases**:
$Cu(s) \rightarrow Cu^{2+}(aq) + 2e^-$

Pure copper rods are used as the **negative cathodes**. The Cu^{2+} ions formed at the anode migrate to the cathodes where they are reduced to Cu metal:
$Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$
The mass of each pure copper cathode therefore **increases**.

Impurities like silver (Ag), gold (Au) and platinum (Pt) which are found in the copper ore form a **sludge** which settles at the bottom of the reaction vessel. These impurities are removed from the vessel, purified and sold as they are valuable, precious metals.

e.g. Worked example 5

Impure copper can be purified by the process of electrolysis. The simplified diagram represents an electrolytic cell used to purify copper.



1. Define the term electrolysis.
2. Which electrode, P or Q, consists of the impure copper? Explain how you arrived at your answer.
3. Write down the half-reactions that take place at electrodes P and Q.
4. During purification, metals such as silver and platinum form sludge at the bottom of the container. Refer to the relative strengths of reducing agents to explain why these two metals do not form ions during the purification process.
5. Explain why the concentration of the copper (II) sulphate solution remains constant. Assume that the only impurities in the copper are silver and platinum.
6. Why is the sludge of economic importance?

Solutions

1. Electrolysis is a process during which electrical energy is converted to chemical energy. It is the process in which electricity is used to bring about a chemical change / decompose / break compounds into components.
2. P: P is the positive electrode / anode. The impure Cu is oxidised at the positive electrode / anode.
3. P: Anode: $\underset{\text{impure}}{Cu(s)} \rightarrow Cu^{2+}(aq) + 2e^-$ oxidation

   Q: Cathode: $Cu^{2+}(aq) + 2e^- \rightarrow \underset{\text{pure}}{Cu(s)}$ reduction
4. Platinum and silver are both weaker reducing agents than copper and will not be oxidised to form ions.
5. The rate at which copper is oxidised (at the anode) is equal to the rate at which copper ions are reduced (at the cathode).
6. Silver and platinum are valuable and expensive metals and can therefore be sold at a profit.

Activity 4

1. Refer to the diagram in the worked example above. One of the electrodes consists of impure copper and the other one of pure copper.
    1. What type of power source is used to drive the reaction in this cell? Write down only AC or DC. (1)
    2. Give a reason why the copper(II) sulphate is dissolved in water before it is used in this cell. (1)

    When an electric current passes through the solution, electrode **P** becomes coated with copper.

    3. Is electrode **P** the cathode or the anode? Support your answer by writing the half-reaction that takes place at electrode **P.** (2)
    4. Write down the half-reaction that takes place at electrode **Q**. (2)

    It is found that the impure copper plate contains platinum. The platinum forms a residue at the bottom of the container during electrolysis.

    5. Refer to the relative strengths of reducing agents to explain why platinum forms a residue at the bottom of the container. (2)
    6. How will the concentration of the copper(II) sulphate solution change during electrolysis? Write down only INCREASES, DECREASES or REMAINS THE SAME. (3)

[11]

Solutions

1. DC ✓ (1)
2. Free ions needed to conduct electricity ✓ (1)
3. Cathode. ✓ $Cu^{2+} + 2e^- \rightarrow Cu$ ✓ (2)
4. $Cu \rightarrow Cu^{2+} + 2e^-$ ✓ ✓ (2)
5. Pt is a weaker reducing agent than Cu ✓and will not be oxidised ✓ (2)

    OR

    Cu is a stronger reducing agent than Pt and will be oxidised
6. Remains the same.✓ The rate at which Cu is oxidised at the anode ✓ equals the rate at which $Cu^{2+}(aq)$ is reduced at the cathode ✓ (3)

[11]

c) The recovery or extraction of aluminium metal from bauxite

Aluminium:

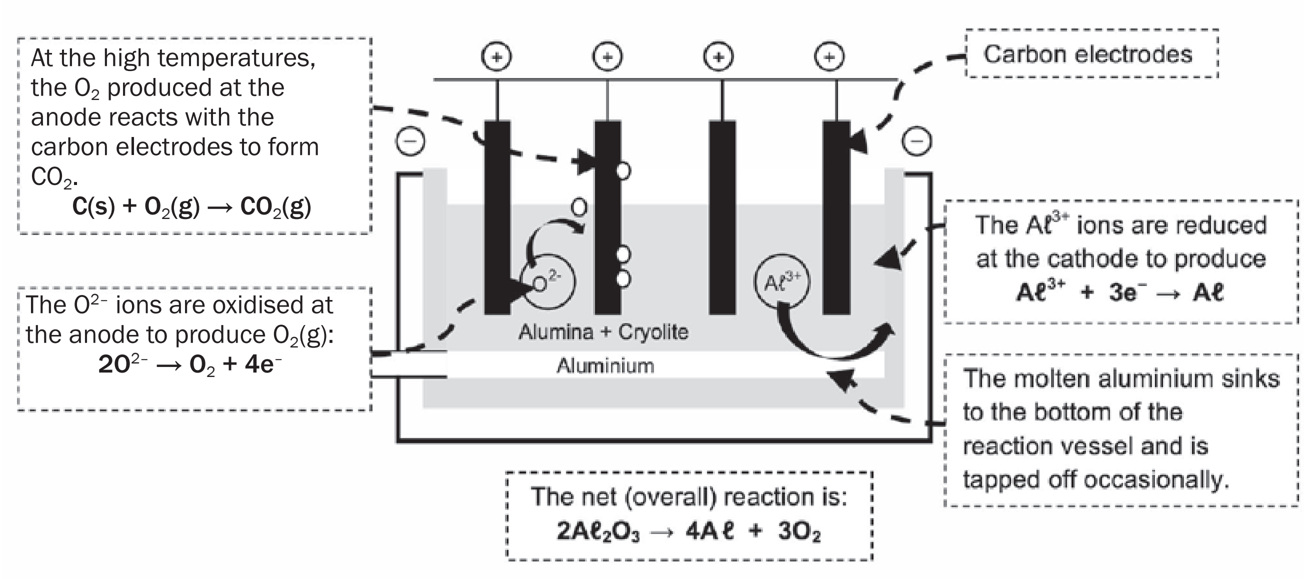
- is one of the most abundant metals on earth, yet it is expensive – largely because of the amount of electricity needed to extract it.
- has the following properties: a low density; the ability to resist corrosion; is very ductile; can be rolled out in thin layers; is lightweight and is a good electrical conductor.

NB

A very important application of electrolysis is the recovery of **aluminium**. South Africa imports bauxite, an aluminium ore.

The process involves:

- Aluminium oxide ($A\ell_2O_3$) is extracted from the bauxite and it is then heated.
- The melting point of $A\ell_2O_3$ is higher than 2 000 °C. Cryolite ($Na_3A\ell F_6$) is added to the ore before it is heated. Cryolite does not lower the melting point of $A\ell_2O_3$ but dissolves it. $A\ell_2O_3$ dissolved in a molten cryolite can be electrolysed easily. This means that less electricity is required to extract the aluminium, thereby decreasing the extraction cost.
- The ions, $A\ell^{3+}$ and O^{2-}, are formed during the extraction.
- The mass of the anode therefore gradually decreases. The cost of replacing the anode when it is depleted adds to the high cost of the aluminium extraction.



At the high temperatures, the O_2 produced at the anode reacts with the carbon electrodes to form CO_2.
$C(s) + O_2(g) \rightarrow CO_2(g)$

The O^{2-} ions are oxidised at the anode to produce $O_2(g)$:
$2O^{2-} \rightarrow O_2 + 4e^-$

The $A\ell^{3+}$ ions are reduced at the cathode to produce
$A\ell^{3+} + 3e^- \rightarrow A\ell$

The molten aluminium sinks to the bottom of the reaction vessel and is tapped off occasionally.

The net (overall) reaction is:
$2A\ell_2O_3 \rightarrow 4A\ell + 3O_2$

- **The ecological impact of Aℓ extraction:** Loss of landscape due to the size of the chemical plant needed; disposal of red mud (iron (III) oxide) formed during extraction of aluminium oxide from bauxite, into rivers and lagoons and into ground water.
- **Environmental impact of Aℓ extraction:** Carbon dioxide from the burning of the anodes contributes to the greenhouse effect, causing **global warming**. Fluorine and its compounds lost from the cryolite during the electrolysis process are **poisonous**. Chemicals in the red mud dams drain into the soil and contaminate groundwater. **Pollution** caused by power generation (for electrolytic process) using coal fired plants leads to **acid rain** and adds to the **greenhouse effect. Noise pollution** from the extraction plant.

Activity 5

Give ONE word for the following phrase:

1. The main ore from which aluminium is extracted. (1)
2. The name of the chemical substance in which $A\ell_2O_3$ is dissolved to lower its melting point during the industrial extraction of aluminium. (1)

[2]

Solutions

1. Bauxite ✓
2 Cryolite ✓ **[2]**

Activity 6

1. In an aluminium smelter, aluminium metal is extracted from bauxite, a hydrated aluminium oxide, via an electrolytic process.
   - **1.1** Write down the energy conversion that takes place in an electrolytic cell. (2)
   - **1.2** Write down the equation for the half reaction responsible for the formation of aluminium metal in a smelter. (2)
   - **1.3** Explain in terms of the relative strength of oxidizing agents why the electrolytic production of aluminum requires more electrical energy than that of iron or copper. (2)
   - **1.4** Name TWO advantages that the use of aluminium has over that of iron. (2)
2. A huge aluminium smelter is planned for Coega in the Eastern Cape. When operational, it will consume 1350 MW of electricity, or 4% of the nation's total electrical energy. It is estimated that 5200 jobs will be created at the peak of construction. About 1000 workers will be employed on a full-time permanent basis, and between 200 and 300 full-time subcontractors will also be directly associated with the smelter. (Source: www.engineeringnews.co.za; www.groundwork.org.za).
   - **2.1** Taking the present South African socio-economic realities into account, give ONE reason why the aluminium smelter should:
     - (a) Not be built (1)
     - (b) Be built (1)
   - **2.2** Give ONE reason why environmental activists oppose the construction of the smelter. (1)

[11]

Solutions

1.1 Electrical energy → chemical energy ✓✓ (2)

1.2 $A\ell^{3+} + 3e^- \rightarrow A\ell$ ✓✓ (2)

1.3 Aluminium has a lower reduction potential (–1,66 V) ✓/ Weaker oxidizing agent compared to that of iron (–0,44 V) [and copper (+0,34 V)]. The aluminium ions therefore require a large amount of energy to be reduced/ will reduce more difficultly than iron (and copper). ✓ (2)

1.4 It is much lighter for the same strength (or stronger for the same mass). ✓

It is corrosion free.✓ (2)

2.1 (a) It will consume huge amount of electricity. ✓/ Will cause power failures ✓ (any 2) (1)

(b) It will create jobs ✓/Create foreign investment. ✓ Contribute to GDP ✓ (any 3) (1)

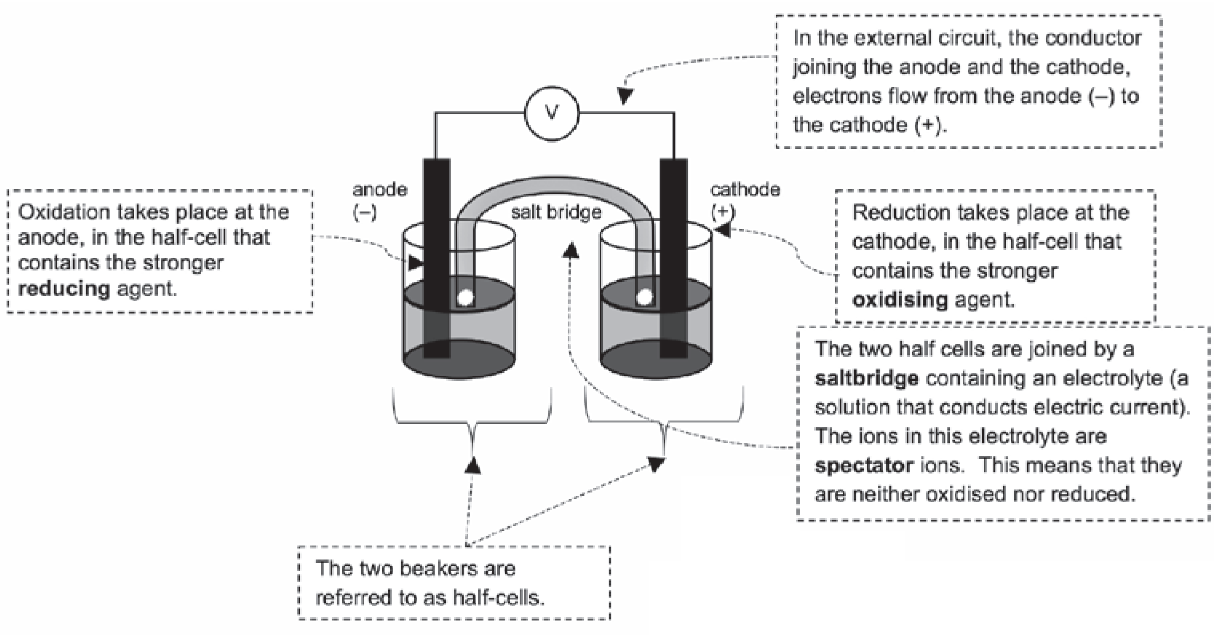
2.2 The production of the large amount of electricity used ✓ enhances the greenhouse effect (or climate change) ✓ **OR** The process is responsible for toxic fluoride waste **OR** pollution. (any one) (1)

[11]

5.6 Voltaic (Galvanic) cells

REMEMBER:

- A **Galvanic** or **voltaic cell** is a cell in which chemical energy is converted to electrical energy spontaneously. We therefore use a chemical reaction to produce electricity. E.g. standard AA / penlight batteries.



In the external circuit, the conductor joining the anode and the cathode, electrons flow from the anode (–) to the cathode (+).

Oxidation takes place at the anode, in the half-cell that contains the stronger **reducing** agent.

Reduction takes place at the cathode, in the half-cell that contains the stronger **oxidising** agent.

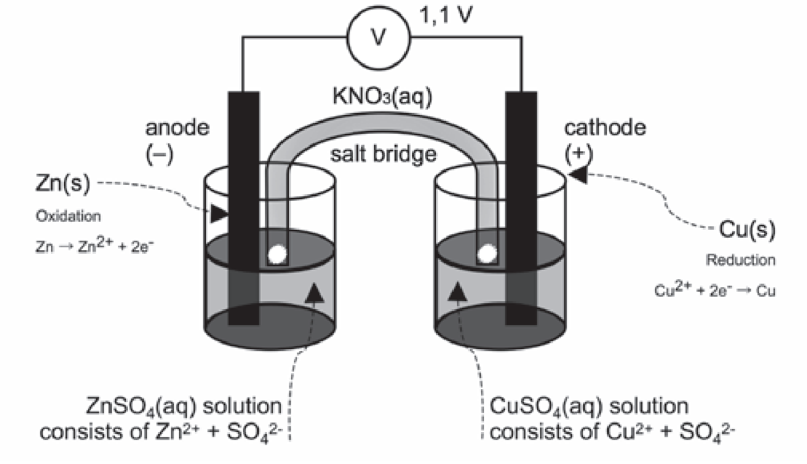
The two half cells are joined by a **saltbridge** containing an electrolyte (a solution that conducts electric current). The ions in this electrolyte are **spectator** ions. This means that they are neither oxidised nor reduced.

The two beakers are referred to as half-cells.

Consider a copper-zinc cell:

A strip of zinc metal is placed in a zinc ion solution. A strip of copper is placed in a separate beaker in an aqueous copper (II) ion solution. These solutions are the **electrolytes.** As they contain ions which dissociated when the salts were dissolved in water, they are good electric conductors.

- The half reactions that occur in each half cell:
  $Zn(s) \rightarrow Zn^{2+} + 2e^-$
  $Cu^{2+} + 2e^- \rightarrow Cu(s)$



REMEMBER

When redox half-reactions are to be written, the correct **single arrow** should be used.

Zn half-cell	Cu half-cell
Oxidation half-reaction at the **anode** which is always the **negative** electrode (e^- are given off).	**Reduction half-reaction** at the **cathode** which Is always the **positive** electrode.
The stronger reducing agent is oxidised (**gives off** electrons)	The stronger oxidising agent is reduced (**receives electrons**)
$Zn(s) \rightarrow Zn^{2+} + 2e^-$ (read from right to left)	$Cu^{2+} + 2e^- \rightarrow Cu(s)$ (read from left to right)
Zn is the stronger **reducing** agent	Cu^{2+} is the stronger **oxidising** agent
The anode always **decreases** in mass if the reducing agent is a solid (The Zn rod is corroding).	The cathode always **increases** in mass if the reduced product is a solid (copper deposits on rod).

Net cell reaction:

- Add the two half reactions together, eliminating the electrons from both sides.
- If necessary, multiply each half-reaction with suitable coefficients to ensure that the number of electrons lost equals the number of electrons gained.

Oxidation half-reaction: $Zn(s) \rightarrow Zn^{2+} + 2e^-$

Reduction half-reaction: $Cu^{2+} + 2e^- \rightarrow Cu(s)$

Net cell reaction: $Zn(s) + Cu^{2+}(aq) \rightarrow Zn^{2+}(aq) + Cu(s)$

NB

- In **redox reactions**, most learners struggle to understand the difference between the name of the process, such as oxidation and the substance, for example the reducing agent.
- Be very careful not to write reduction agent instead write reducing agent.
- Be able to clearly distinguish between the oxidising and the reducing agent.

a) **Salt bridge** – part of electrochemical cell (usually a tube) containing electrolyte providing electrical contact between two solution.

The salt bridge:

- Completes the circuit.
- Keeps the two electrolytes in the two half-cells separate so that they do not mix.
- Allows movement of ions between the electrolytes, so as to ensure electrical neutrality i.e. it acts as an ion **exchanger**.
- Contains a saturated salt solution (not 1 $mol{\cdot}dm^{-3}$) of either KNO_3 or $KC\ell$.
- The electrolyte in the salt bridge must contain ions which are weak reducing agents and weak oxidising agents. This will ensure that these ions are not oxidised or reduced, but act as spectator ions.

NB

Potassium chloride is not suitable for a silver half-cell, because $AgC\ell$ is formed and this compound is insoluble, thus a precipitate will form.

b) **Electrolyte:**

- The salt of the compounds need to be soluble.
- Suitable soluble salts of zinc and copper are zinc nitrate and copper nitrate.
- The electrolyte solutions in this cell is $Zn(NO_3)_2(aq)$ and $Cu(NO_3)_2(aq)$.
- As the Zn(s) is oxidised to $Zn^{2+}(aq)$, the concentration of the **Zn^{2+} ions increases** in the diagram above. This means that the Zn half-cell will start building up a positive charge. As the electrons will only move away from a **negative** potential, the function of the cell would become impaired.
- In the same way as the Cu^{2+} ions are reduced to Cu(s), the concentration of the **Cu^{2+} ions decreases**. This leads to the copper

NB

The nitrate salts of ionic compounds are very suitable as an electrolyte, since the salts are soluble in water.

half-cell becoming less positive. The electrons are therefore not attracted to the cathode as strongly and the function of the cell would become impaired (weaker).

- The migration of the NO_3^- anions in the salt bridge to the anode (the Zn half-cell) and of the K^+ ions in the salt bridge to the cathode (the Cu half-cell), cancel this build-up of undesired charge and maintain the cell's electric neutrality. The cell therefore continues to function properly.

c) **Electron current:**
  - Electrons always flow from the anode, through the external circuit, to the cathode.
  - In the Cu/Zn cell, electrons therefore flow from the zinc (Zn) to the copper (Cu).

5.7 Cell notation

The structure of the galvanic cell may also be represented in symbols.

Rules:

- Always start with the anode on the left and end with the cathode on the right.
- Use a / to separate the anode or cathode from its electrolyte.
- Represent the salt bridge with the symbol //.
- Inert electrodes (usually Pt or C) and phases are usually included:

$Zn(s)$ / $Zn^{2+}(aq)$	**//**	**$Cu^{2+}(aq)$ / $Cu(s)$**
electrode / electrolyte	**//**	**electrolyte / electrode**
anode (–)	**salt bridge**	**cathode (+)**

e.g. Pt/reducing agent/oxidised species//oxidising agent/reduced species/Pt

$Pt / C\ell^-(aq) / C\ell_2(g) // F_2(g) / F^-(aq) / Pt$

Activity 7

Give ONE word for the following phrase:

1. The electrode in a galvanic cell at which reduction occurs. (1)
2. The component of a galvanic cell that allows for the movement of ions between the half-cells. (1)
3. Which statement is CORRECT for a Zn-Cu galvanic cell that operates under standard conditions? (Standard Conditions are defined in the tables at the beginning of this book)
   - **A** The concentration of the Zn^{2+} ions in the zinc half-cell gradually decreases.
   - **B** The concentration of the Cu^{2+} ions in the copper half-cell gradually increases.
   - **C** Negative ions migrate from the zinc half-cell to the copper half-cell.
   - **D** The intensity of the colour of the electrolyte in the copper half-cell gradually decreases. (2)
4. The reactions below occur in two different electrochemical cells X and Y.

   Cell X: $CuC\ell_2(aq) \rightarrow Cu(s) + C\ell_2(g)$
   Cell Y: $Zn(s) + CuSO_4(aq) \rightarrow Cu(s) + ZnSO_4(aq)$

   Which ONE of the following correctly describes the substance that forms at the CATHODE of each of these cells?

	Cell X	Cell Y
A	$C\ell_2(g)$	$Cu(s)$
B	$Cu(s)$	$Cu(s)$
C	$C\ell_2(g)$	$ZnSO_4(aq)$
D	$Cu(s)$	$ZnSO_4(aq)$

(2)

5. Which one of the following statements regarding a copper-silver galvanic cell is TRUE?
   - **A** Silver is formed at the anode
   - **B** Copper is formed at the anode
   - **C** Silver is formed at the cathode
   - **D** Copper is formed at the cathode (2)

[8]

Solutions

1. Cathode ✓ (1)
2. Salt bridge ✓ (1)
3. D ✓✓ (2)
4. B ✓✓ (2)
5. C ✓✓ (2)

[8]

5.8 Standard electrode potentials

The **Reactivity Series** is a list of substances which are arranged in order of their ability to act as **reducing agents** or as **oxidising agents.**

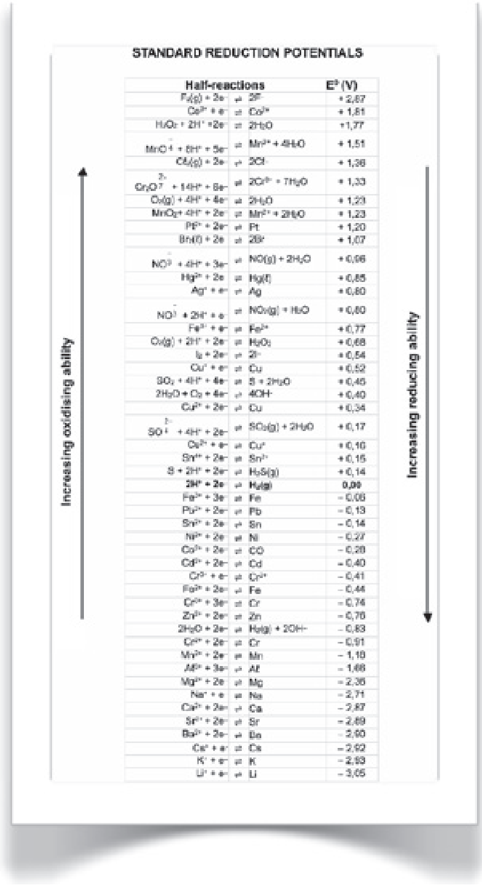
The Table of Standard Reduction Potentials lists the standard electrode potentials (E^0 values) for various compounds. There are two tables, they are similar, but the entries are arranged in opposite directions.

- The tables of Standard Reduction Potentials can be used to:
  - identify oxidising and reducing agents
  - write balanced redox reaction equations
  - predict whether a redox reaction takes place spontaneously or not
  - calculate the emf of a voltaic cell by using one of the following formulae (formulas):

$$E^0_{cell} = E^0_{cathode} - E^0_{anode} \quad \text{OR} \quad E^0_{cell} = E^0_{oxidising\ agent} - E^0_{reducing\ agent}$$

NB

You will notice that all ionic compounds, for example, H_2SO_4, HNO_3 and $HC\ell$ must be dissociated into ions, before we can use the information in the Table of Standard Reduction Potentials.


STANDARD REDUCTION POTENTIALS

Half-reactions			E^θ (V)
$F_2(g) + 2e^-$	$\rightleftharpoons$	$2F^-$	+ 2,87
$Co^{3+} + e^-$	$\rightleftharpoons$	Co^{2+}	+ 1,81
$H_2O_2 + 2H^+ + 2e^-$	$\rightleftharpoons$	$2H_2O$	+1,77
$MnO_4^- + 8H^+ + 5e^-$	$\rightleftharpoons$	$Mn^{2+} + 4H_2O$	+ 1,51
$Cl_2(g) + 2e^-$	$\rightleftharpoons$	$2Cl^-$	+ 1,36
$Cr_2O_7^{2-} + 14H^+ + 6e^-$	$\rightleftharpoons$	$2Cr^{3+} + 7H_2O$	+ 1,33
$O_2(g) + 4H^+ + 4e^-$	$\rightleftharpoons$	$2H_2O$	+ 1,23
$MnO_2 + 4H^+ + 2e^-$	$\rightleftharpoons$	$Mn^{2+} + 2H_2O$	+ 1,23
$Pt^{2+} + 2e^-$	$\rightleftharpoons$	Pt	+ 1,20
$Br_2(\ell) + 2e^-$	$\rightleftharpoons$	$2Br^-$	+ 1,07
$NO_3^- + 4H^+ + 3e^-$	$\rightleftharpoons$	$NO(g) + 2H_2O$	+ 0,96
$Hg^{2+} + 2e^-$	$\rightleftharpoons$	$Hg(\ell)$	+ 0,85
$Ag^+ + e^-$	$\rightleftharpoons$	Ag	+ 0,80
$NO_3^- + 2H^+ + e^-$	$\rightleftharpoons$	$NO_2(g) + H_2O$	+ 0,80
$Fe^{3+} + e^-$	$\rightleftharpoons$	Fe^{2+}	+ 0,77
$O_2(g) + 2H^+ + 2e^-$	$\rightleftharpoons$	H_2O_2	+ 0,68
$I_2 + 2e^-$	$\rightleftharpoons$	$2I^-$	+ 0,54
$Cu^+ + e^-$	$\rightleftharpoons$	Cu	+ 0,52
$SO_2 + 4H^+ + 4e^-$	$\rightleftharpoons$	$S + 2H_2O$	+ 0,45
$2H_2O + O_2 + 4e^-$	$\rightleftharpoons$	$4OH^-$	+ 0,40
$Cu^{2+} + 2e^-$	$\rightleftharpoons$	Cu	+ 0,34
$SO_4^{2-} + 4H^+ + 2e^-$	$\rightleftharpoons$	$SO_2(g) + 2H_2O$	+ 0,17
$Cu^{2+} + e^-$	$\rightleftharpoons$	Cu^+	+ 0,16
$Sn^{4+} + 2e^-$	$\rightleftharpoons$	Sn^{2+}	+ 0,15
$S + 2H^+ + 2e^-$	$\rightleftharpoons$	$H_2S(g)$	+ 0,14
$2H^+ + 2e^-$	$\rightleftharpoons$	**$H_2(g)$**	**0,00**
$Fe^{3+} + 3e^-$	$\rightleftharpoons$	Fe	− 0,06
$Pb^{2+} + 2e^-$	$\rightleftharpoons$	Pb	− 0,13
$Sn^{2+} + 2e^-$	$\rightleftharpoons$	Sn	− 0,14
$Ni^{2+} + 2e^-$	$\rightleftharpoons$	Ni	− 0,27
$Co^{2+} + 2e^-$	$\rightleftharpoons$	Co	− 0,28
$Cd^{2+} + 2e^-$	$\rightleftharpoons$	Cd	− 0,40
$Cr^{3+} + e^-$	$\rightleftharpoons$	Cr^{2+}	− 0,41
$Fe^{2+} + 2e^-$	$\rightleftharpoons$	Fe	− 0,44
$Cr^{3+} + 3e^-$	$\rightleftharpoons$	Cr	− 0,74
$Zn^{2+} + 2e^-$	$\rightleftharpoons$	Zn	− 0,76
$2H_2O + 2e^-$	$\rightleftharpoons$	$H_2(g) + 2OH^-$	− 0,83
$Cr^{2+} + 2e^-$	$\rightleftharpoons$	Cr	− 0,91
$Mn^{2+} + 2e^-$	$\rightleftharpoons$	Mn	− 1,18
$A\ell^{3+} + 3e^-$	$\rightleftharpoons$	$A\ell$	− 1,66
$Mg^{2+} + 2e^-$	$\rightleftharpoons$	Mg	− 2,36
$Na^+ + e^-$	$\rightleftharpoons$	Na	− 2,71
$Ca^{2+} + 2e^-$	$\rightleftharpoons$	Ca	− 2,87
$Sr^{2+} + 2e^-$	$\rightleftharpoons$	Sr	− 2,89
$Ba^{2+} + 2e^-$	$\rightleftharpoons$	Ba	− 2,90
$Cs^+ + e^-$	$\rightleftharpoons$	Cs	− 2,92
$K^+ + e^-$	$\rightleftharpoons$	K	− 2,93
$Li^+ + e^-$	$\rightleftharpoons$	Li	− 3,05

REMEMBER

The formula must be written without any abbreviation in the subscript.

NB

Further information is discussed on the Table of Standard Electrode Potentials (shown here so you know which table to look for). This table is given at the beginning of this book.

E.g. Stronger reducing agents displace weaker reducing agents, and remember to always start with the oxidation half-reaction. **Please read that information now**.

Worked example 6

A piece of zinc metal (Zn) is placed in a beaker containing a copper (II) sulphate solution and a piece of copper metal (Cu) is placed in a beaker containing a zinc (II) sulphate solution.

1. Predict which redox reaction will take place spontaneously.
2. Motivate your answer.
3. Write the oxidation half-reaction, the reduction half-reaction and the net cell reaction for the spontaneous redox reaction.

Solutions

1. Zn is oxidised to Zn^{2+} and Cu^{2+} is reduced to Cu. The redox reaction in the beaker containing the piece of zinc (Zn) and the copper (II) sulphate solution with Cu^{2+} ions is spontaneous.

2. Zn is a stronger reducing agent than Cu (see reducing ability on table), i.e. Zn will be oxidised more readily than Cu and Cu^{2+} is a stronger oxidising agent than Zn^{2+} (see oxidising ability on table) i.e. Cu^{2+} will be reduced more readily than Zn^{2+}. Therefore Zn will displace Cu from $CuSO_4(aq)$.

3. oxidation half-reaction : $Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$
   reduction half-reaction: $Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$
   Overall or net ionic reaction is: $Zn(s) + Cu^{2+}(aq) \rightarrow Zn^{2+}(aq) + Cu(s)$

Worked example 7

1. Use the Table of Standard Reduction Potentials to determine whether Ag will spontaneously displace Zn^{2+} ions from a zinc sulphate ($ZnSO_4$) solution. Motivate your answer.
2. Write the oxidation half-reaction, the reduction half-reaction and the net ionic reaction which takes place when a piece of copper (Cu) is dipped in a silver nitrate ($AgNO_3$) solution.

Solutions

1. No, the reaction will not take place.
   Ag is a weaker reducing agent than Zn, therefore it will not be able to displace Zn from the zinc sulphate solution.

2. oxidation half-reaction: $Cu \rightarrow Cu^{2+} + 2e^-$
   reduction half-reaction: $Ag^+ + e^- \rightarrow Ag^+$

   Multiply this reaction by 2, so that the number of electrons released by the copper atom equals the number of electrons gained.

   $2Ag^+ + 2e^- \rightarrow 2Ag^+$

   net ionic reaction: $Cu + 2Ag^+ \rightarrow Cu^{2+} + 2Ag^+$

Activity 8

1. Which one of the following solutions can be stored in an aluminium container?
   (Use the Table of Standard Reduction Potentials.)
   - **A** $CuSO_4(aq)$
   - **B** $ZnSO_4(aq)$
   - **C** $NaC\ell(aq)$
   - **D** $Pb(NO_3)_2(aq)$ (2)

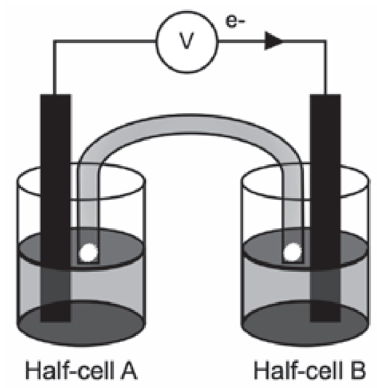
[2]

Solution

1. C ✓✓ **[2]**

Activity 9

The galvanic cell represented in the diagram consists of a Mg electrode dipped into a $Mg(NO_3)_2$ solution, and a Pb electrode dipped into a $Pb(NO_3)_2$ solution. Assume that the cell operates under standard conditions.



1. State TWO standard conditions under which this cell operates. (2)
2. Write down the half-reaction that takes place in half-cell A. (2)
3. Write down the cell notation for this cell. (2)
4. Calculate the emf of this cell. (3)
5. How will each of the following changes influence the value of the cell's emf calculated in QUESTION 2.4? Write down only INCREASES, DECREASES or REMAINS THE SAME
   - **5.1** An increase in $[Mg^{2+}(aq)]$ (1)
   - **5.2** An increase in $[Pb^{2+}(aq)]$ (1)
6. In which direction, from half-cell A to B or from half-cell B to A, do cations move within the salt bridge to maintain electrical neutrality? Explain how you arrived at your answer. (3)

[14]

Solutions

1. Temperature: 298 K (25 °C) ✓✓ (2)
2. $Mg(s) \rightarrow Mg^{2+}(aq) + 2e^-$ ✓✓ (2)
3. $Mg(s)/Mg^{2+}(1\ mol{\cdot}dm^{-3})$ ✓// $Pb^{2+}(aq)(1\ mol{\cdot}dm^{-3})/Pb(s)$ ✓ (2)
4. $E^0_{cell} = E^0_{cathode} - E^0_{anode}$ ✓
   $= -0{,}13 - (-2{,}36)$ ✓
   $= 2{,}23$ V ✓ (3)
5.
   5.1 DECREASES ✓ (1)
   5.2 INCREASES ✓ (1)
6. Half-cell A to half-cell B ✓
   Concentration of positive ions/cations ✓/ Pb^{2+} ions decreases in half-cell B. ✓
   OR
   Concentration of positive ions/cations/Mg^{2+} ions increases in half-cell A
   To prevent a build-up of positive ions in half-cell A and negative ions in half-cell B /for electrical neutrality.
   Positive ions migrate from/through the salt bridge (3)

[14]

Activity 10

Learners conduct an investigation to determine which combination of two half-cells will provide the largest emf under standard conditions.

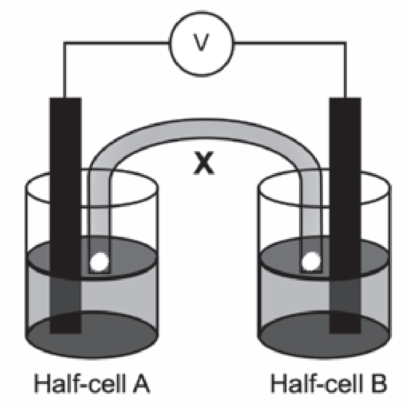
Three half-cells, represented as **A**, **B** and **C** in the table below, are available.

Half-cell A	Half-cell B	Half-cell C
Mg/Mg^{2+}	Pb/Pb^{2+}	$A\ell/A\ell^{3+}$

The learners set up galvanic cells using different combinations of the above half-cells.

1. Write down the standard conditions under which these cells operate. (2)
2. Write down the dependent variable in this investigation. If you can't remember what the dependent (and independent) variables are, please see the introductory materials at the beginning of this book. (1)
3. Use the Table of Standard Reduction Potentials to determine which one of the three half-cells (**A**, **B** or **C**) contains the:
   3.1 Strongest reducing agent. (1)
   3.2 strogest oxidizing agent. (1)

4. Without any calculation, write down the combination of two half-cells which will produce the highest emf. Write down only **AB**, **BC** or **AC**. (1)
5. One group of learners set up a galvanic cell using half-cells A and **B**, as shown below. X is one of the components of the galvanic cell.



   5.1 Write down the NAME or SYMBOL of the substance that will act as the anode in this cell. Give a reason for the answer. (2)
   5.2 Calculate the initial emf of this cell. (3)
   5.3 How will an increase in the concentration of the electrolyte in half-cell **B** affect the initial emf of this cell? Write down only INCREASES, DECREASES or REMAINS THE SAME. (1)
   5.4 Briefly explain how component X ensures electrical neutrality while the cell is functioning. (1)

[13]

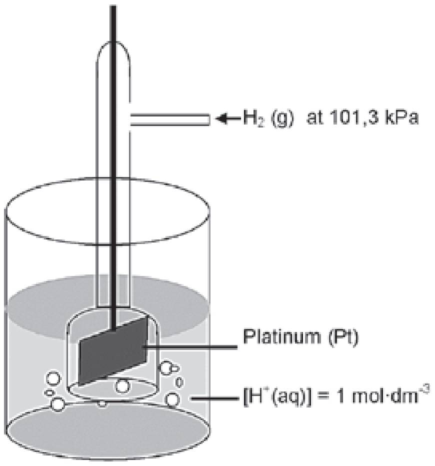
Solutions

1. Temperature 25 °C /298 K ✓
   Concentration of electrolytes = 1 mol·dm^{-3} ✓ (2)
2. emf/potential difference ✓ (1)
   3.1 Half-cell A ✓ (1)
   3.2 Half-cell B ✓ (1)
4. Combination AB ✓ (1)
   5.1 Magnesium/Mg. ✓Is oxidised/loses electrons/increase in oxidation number/stronger reducing agent ✓ (2)
   5.2 $E^0_{cell} = E^0_{cathode} - E^0_{anode}$ ✓
   $= -0,13 - (-2,36)$ ✓
   $= 2,23$ V ✓ (3)
   5.3 Increases ✓ (1)
   5.4 Allows for the migration of positive ions to the cathode half-cell ✓ (1)
   OR
   Allows for the migration of negative ions to the anode half-cell

[13]

5.9 The standard hydrogen electrode

The hydrogen gas/hydronium ion electrode has been chosen as **standard half-cell.**



A glass tube through which hydrogen gas is bubbled over a platinum electrode. Hydrogen becomes absorbed on the surface of the platinum to enable it to react with its solution. The whole electrode is immersed in an acid solution (**H^+ ions**).

Activity 11

1. Which is the the reference electrode in the diagram above? (1)
2. TRUE or FALSE? A standard cell that has a negative emf cannot be used as a galvanic cell. (2)
3. TRUE or FALSE? The standard conditions used to measure standard electrode potentials are: A temperature of 273 K, a concentration of 1 $mol{\cdot}dm^{-3}$, and a pressure of 101,3 kPa. (2)
4. Which ONE of the following containers can be used to store an iron(II) sulphate solution?

   A Aℓ
   B Mg
   C Ni
   D Zn (2)

[7]

Solutions

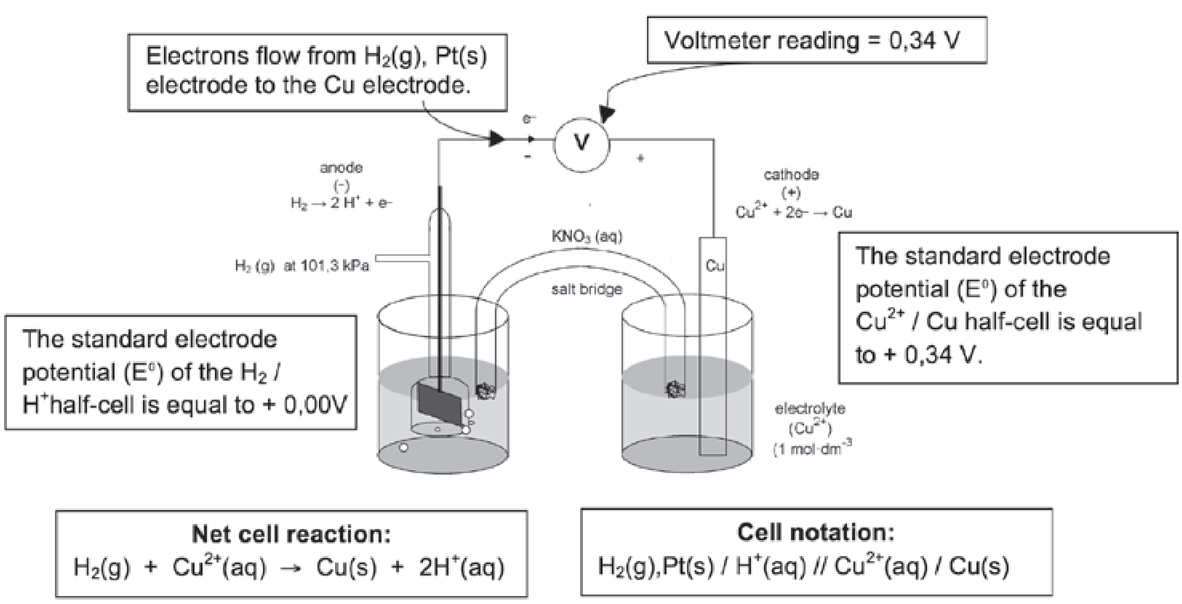
1. Hydrogen half-cell ✓ (1)
2. TRUE ✓✓ (2)
3. FALSE. ✓ A temperature of 298 K (25 °C) – the question gives the temperature incorrectly ✓ (2)
4. C ✓✓ (2)

[7]

NB

A half-cell potential of **0,00 V** has been assigned to the standard hydrogen electrode. The half-cell potential values are given on the right hand side of the table.

a) To determine the standard electrode potential of the copper half-cell



Electrons flow from H_2(g), Pt(s) electrode to the Cu electrode.

Voltmeter reading = 0,34 V

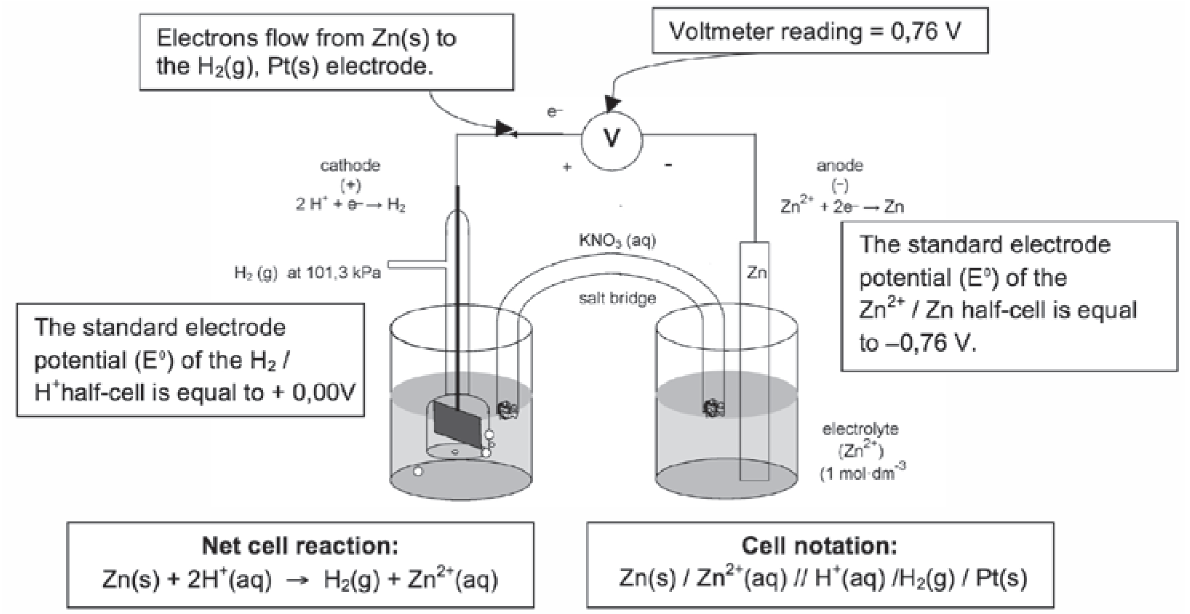
The standard electrode potential (E^θ) of the H_2 / H^+half-cell is equal to + 0,00V

The standard electrode potential (E^θ) of the Cu^{2+} / Cu half-cell is equal to + 0,34 V.

Net cell reaction:
$H_2(g) + Cu^{2+}(aq) \rightarrow Cu(s) + 2H^+(aq)$

Cell notation:
H_2(g),Pt(s) / H^+(aq) // Cu^{2+}(aq) / Cu(s)

b) To determine the standard electrode potential of the zinc half-cell



Electrons flow from Zn(s) to the H_2(g), Pt(s) electrode.

Voltmeter reading = 0,76 V

The standard electrode potential (E^θ) of the H_2 / H^+half-cell is equal to + 0,00V

The standard electrode potential (E^θ) of the Zn^{2+} / Zn half-cell is equal to –0,76 V.

Net cell reaction:
$Zn(s) + 2H^+(aq) \rightarrow H_2(g) + Zn^{2+}(aq)$

Cell notation:
Zn(s) / Zn^{2+}(aq) // H^+(aq) /H_2(g) / Pt(s)

5.10 The emf of an electrochemical cell

- A **voltmeter** connected to the zinc / copper cell has a reading of 1,1 V. It reads the **difference** between the electric potentials of the two separate electrodes.
- This reading of 1,1 V can also be referred to as the **potential difference** or **cell potential** or **emf** of the cell.

NB

Always use the values exactly as they stand on the table; do not round off.

Worked example 8

Using the Cu / Zn cell as an example:

$E^0_{cell} = E^0_{cathode} - E^0_{anode}$

$= +0{,}34 - (-0{,}76) = +0{,}34 + 0{,}76$

$= +1{,}1$ V

- The cell potential (voltage) does not depend on the surface area of the electrode.
- The **bigger the surface area** of the electrode, the **bigger the current** produced by the cell.
- In general the cell potential increases slightly with an increase in temperature.
- The reaction in the cell reaches **equilibrium** when the cell is completely discharged (flat or dead). This usually means that the concentration of the cations in the reduction half-cell (i.e. at the cathode) has **decreased** to zero.

Using the Table of Standard Reduction Potentials to predict whether a redox reaction will be spontaneous or not:

- Assume that the reaction will take place as suggested in the question.
- Identify the reducing agent and the oxidising agent according to the given equation.
- Calculate the cell potential for this reaction.
- If the cell potential is **positive**, the reaction will be **spontaneous** i.e. it will take place without the addition of any other form of energy. If it is **negative**, the reaction will **not** occur spontaneously.
- If the two half reactions are very close to each other on the Table of Standard Reduction Potentials, heating the reaction mixture may supply enough additional energy for the reaction to take place.

Steps

Step 1. Use the Reduction Potentials to determine whether a reaction will take place spontaneously.

Step 2. If the calculated cell potential is a positive value the redox reaction will take place spontaneously.

NB

$H_2S \longrightarrow S + 2H^+ + 2e^-$

OR

$S + 2H^+ + 2e^- \longleftarrow H_2S$

is the **only** correct way of writing a half-reaction

- Note the direction of the single arrow changes, depending on whether the reaction is an oxidation or reduction half reaction.
- Please do NOT include the double arrow in the half reaction.
- Always remember to include the charges on the ions in the half-cell reactions.

NB

When you have to explain the relative strength of oxidizing and reducing agents, write the explanations as follows:

- Cu is a stronger oxidising agent than Mg. Do NOT state the position of a substance in terms of its position in the Reduction Table (e.g. Cu is above Mg)
- Do NOT state the relative strength in terms of relative reactivity only, for example, Mg is more reactive than Cu.

  Your correct answer would read as follows:

  Mg is a stronger reducing agent than Cu and therefore Mg will be able to reduce Cu^{2+} ions to Cu.

  OR

  Explain the relative strength of the oxidizing and reducing agents in terms of their relative strength as electron acceptor and donors.

  Mg is a stronger reducing agent than Cu because Cu has a stronger tendency to accept electrons than Mg. OR: Mg has a stronger tendency to donate electrons to Cu than Cu has to donate electrons to Mg.

e.g. Worked example 9

Batteries consist of one or more galvanic cells. A galvanic cell is a combination of two half-cells. John wants to determine which one of Options A or B, shown below, can be used to assemble a galvanic cell with the highest potential difference.

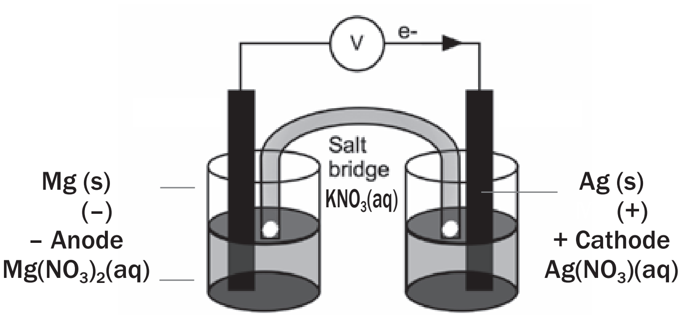
Option	Combination of half-cells
A	Ag(s) in $AgNO_3$(aq) & Ni(s) in $Ni(NO_3)_2$(aq)
B	Mg(s) in $Mg(NO_3)_2$(aq) & Ag(s) in $AgNO_3$(aq)

1. Draw a fully labelled diagram of the galvanic cell that John can use to measure the potential difference for the cell in Option B. Use a positive (+) and negative (–) sign to indicate the positive and negative electrodes respectively.

2. Write down the oxidation and reduction half reactions as well as a balanced chemical equation, excluding spectator ions, for the net (overall) cell reaction for the galvanic cell in Option B.
3. Calculate the initial potential difference that can be obtained under standard conditions for the galvanic cell in Option B.
4. State TWO standard conditions that John must adhere to during the experiment, to ensure that the measured potential difference is the same as the calculated potential difference.
5. Write down the cell notation for the galvanic cell in Option A.
6. Without doing any calculations, determine which one of Option A or Option B should result in the galvanic cell with the highest potential difference. Refer to the relative strengths of the two reducing agents, as well as the two oxidising agents involved, to explain your answer.
7. How will each of the following changes influence the value of the cell's emf calculated in Question 3?
   - **7.1** An increase in [$Mg^{2+}(aq)$].
   - **7.2** An increase in [$Ag^{+}(aq)$].
8. In which direction, from half-cell Mg^{2+} / Mg to Ag^{+} / Ag, or from half-cell Ag^{+} / Ag to Mg^{2+} / Mg, do cations move within the salt bridge to maintain electrical neutrality? Explain how you arrived at your answer.
9. Give two functions of the salt bridge.
10. Name the cathode and the anode for the galvanic cell in option B.
11. Which electrode will show an increase in mass for the galvanic cell in option B?
12. Distilled water is added to the Ag^{+} solution for the galvanic cell in Option B. How will the emf of the cell be influenced? Explain your answer.
13. Consider the galvanic cell in Option B. If 0,6 moles of electrons flow from the anode to the cathode, what will the decrease in mass of the anode be?
14. A 2 V bulb is connected to the cell in option B instead of the voltmeter. Will the bulb light up? Justify your answer.
15. Consider the galvanic cell in Option B. It is observed that after a while, the reading on the voltmeter drops to zero. We say the cell is 'flat' or 'dead'. Explain this observation in terms of the concentrations of the solutions in the cell.
16. Give two uses of galvanic cells.

Solutions

1.



2. oxidation: $Mg(s) \rightarrow Mg^{2+}(aq) + 2e^-$

   reduction: $Ag^+(aq) + e^- \rightarrow Ag(s)$

   net reaction: $Mg(s) + 2Ag^+(aq) \rightarrow Mg^{2+}(aq) + 2\,Ag(s)$

3. $E^0_{cell} = E^0_{cathode} - E^0_{anode} = 0{,}80 - (-2{,}36) = 3{,}16$ V

4. Ensure a temperature of 25 °C and Mg^{2+}, Ni^{2+} and Ag^+ solutions of concentration 1 mol·dm^3.

5. $Ni(s) / Ni^{2+}(aq)$ (1 mol·dm^{-3}) // $Ag(s)^+(aq)$ (1 mol·dm^{-3}) /$Ag(s)$

6. Option B. The reaction leading to the highest emf (or potential difference) will be between the strongest reducing agent (Mg) and the strongest oxidising agent (Ag^+).

7. An increase in the rate of the forward reaction will increase the emf of a galvanic cell.
7.1 decreases; the reverse reaction is favoured
7.2 increases; the forward reaction is favoured

8. Half-cell Mg^{2+} / Mg to Ag^+ / Ag
Concentration of positive ions or cations; [Ag^+] ions decreases in half-cell Ag^+ / Ag. OR
Concentration of positive ions or cations; [Mg^{2+}] ions increases in half-cell Mg^{2+} / Mg.
To prevent a build-up of positive ions in half-cell Mg^{2+} / Mg and negative ions in half-cell Ag^+ / Ag.
For electrical neutrality, positive ions migrate from/through the salt bridge to the cathode.

9. Any two: It completes the circuit. It ensures electrical neutrality by allowing the migration of ions through the salt bridge. It separates the electrolytes.

10. cathode = Ag anode = Mg

11. cathode = Ag

12. By adding water to the solution, the [Ag^+] will decrease. Thus the reverse reaction is favoured and emf decreases.

13. $Mg(s) \rightarrow Mg^{2+}(aq) + 2e^-$ (anode)
From the balanced equation 1 mol Mg → 2 mol e^-
thus 0,3 mol Mg → 0,6 mol e^-
$n = \frac{m}{M}$
$m = n \times M$ molar mass (M) of Mg = 24 g·mol^{-1}
$m = 0{,}3 \times 24 = 7{,}2$ g
mass loss is 7,2 g

14. The bulb will light up, as the emf of the cell is 3,16 V which is more than the required 2 V.

15. While the cell is in operation, the concentration of the cations in the reduction half-cell $Ag^+(aq)$ decreases. At the same time, the concentration of the cations in the oxidation half-cell $Mg^{2+}(aq)$ increases. The result is a gradual decrease in the cell potential until there is no further change in the concentration and equilibrium is reached, and the cell potential will be zero.

16. Any two: Torch cells, car batteries, batteries in toys and small appliances like remote controls.

Worked example 10

Rusting is an unwanted redox reaction. Iron rusts when exposed to oxygen and moisture. The unbalanced ionic equation for one reaction that occurs during rusting is represented below.

$$Fe(s) + O_2(g) + H_2O(\ell) \rightarrow Fe^{2+}(aq) + OH^-(aq)$$

Use the Table of Standard Reduction Potentials to answer the following questions for this reaction:

1. Write down the oxidation and the reduction half-reactions.

2. Write down the NAME of the substance that is reduced.

3. Perform a calculation to verify that this reaction is spontaneous.

Solutions

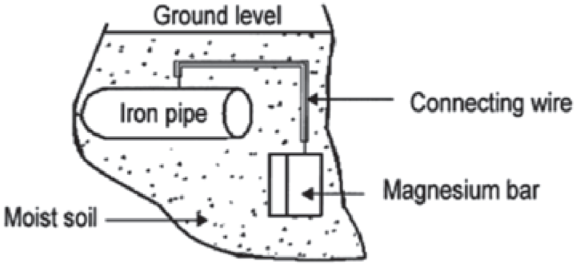
1. oxidation: $Fe \rightarrow Fe^{2+} + 2e^-$
reduction: $2H_2O + O_2 + 4e^- \rightarrow 4OH^-$

2. oxygen

3. oxidation: $Fe \rightarrow Fe^{2+} + 2e^-$ $E^0_{anode} = -0{,}44\ V$
reduction: $2H_2O + O_2 + 4e^- \rightarrow 4OH^-$ $E^0_{cathode} = 0{,}40\ V$
$E^0_{cell} = E^0_{cathode} - E^0_{anode} = 0{,}4 - (-0{,}44) = 0{,}84\ V$
Because E^0_{cell} is positive, the reaction is spontaneous.

Worked example 11

Magnesium is used to protect underground iron pipes against rusting (cathodic protection). The diagram here shows an iron pipe connected to a magnesium bar.



1. Use the Table of Standard Reduction Potentials to explain why magnesium can be used to protect an iron pipe against rusting.
2. The iron pipe in contact with the magnesium bar forms an electrochemical cell. What serves as the salt bridge of this cell?
3. Give a reason why the magnesium bar must be replaced after some time.
4. Write down a half-reaction to support your answer to Question 3.3.
5. Name TWO other methods that can be used to protect iron pipes against rust.
6. State ONE advantage and ONE disadvantage of using plastic pipes instead of iron pipes.

Solutions

1. Mg is a **stronger reducing agent** (than Fe) and will be **oxidised more readily** than Fe which is a **weaker reducing agent.**
2. The **salts** which are **dissolved in the moist soil.**
3. Mg is continuously oxidised to Mg^{2+} and therefore its mass decreases i.e. it is used up.
4. $Mg \rightarrow Mg^{2+} + 2e^-$
5. Any two: Paint; electroplating e.g. galvanising; oil or waterproofing; plastic coating.
6. Advantages: Plastic is cheaper; plastic does not rust.
   Disadvantages: Plastic not biodegradable; plastic is not as strong as iron.

Activity 12

Give ONE word for the following phrase:

1. The process taking place in a cell when an electric current passing through its electrolyte, results in chemical reactions at its electrodes. (1)
2. TRUE or FALSE? A battery labelled as 3 000 mA·h can deliver a current of 500 mA for 6 hours. (2)

[3]

Solutions

1. Electrolysis ✓ (1)
2. True. ✓✓ (2)

[3]

Activity 13

1. The most common filling for tooth cavities is 'dental amalgam' – a solid solution of tin and silver in mercury. If you bite on a piece of aluminium foil that is in contact with a dental filling in your mouth, you may feel a painful sensation because
   A the aluminium foil is hard.
   B a temporary galvanic cell has been set up whilst the aluminium and filling are in contact.
   C electrons are being transferred to the aluminium.
   D a temporary electrolytic cell has been set up whilst the aluminium and filling are in contact. (2)

2. Which one of the following can be classified as a redox reaction?

A $NH_3(g) + HNO_3(g) \rightarrow NH_4NO_3(s)$

B $FeS(aq) + 2HC\ell(aq) \rightarrow FeC\ell_2(aq) + H_2S(g)$

C $A\ell(s) + C\ell_2(g) \rightarrow A\ell C\ell_3(s)$

D $Mg(NO_3)_2(s) \rightarrow Mg^{2+}(aq) + 2NO^{3-}(aq)$ [with H_2O catalyst] (2)

3. A silver (Ag) spoon is left in a beaker containing copper nitrate, $Cu(NO_3)_2$, solution. What will be observed after some time?

A The spoon will be covered with a thin layer of copper.

B The nitrate will form NO_2 gas and copper will form in the beaker.

C The spoon will start to erode and its mass will decrease.

D There will be no reaction. (2)

[6]

Solutions

1. B. ✓✓ (2)
2. C. ✓✓ (2)
3. D. ✓✓ (2)
[6]

Activity 14

1. A group of learners set up an electrochemical cell using lead and copper half cells.

1.1 Which ONE of copper or lead will be the negative electrode? Give a reason for your answer. (2)

1.2 Use the Table of Standard Reduction Potentials and write down the reduction half-reaction that will take place in this cell. (2)

1.3 A 2V bulb is connected to the cell. Will the bulb light up? Justify your answer with a calculation. (5)

1.4 A voltmeter is now connected to the cell instead of the bulb. It is observed that after a while the reading on the voltmeter drops to zero. We say the cell is ‘flat’ or ‘dead’. Explain this observation in terms of the concentrations of the solutions in the cell. (3)

2. A cell such as the one described above is not much useful. However, the principle is used in batteries for cars, torches, computers, et cetera. These batteries are called secondary cells. One such battery is the mercury cell. The half reactions occurring in this cell are shown below.

$Zn(s) + 2OH^-(aq) \rightarrow ZnO(s) + H_2O + 2e^-$......... (i)
$HgO(s) + H_2O + 2e^- \rightarrow Hg(\ell) + 2OH^-(aq)$......... (ii)

2.1 Write down the overall cell reaction. (3)

2.2 Why does the use of this battery pose an environmental hazard? (1)

[16]

Solutions

1.1 Lead. ✓ Stronger reducing agent ✓ OR Is oxidised preferably (2)

1.2 $Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$ ✓✓ (2)

1.3 $E^0_{cell} = E^0_{cathode} - E^0_{anode}$ ✓

$= 0,34 - (-0,13)$ ✓

$= 0,47$ V ✓ (5)

Bulb will not light, ✓ energy from cell not sufficient ✓

OR

emf of cell is much less than 2 V needed for the bulb ✓✓

1.4. While the cell is in operation, the concentration of the reactants ($Cu^{2+}(aq)$) decreases. ✓ At the same time the concentration of the products ($Pb^{2+}(aq)$) increases. ✓ The result is a gradual decrease in the cell potential until there is no further change in concentration and equilibrium is reached where the cell potential will be zero. ✓ (3)

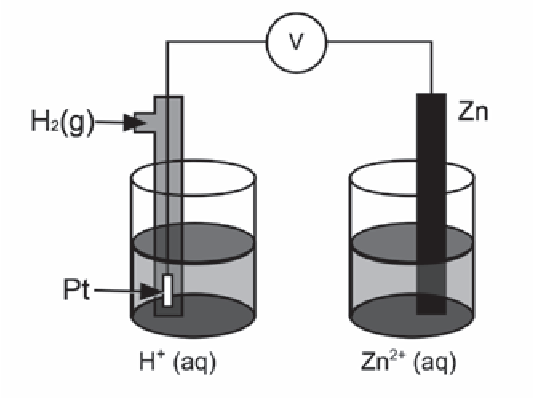
2.1 $Zn(s) + HgO(s) \rightarrow ZnO(s) + Hg(\ell)$ ✓✓✓ (3)

2.2 Mercury is poisonous ✓ (1)

[16]

Activity 15

The discovery of electrochemical cells has revolutionised our way of life. The diagram below represents an electrochemical cell.



1. Name the type of electrochemical cell that converts chemical energy to electrical energy. (1)
2. If the electrochemical cell is set up as illustrated, there will be no reading on the voltmeter. Give a reason for this observation. (1)
3. Write down the value of the standard emf of the electrochemical cell when it is functioning. (1)
4. Write down the voltmeter reading when the net cell reaction in the above electrochemical cell reaches equilibrium. (1)

5. Write down the equation for the reaction that occurs at the anode. (1)
6. Another electrochemical cell is set up under standard conditions by replacing the standard hydrogen half-cell with a standard magnesium half-cell.
    - 6.1 Which electrode will undergo a decrease in mass? Give a reason for your answer. (2)
    - 6.2 Calculate the initial emf of this electrochemical cell under standard conditions. (3)
    - 6.3 After a while the emf of this electrochemical cell decreases. Explain this observation by referring to the concentration of the electrolytes. (2)
7. Electrochemical cells such as motor car batteries with plastic casings can harm the environment if not disposed of safely. Suggest TWO ways how motor car batteries can be safely disposed of. (2)

[14]

Solutions

1. Galvanic/voltaic cell ✓ (1)
2. Incomplete circuit/No salt bridge ✓ (1)
3. 0,76 V ✓ (1)
4. Zero ✓ (1)
5. $Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$ ✓ (1)
6.1 Mg. ✓ Mg is oxidised ✓ (2)
6.2 $E^0_{cell} = E^0_{cathode} - E^0_{anode}$ ✓ = 0,76 – (–2,36) ✓ = 1,6 V ✓ (3)
6.3 As the cell functions, the concentration of zinc ions (reactants) decreases ✓ relative to the standard conditions and the concentration of magnesium ions (products) increases relative to standard conditions. The reverse reaction starts opposing the forward reaction causing the emf to decrease relative to standard conditions. ✓ (2)
7. Neutralise acid before disposal. ✓
Recycle plastic casing and lead electrodes ✓ (2)

[14]

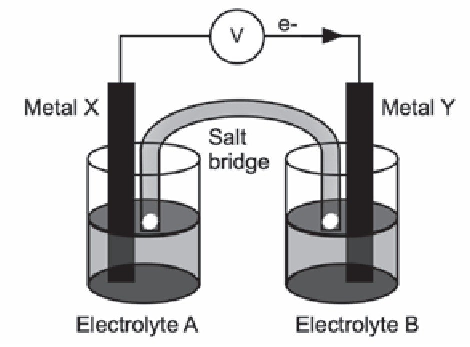
Activity 16

In 1780, Luigi Galvani discovered that when copper and zinc metal were connected to each other and if each free end touched different parts of the same nerve of a frog leg at the same time, the frog's leg contracted. He called this "animal electricity".

1. Briefly explain what this "animal electricity" really was. (1)

The diagram shows an electrochemical cell setup under standard conditions using aluminium ($A\ell$) and nickel (Ni) electrodes. $A\ell C\ell_3$(aq) and $NiC\ell_2$(aq) are used as the electrolytes, and a solution of sodium nitrate ($NaNO_3$(aq)) is used in the salt bridge.

Answer each of the following questions on this electrochemical cell:



2. The diagram indicates that electrons flow from metal X to metal Y. Identify:

2.1 Metal X (1)

2.2 Electrolyte B (1)

3. What is the concentration of electrolyte B? (1)

4. Write down the FORMULA of the substance that moves towards metal Y in the salt bridge. (1)

5. Write down the half-reaction that occurs at the cathode of this cell. (2)

6. Calculate the reading on the voltmeter. (3)

7. State what happens to the concentration of metal ions in the solution containing electrolyte as time goes by? (1)

8.

8.1 Consider 5.7 again and recall your answer. What effect does this have on the voltmeter reading? (1)

8.2 Briefly explain your answer to 5.8.1. (2)

[14]

Solutions

1. The chemical reaction between the zinc and the copper r eleased electrical energy ✓ (1)

2.1 Metal X: $A\ell$ ✓ (1)

2.2 Electrolyte B: $NiC\ell_2$ ✓ (1)

3. 1mol·dm^{-3} ✓ (1)

4. NO_3^- ✓ (1)

5. $Ni^{2+} + 2e^- \rightarrow Ni$ ✓ ✓ (2)

6. $E^0_{cell} = E^0_{oxidising\ agent} - E^0_{reducing\ agent}$ ✓

$= -0{,}25V - (-1{,}66V)$ ✓

$= 1{,}41$ V ✓ (3)

7. Increase ✓ (1)

8.1 The voltmeter reading decreases ✓ (1)

8.2 As the $[A\ell^{3+}]$ increases, ✓ the reverse reaction in the $A\ell|A\ell^{3+}$ half-cell:

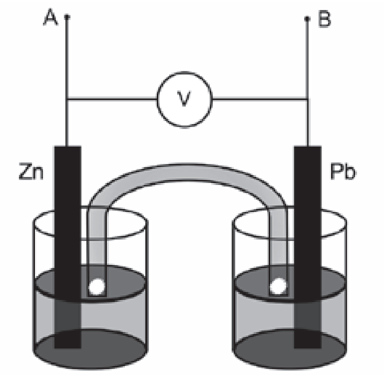
$A\ell \leftrightharpoons A\ell^{3+} + 3e^-$ is favoured.✓ (2)

OR

The tendency of the net reaction $A\ell + Ni^{2+} \rightarrow A\ell^{3+} + Ni$ to proceed from left to right is reduced. This lowers the electrode potential of this half-cell, resulting in a lower cell potential. **[14]**

Activity 17

Tina wants to investigate the effect of the area of the metal plates used as electrodes in a galvanic cell on the emf of the cell. She sets up the following Zn/Pb cell under standard conditions and measures the emf.



1. Which electrode will show an increase in mass when this cell is functioning? (1)
2. Write down the equation for the half-reaction occurring at the anode. (2)
3. Calculate the emf that you would expect Tina to read on the voltmeter. (3)
4. Name TWO variables that should be controlled for during this investigation. (2)
5. Tina now replaces the two metal plates with ones of larger surface area, and takes the readings again.
   - **5.1** How would you expect the new emf to compare with the one calculated in Question 6.3? (Only write SMALLER THAN, LARGER THAN or EQUAL TO) (1)
   - **5.2** Explain your answer to Question 5.1 (1)
6. Tina now connects a resistor of low resistance across terminals A and B. She notes that the reading on the voltmeter immediately drops.
   - **6.1** Give a reason for this observation. (1)
   - **6.2** After some time she observes a further drop in the reading on the voltmeter. Give a reason for this observation. (2)

[13]

Solutions

1. Pb ✓ (1)
2. $Zn \rightarrow Zn^{2+} + 2e^-$ ✓✓ (2)

3. $E^0_{cell} = E^0_{oxidising\ agent} - E^0_{reducing\ agent}$ ✓
   $= -0{,}13 - (-0{,}76)$ ✓
   $= 0{,}63$ V ✓ (3)

4. Temperature, ✓ (initial) concentration of electrolytes ✓ (2)

5.1 Equal to ✓ (1)

5.2 Area/size of electrodes has no effect on the emf of a cell. It is still a standard cell ✓ (1)

6.1 the cell has internal resistance ✓ (1)

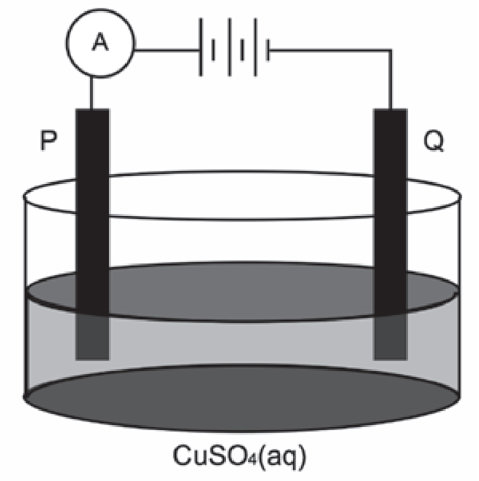
6.2 The emf decreases ✓ as the concentration of $Pb^{2+}(aq)$ decreases. ✓/The cell is running flat as the electrolyte concentration in the Pb cell decreases. ✓✓ (any 2) (2)

[13]

Activity 18

Electrolysis is an important industrial process used to decompose compounds, extract metals from their ores and to purify metals like gold or copper.

The simplified diagram below represents an electrolytic cell used to purify copper.



1. Define the term electrolysis. (2)
2. Which electrode, P or Q, consists of the impure copper? Explain how you arrived at your answer. (2)
3. Write down the half-reaction that takes place at electrode Q. (2)
4. During purification, metals such as silver and platinum form sludge at the bottom of the container. Refer to the relative strengths of reducing agents to explain why these two metals do not form ions during the purification process. (2)
5. Explain why the concentration of the copper(II) sulphate solution remains constant. Assume that the only impurities in the copper are silver and platinum. (2)
6. Why is the sludge of economic importance? (1)

[11]

Solutions

1. The process in which electricity is used to bring about a chemical change / decompose / break compounds into components ✓✓ (2)

   OR

   A process in which electrical energy is converted to chemical energy.
2. P. ✓

   P is the positive electrode /anode ✓ (2)

   OR

   Oxidation takes place at the positive electrode/anode
3. $Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$ ✓✓ (2)
4. Pt and Ag are both weaker reducing agents ✓ (than copper) and will not be oxidised ✓ (2)

   OR

   Cu is a stronger reducing agent (than Pt and Ag) and will be oxidised
5. The rate at which copper is oxidised at the anode, ✓ is equal to the rate at which copper ions are reduced at the cathode. ✓ (2)
6. Contains platinum and silver that are valuable/expensive metals ✓ (1)

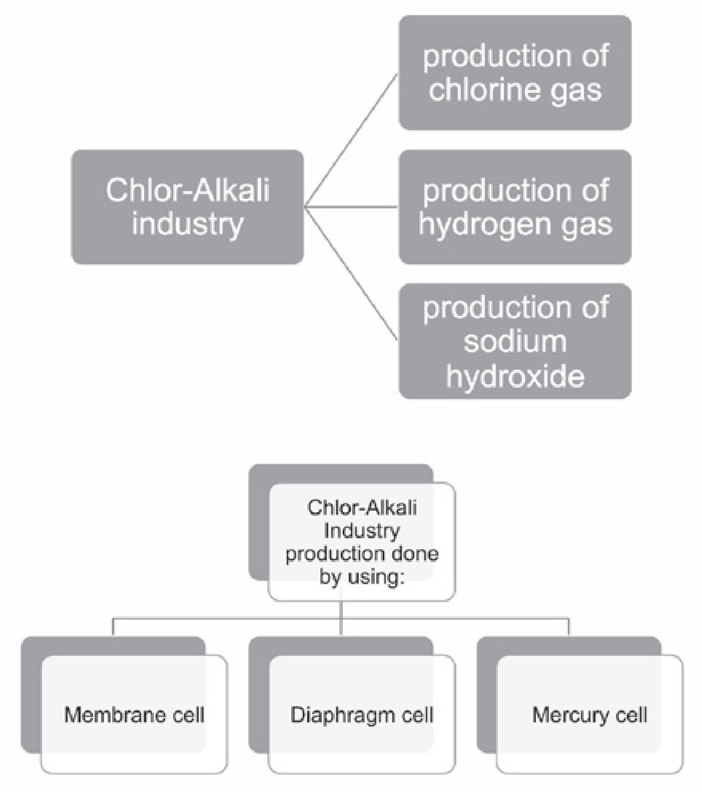
[11]

Unit 6

The chlor-alkali industry

The chlor-alkali industry is a large worldwide multimillion industry which produces compounds that are essential to human existence. The industry is based on the **electrolysis of sodium chloride** solutions.

6.1 Summary



Chlor-Alkali industry involves the **electrolysis** of a sodium chloride solution which produces:

- **chlorine** gas;
- **hydrogen** gas and
- **sodium hydroxide** (aq).

6.2 Definitions and terminology

The processes involved are electrolysis, oxidation and reduction.

Electrolysis:
- is an **endothermic reaction**
- involves a process during which electric energy is converted to chemical energy or brings about a chemical change
- involves a **non-spontaneous redox reaction.**

Oxidation:
- takes place when electrons are **given off**
- at the **anode.**

Reduction:
- takes place when electrons are **received**
- at the **cathode.**

Terminology:

Corrosive: Substance that damages and destroys substances (including living matter) it comes into contact with (touches).

Leaching: Movement of a substance (like NaOH (aq), pesticides or fertilisers) that are carried by water, down through soil (ground) to the underground water table. The water table is the level below which the ground is saturated with water.

Carbon footprint: The amount of carbon dioxide and other greenhouse gases released into the atmosphere due to the activities of a person, organisation or process.

Brine: A concentrated solution of $NaC\ell(aq)$

Standard warning sign for corrosive substances

6.3 The Chlor-alkali industry – reactants and products

<table>
<tr><th colspan="4">REACTANTS</th></tr>
<tr><td colspan="4">• Sodium chloride solution, $NaC\ell(aq)$
• Produced by evaporation from sea water, salt lakes</td></tr>
<tr><th colspan="4">PRODUCTS</th></tr>
<tr><th></th><th>Chlorine gas
$C\ell_2(g)$</th><th>Hydrogen gas
$H_2(g)$</th><th>Sodium hydroxide (caustic soda)
$NaOH(aq)$</th></tr>
<tr><th>PROPERTIES & PRECAUTIONS</th><td>• Yellow-green gas
• Poisonous: Do not inhale.</td><td>• Colourless gas
• Explosive: No open flames or electronic sparks nearby.</td><td>• Colourless solution
• Highly corrosive
• Prevent leaching into the ground
• Prevent skin and eye contact.</td></tr>
<tr><th>USES</th><td>Reactant for production of:
• hydrochloric acid, $HC\ell(aq)$;
• extraction of Cu, Au, Ti;
• paint;
• PVC plastics;
• insecticides and weed killers;
• bleaching agents.
Used to:
• disinfect water.</td><td>Reactant for production of:
• hydrochloric acid, $HC\ell(aq)$;
• ammonia, $NH_3(g)$,
• $H_2O_2(g)$ (hydrogen peroxide);
• nylon;
• rocket fuel;
• margarine from plant oils (hydrogenation of unsaturated hydrocarbons).</td><td>Reactant for production of:
• soap and bleaching agents;
• paper;
• textiles;
• oven cleaners.
Used to:
• treat waste water (sewage water).</td></tr>
</table>

NB

REMEMBER:

The **membrane cell** is preferred because the:

- components of the cell are non-toxic;
- products are more pure and
- production costs are relatively low.
- Sodium chloride (table sale) $NaC\ell(s)$ is an ionic compound and is very soluble in water (a polar solvent).
- $NaC\ell$ (s) dissociates in an aqueous solution – the ions in the ionic crystal lattice separate.
- $NaC\ell(s) \xrightarrow{H_2O(\ell)} Na^+(aq) + C\ell^-(aq)$
- A sodium chloride solution, $NaC\ell$ (aq), is known as **brine**.

6.4 The chlor-alkali industry – industrial process

The chlor-alkali industry products can be produced by using a:

- **membrane cell**
- **mercury cell**
- **diaphragm cell**

	Membrane Cell	Diaphragm Cell	Mercury Cell
Purity and yield of $C\ell_2$ (g) produced	• Produces relatively pure $C\ell_2$(g) that is mixed with very small amount of O_2(g).	• Produces $C\ell_2$(g) that is mixed with O_2(g) so the product is less pure.	• Low yield of $C\ell_2$(g) and of NaOH(aq).
Purity of NaOH (aq) produced	• High	• Medium • NaOH (aq) is mixed with NaCℓ (aq)	• Low
Energy consumption (Affects costs)	• Lowest	• Relatively low	• Very high
Environmental impact	• Lowest • Non-toxic, reusable components - low setup costs. • Lowest energy consumption therefore small carbon footprint.	• High • Diaphragm is made from asbestos.	• Highest • Mercury reacts with the NaCℓ (aq) and leaches into the groundwater.
Health risks	• No potential health risks / environmental risks due to components. • H_2(g) is explosive and $C\ell_2$(g) is poisonous.	• Diaphragm is made from asbestos – health risk for workers – asbestosis and cancer. • H_2(g) is explosive and $C\ell_2$(g) is poisonous.	• Mercury is toxic. • Risks due to contamination of groundwater. (Fish, animals and humans use the water. • H_2(g) is explosive and $C\ell_2$(g) is poisonous.

NB

- Very few companies still use mercury cells but many still use diaphragm cells. When new industrial sites are set up today, **membrane cells** are mostly used.

CHEMICAL CHANGE: ELECTROCHEMICAL REACTIONS: THE CHLOR-ALKALI INDUSTRY

THE MEMBRANE CELL

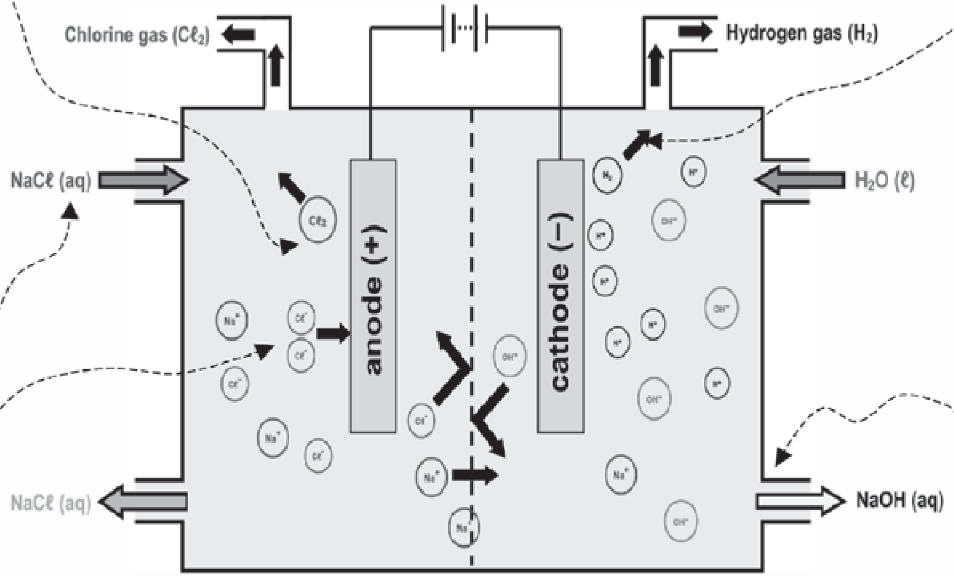
At the anode (+):

- $C\ell^-$(aq) anions are oxidised to **$C\ell_2$(g)**
- **$2C\ell^-(aq) \rightarrow C\ell_2(g) + 2e^-$** ($E^\circ$=-0,83 V)
- The $C\ell_2$(g) is removed from the compartment and stored.
- A **small amount** of oxygen gas, O_2(g) may be produced when the hydroxyl ions, OH^-(aq) from the H_2O solvent in the NaCℓ (aq) solution is oxidised – this decreases the purity of the chlorine gas. **$2H_2O(\ell) \rightarrow O_2(g) + 4H^+(aq) + 4e^-$**

In the anode compartment:

- Concentrated NaCℓ(aq) is pumped into the anode compartment
- The **Na^+ (aq) cations** move through the **cationic membrane** towards the **cathode**.
- The **$C\ell^-$ (aq) anions** move towards the **anode**
- The depleted (diluted) NaCℓ (aq) solution is pumped out of the anode compartment.
- After more NaCℓ(s) is added to it, the concentrated solution is again pumped into the compartment.

- Electrolytic cell – uses large amounts of electricity
- Electric energy → chemical energy
- Reactants: NaCℓ (aq), H_2O (ℓ)
- Products: $C\ell_2$ (g), H_2 (g), NaOH (aq)



At the cathode (−):

- The **Na^+(aq)** cations which have migrated through the cationic membrane from the anode compartment and
- the **H^+(aq) cations** (from H_2O) compete to be **reduced**
- **H^+** (from H_2O) is **reduced** to **H_2(g)** as H_2O is a **stronger oxidising agent** than Na^+ and is more readily reduced.
- **$2H_2O(\ell) + 2e^- \rightarrow H_2(g) + 2OH^-(aq)$** ($E^\circ$=-0,83 V)
- The H_2 (g) is removed from the compartment and stored.

In the cathode compartment:

- The cations **H^+(aq)** and **Na^+(aq)** move towards the cathode.
- The **Na^+(aq) cations** which have migrated through the cationic membrane
- from the anode compartment and
- the **OH^- (aq) anions** which cannot migrate through the cation exchange membrane to the anode
- form a **sodium hydroxide solution, NaOH(aq)**.

Cation exchange membrane (cationic membrane).

- Only allows cations (**+ ions**), therefore Na^+(aq) to pass through it and to migrate from the anode compartment to the cathode compartment.
- Prevents anions (− **ions∴ OH^- ions**) in the cathode compartment from migrating to the anode, as this would result in a mixed product of $C\ell_2$(g) and O_2(g) being formed.

Net (overall) cell reaction:

$2NaC\ell(aq) + 2H_2O(\ell) \rightarrow C\ell_2(g) + H_2(g) + 2NaOH(aq)$

Worked example 1

1. Chlorine is produced industrially by electrolysis in an electrolytic cell and can be represented as follows:

$$2NaC\ell(aq) + 2H_2O(\ell) \rightarrow H_2(g) + C\ell_2(g) + 2NaOH(aq)$$

I	$2H_2O$	+	$2e^-$	→	H_2	+	$2OH^-$
II	$C\ell_2$	+	$2e^-$	→	$2C\ell^-$		
III	$2C\ell^-$			→	$C\ell_2$	+	$2e^-$
IV	H_2	+	$2OH^-$	→	$2H_2O$	+	$2e^-$

The correct statement(s) is/are:
A I and III
B I only
C II and IV
D III only

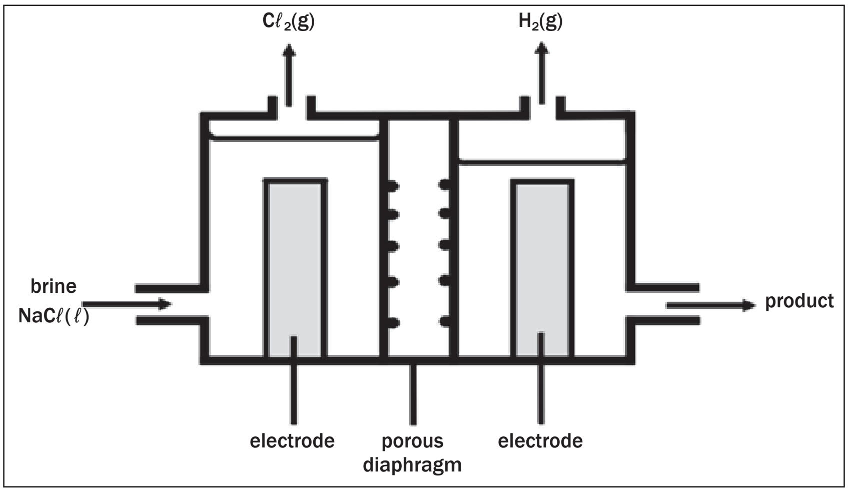
2. Chlorine is a poisonous gas commonly used as a bleaching agent. Chlorine is produced in industry by ______________.

Solutions

1. A
2. Electrolysis of brine

Activity 1

The electrolysis of saturated sodium chloride can be illustrated as follows: Hydrogen and chlorine bubble off at the electrodes.



1. Give an equation to show how chlorine bubbles are formed at the electrode. (2)
2. At which electrode are the chlorine bubbles formed? (1)
3. At which electrode does hydrogen gas form? (1)
4. What is the name of the product which leaves the cell? (1)
5. Give TWO applications of the product formed in 2.4. (2)
6. What purpose does the porous diaphragm serve? (2)
7. The chlorine gas produced, dissolves in water to form chlorine water. Write down a balanced equation for the reaction that takes place. (2)

[11]

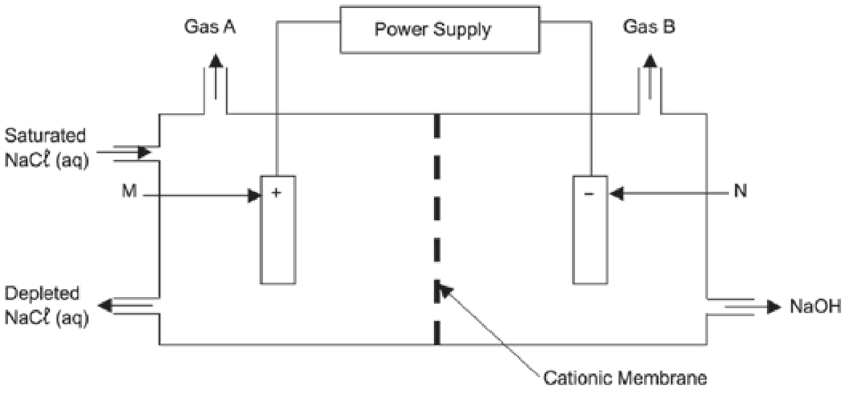
Solutions

1. $2C\ell^-(aq) \rightarrow C\ell_2(g)$ ✓ $+ 2e^-$ ✓ (2)
2. Anode ✓ (1)
3. Cathode ✓ (1)
4. Sodium hydroxide ✓ (1)
5. Making soap and detergents✓; paper✓; rayon and other fibres✓; dyeing textiles ✓ (any 2) (2)
6. Stops chlorine passing through; helps to separate sodium hydroxide from NaCℓ(aq). ✓ ✓ (2)
7. $C\ell_2 + H_2O \rightarrow HC\ell$ ✓ $+ HOC\ell$ ✓ (2)

[11]

Worked example 2

The diagram below shows a type of **membrane cell** used in the chlor-alkali industry.



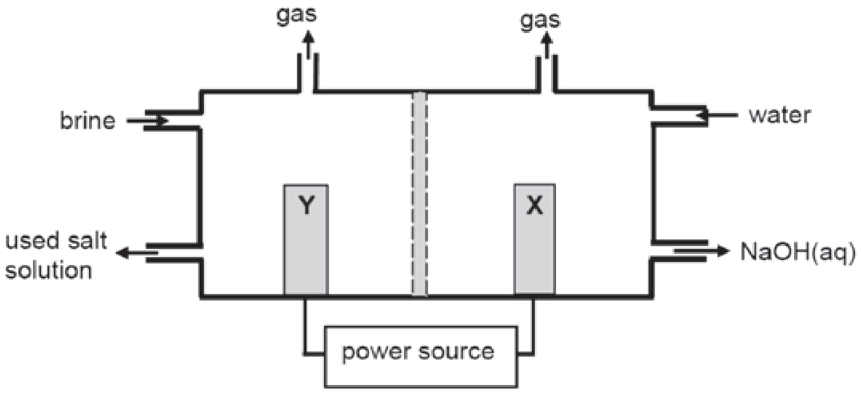
1. Name the gases A and B
2. Why is the membrane called a cationic membrane?
3. Write down the half-reaction that takes place at electrode N.
4. Apart from its use in household products, name ONE industrial use of chlorine.
5. Explain why this electrolytic process cannot be done in one large container without a membrane.

Solutions

1. A: Chlorine
   B: Hydrogen
2. Allows only the positive ions (cations) to pass through it.
3. $2H_2O + 2e^- \rightarrow H_2 + 2OH^-$
4. Manufacture of PVC, paper, drugs, etc
   Disinfectant for water
5. In a single pot the chlorine will react with water to form chlorine water/or the chlorine will react with the OH^- ions to form bleach OR the products formed will be contaminated

Activity 2

The simplified diagram of a cell used in the chlor-alkali industry is shown below.



1. Write down the CHEMICAL FORMULA of brine. (1)
2. At which electrode, **X or Y** is chlorine gas formed? (1)
3. Write down a half-reaction that explains the formation of hydrogen gas at one of the electrodes. (4)
4. The purity of the sodium hydroxide produced in the chlor-alkali industry depends on the extent to which it is separated from the chlorine gas produced by this cell. Briefly describe how chlorine gas and sodium hydroxide are prevented from mixing in this cell. (2)
5. Apart from the advantages and disadvantages of products produced, write down for this process:
   - **5.1** ONE positive impact on humans. (1)
   - **5.2** ONE negative impact on humans (1)

[10]

Solutions

1. $NaC\ell$ (aq) ✓ (1)
2. Y ✓ (1)
3. $2H_2O$ ✓ + $2e^-$ ✓ → H_2 ✓ + $2OH^-$ ✓ (4)
4. The membrane prevents chloride ions from moving to the cathode ✓, only allows positive ions through. ✓ (2)
5.1 Job creation resulting in more people having a better life. ✓ (1)
5.2 Uses huge amounts of electricity resulting in load shedding. ✓
OR
Chemical plant uses a lot of space that could have been used for housing/gardens, etc. ✓ (any one) (1)

[10]

7 Unit

The fertiliser industry

The need for fertilisers is increasing due to:

- the growth in the world population – more people means more food is necessary and
- the decrease in available agricultural land – less land means the available land must produce a lot of high quality food at a high rate (fast).

Nutrients in the soil are used by the plants that grow and these nutrients must be replaced.

Inorganic fertilisers are produced industrially in the Haber, Contact & Ostwald processes at chemical plants like SASOL.

7.1 Nutrients required by plants

	MACRO NUTRIENTS			MICRONUTRIENTS
	Primary non-mineral nutrients	Primary mineral nutrients	Secondary nutrients	Trace elements
Elements	• C carbon • H hydrogen • O oxygen	• N nitrogen • P phosphorus • K potassium	• Ca calcium • Mg magnesium • S sulphur	• Cu copper • Fe iron • Mn manganese • Zn zinc • I iodine
Sources	• From the air as $CO_2(g)$ and • in rainwater as $H_2O(\ell)$	• Absorbed from the soil • by the roots • as water-soluble salts.	• Absorbed from the soil • by the roots • as water-soluble salts.	• Absorbed from the soil • by the roots • as water-soluble salts.
Availability	• Sufficient available in the air	• Used up and must be replaced by using fertilisers	• Sufficient available in the soil	• Sufficient available in the soil

DID YOU KNOW?

- **Bone meal** is produced when the bones of dead animals are ground into powder.
- **Kelp meal** is dried seaweed.
- **Granite meal** is finely ground granite rock.

NB

DEFINITIONS

Promote: to help or encourage

Essential: absolutely necessary

Inorganic: not produced by a living organism; not containing carbon

Mineral: an inorganic solid substance that occurs naturally (not man-made)

Inert: unreactive

Sufficient: enough

Activity 1

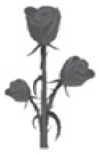
1. Which of the following is a primary mineral nutrient that is needed by plants?
   A) N B) C C) Mg D) Na (2)

[2]

Solution

1. A ✓✓ **[2]**

7.2 Functions and sources of the primary mineral nutrients

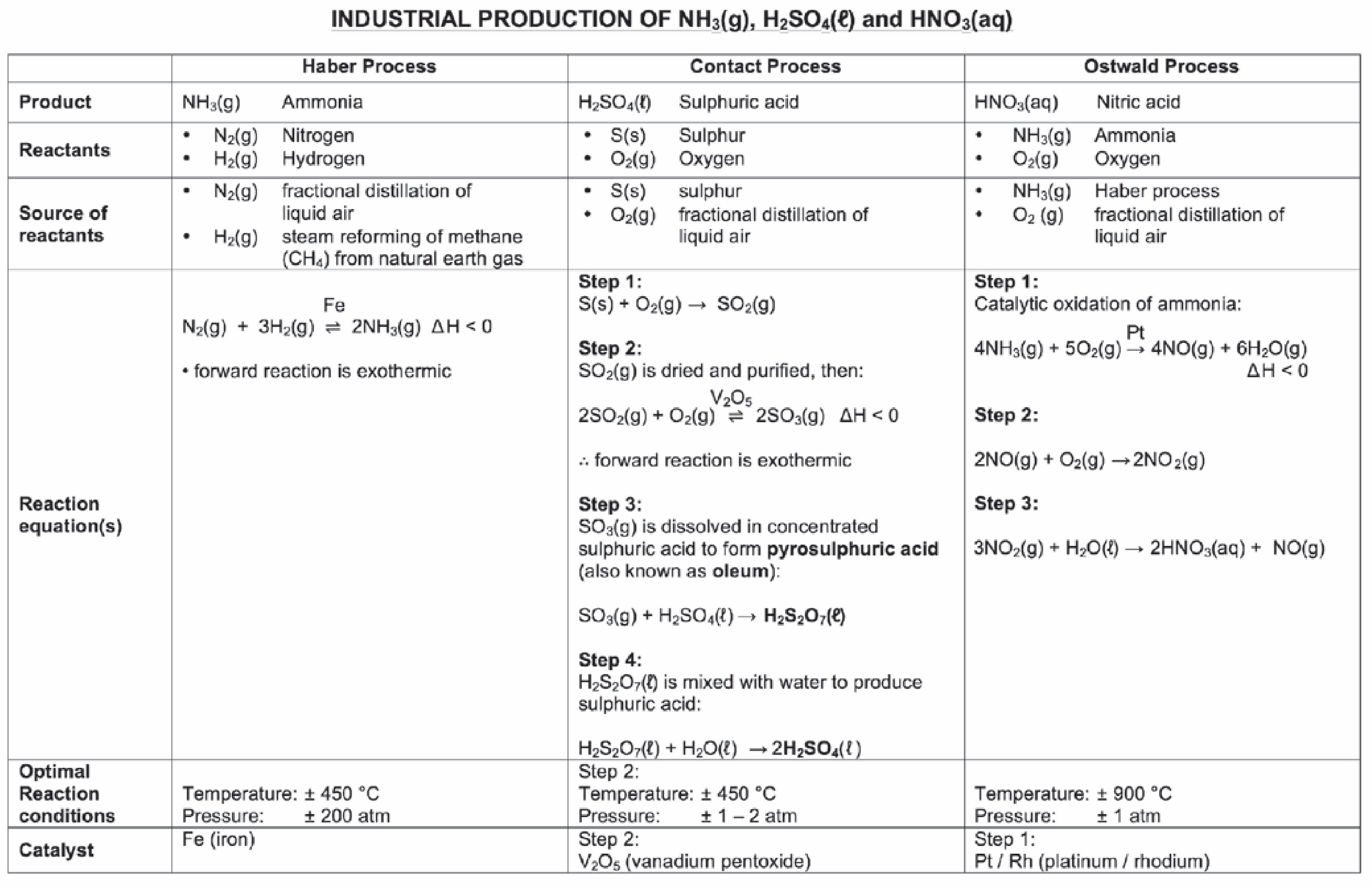
<table>
<tr><th colspan="5">PRIMARY MINERAL NUTRIENTS</th></tr>
<tr><th colspan="2">Nutrient</th><th>(N)</th><th>Phosphorous (P)</th><th>Potassium (K)</th></tr>
<tr><td colspan="2">Function</td><td>• Promotes growth of leaves;
• gives a healthy green colour to the plant;
• is part of chlorophyll which is needed for photosynthesis.
</td><td>• Promotes development of roots and stems;
• is essential for good growth;
• is necessary for photosynthesis;
• is active during production of oils, sugar and starch.
</td><td>• Ensures high quality and colourful flowers, fruit and vegetables;
• promotes resistance against diseases.
</td></tr>
<tr><td colspan="2">Sources Pre-World War II</td><td>• Guano (Sea bird excrement)
• Plant Compost</td><td>• Bone meal</td><td>• Wood ash
• Mined in Germany</td></tr>
<tr><td rowspan="2">Sources Post World War II</td><td>Organic</td><td>• Animal manure
• Fish emulsion
• Dried animal blood
• Guano (bat excrement)
• Compost</td><td>• Bone meal</td><td>• Kelp meal (ground seaweed)</td></tr>
<tr><td>Inorganic</td><td>• Nitrate (NO_3^-) salts and
• ammonium (NH_4^+) salts
• from ammonia (NH_3) produced in the Haber process
• E.g.
  • NH_4NO_3 ammonium nitrate
  • KNO_3 potassium nitrate
  • $(NH_4)_2SO_4$ ammonium sulphate</td><td>• Superphosphates
• $CaH_4(PO_4)_2 \cdot H_2O$
• Monoammonium phosphate (MAP) $NH_4H_2PO_4$
• Diammonium phosphate (DAP): $(NH_4)_2HPO_4$</td><td>• $KC\ell$, potassium chloride
• is imported to South Africa.
• Also:
  • KNO_3 potassium nitrate
  • K_2SO_4 potassium sulphate</td></tr>
</table>

hint

"Fixed" means "attached".

Atmospheric nitrogen is fixed into compounds containing nitrates (NO_3^-) or ammonium ions (NH_4^+) so that the nitrogen can be taken in by plants and used as nutrient.

- Atmospheric fixation: fixation by lightning;
- Biological fixation: fixation by bacteria in the ground and by the roots of legumes;
- Industrial fixation: fixation by industrial processes like the Haber process.



INDUSTRIAL PRODUCTION OF $NH_3(g)$, $H_2SO_4(\ell)$ and $HNO_3(aq)$

	Haber Process	Contact Process	Ostwald Process
Product	$NH_3(g)$ Ammonia	$H_2SO_4(\ell)$ Sulphuric acid	$HNO_3(aq)$ Nitric acid
Reactants	• $N_2(g)$ Nitrogen • $H_2(g)$ Hydrogen	• $S(s)$ Sulphur • $O_2(g)$ Oxygen	• $NH_3(g)$ Ammonia • $O_2(g)$ Oxygen
Source of reactants	• $N_2(g)$ fractional distillation of liquid air • $H_2(g)$ steam reforming of methane (CH_4) from natural earth gas	• $S(s)$ sulphur • $O_2(g)$ fractional distillation of liquid air	• $NH_3(g)$ Haber process • O_2 (g) fractional distillation of liquid air
Reaction equation(s)	$N_2(g) + 3H_2(g) \overset{Fe}{\rightleftharpoons} 2NH_3(g)$ $\Delta H < 0$ • forward reaction is exothermic	**Step 1:** $S(s) + O_2(g) \rightarrow SO_2(g)$ **Step 2:** $SO_2(g)$ is dried and purified, then: $2SO_2(g) + O_2(g) \overset{V_2O_5}{\rightleftharpoons} 2SO_3(g)$ $\Delta H < 0$ ∴ forward reaction is exothermic **Step 3:** $SO_3(g)$ is dissolved in concentrated sulphuric acid to form **pyrosulphuric acid** (also known as **oleum**): $SO_3(g) + H_2SO_4(\ell) \rightarrow \mathbf{H_2S_2O_7(\ell)}$ **Step 4:** $H_2S_2O_7(\ell)$ is mixed with water to produce sulphuric acid: $H_2S_2O_7(\ell) + H_2O(\ell) \rightarrow \mathbf{2H_2SO_4(\ell)}$	**Step 1:** Catalytic oxidation of ammonia: $4NH_3(g) + 5O_2(g) \xrightarrow{Pt} 4NO(g) + 6H_2O(g)$ $\Delta H < 0$ **Step 2:** $2NO(g) + O_2(g) \rightarrow 2NO_2(g)$ **Step 3:** $3NO_2(g) + H_2O(\ell) \rightarrow 2HNO_3(aq) + NO(g)$
Optimal Reaction conditions	Temperature: ± 450 °C Pressure: ± 200 atm	Step 2: Temperature: ± 450 °C Pressure: ± 1 – 2 atm	Temperature: ± 900 °C Pressure: ± 1 atm
Catalyst	Fe (iron)	Step 2: V_2O_5 (vanadium pentoxide)	Step 1: Pt / Rh (platinum / rhodium)

1. **In the Haber process:**

   Steam reforming of methane (natural gas) in the presence of a platinum catalyst to form a mixture of carbon monoxide (CO) and hydrogen (H_2) gases (synthesis gas).

$$CH_4(g) + \underbrace{H_2O(g) \xrightarrow{Pt} CO(g)}_{\text{synthesis gas}} + 3H_2(g)$$

2. **In the Contact process:**

   2.1 If $SO_2(g)$ is not dried before step 2, it reacts with water to form sulphurous acid, $H_2SO_3(aq)$ which forms acid rain, a type of rain which is produced as a side-effect of human industrial activities, which is corrosive to structures and harmful to living things.

$$SO_2(g) + H_2O(\ell) \rightarrow \mathbf{H_2SO_3(aq)}$$

   2.2 $SO_3(g)$ reacts with water to form gaseous sulphuric acid, $H_2SO_4(g)$ which escapes into the atmosphere and forms acid rain.

$$SO_3(g) + H_2O(\ell) \rightarrow \mathbf{H_2SO_4(g)}$$

3. **In the Contact process:**

   3.1 The 1st step is known as the **catalytic oxidation of ammonia**.

$$4NH_3(g) + 5O_2(\ell) \xrightarrow{Pt} 4NO(g) + 6H_2O(g)$$

   3.2 NO_2 (nitrogen dioxide) is a brown gas which reacts with water to form $HNO_3(g)$ which escapes into the atmosphere and forms acid rain.

Fluorapatite, $Ca_5(PO_4)_3F$

1. is mined at Phalaborwa;
2. is insoluble in water and can't be absorbed by plant roots;
3. reacts with sulphuric acid, $H_2SO_4(\ell)$ to produce phosphoric acid, $H_3PO_4(aq)$.

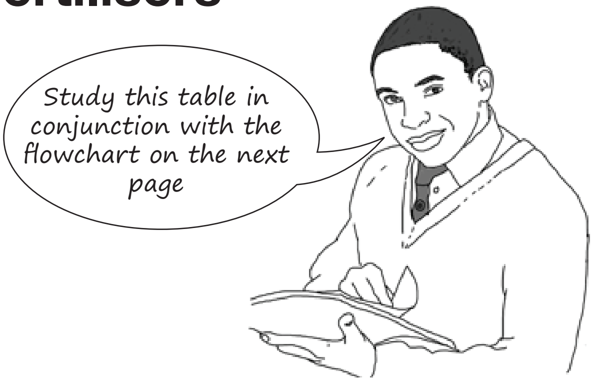
Superphosphate

1. is produced when fluorapatite reacts with sulphuric acid H_2SO_4 and is a mixture of **$Ca(H_2PO_4)_2{\cdot}H_2O$ and $CaSO_4$ (gypsum)**

Triple Superphosphate

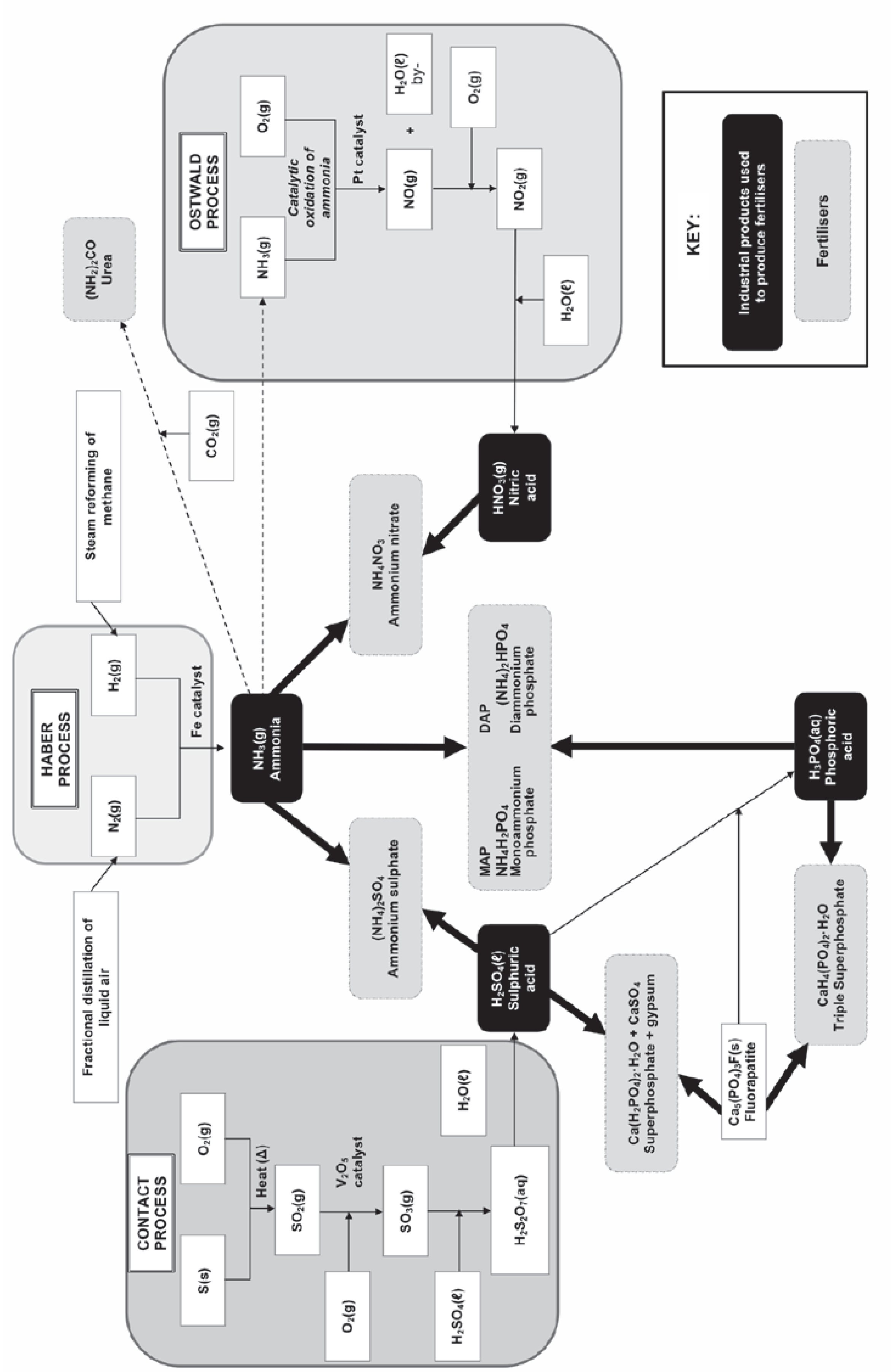
2. is produced when fluorapatite reacts with phosphoric acid H_3PO_4 to form **$Ca(H_2PO_4)_2{\cdot}H2O$ (no $CaSO_4$ is formed)**.

7.3 The industrial production of fertilisers



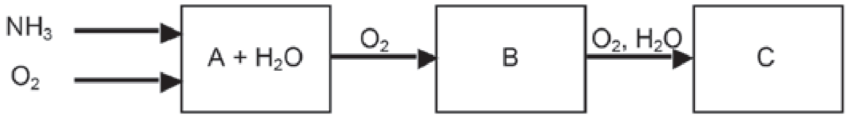
					ORGANIC
Fertiliser	**Ammonium sulphate** **$(NH_4)_2SO_4$**	**Ammonium nitrate** **NH_4NO_3**	**Monoammonium phosphate (MAP)** **$NH_4H_2PO_4$** **Diammonium phosphate (DAP)** **$(NH_4)_2HPO_4$**	**Superphosphate** **$Ca(H_2PO_4)_2 \cdot H_2O$ + $CaSO_4$** **Triple Superphosphate** **$Ca(H_2PO_4)_2 \cdot H_2O$**	**Urea** **$(NH_2)_2CO$**
Reactants	$NH_3(g)$ Ammonia (Haber process) $H_2SO_4(\ell)$ Sulphuric acid (Contact process)	$NH_3(g)$ Ammonia (Haber process) $HNO_3(aq)$ Nitric acid (Ostwald process)	$NH_3(g)$ Ammonia (Haber process) $H_3PO_4(aq)$ Phosphoric acid	$Ca_5(PO_4)_3F$ fluorapatite H_2SO_4 sulphuric acid (Contact process) OR H_3PO_4 Phosphoric acid	$NH_3(g)$ Ammonia (Haber process) $CO_2(g)$ Carbon dioxide (by-product of the Haber process)
Reaction equation	$2NH_3(g) + H_2SO_4(\ell) \rightarrow (NH_4)_2SO_4(aq)$ **memorise!**	$NH_3(g) + HNO_3(aq) \rightarrow NH_4NO_3(aq)$ **memorise!**	$NH_3(g) + H_3PO_4(aq) \rightarrow NH_4H_2PO_4(aq)$ $2NH_3(g) + H_3PO_4(aq) \rightarrow (NH_4)_2HPO_4(aq)$	Not required	$2NH_3(g) + CO_2(g) \rightarrow (NH_2)_2CO(g) + H_2O(g)$
Properties	• Very soluble in water; • easily absorbed by plant roots; • provides plants with both nitrogen (N) and sulphur (S).	• Very soluble in water; • easily absorbed by plant roots; • provides plants with nitrogen (N).	• Very soluble in water; • easily absorbed by plant roots; • provides plants with both nitrogen (N) and phosphorous (P).	• Soluble in water; • superphosphate also supplies the secondary nutrient S, sulphur; • widely used.	• Very soluble in water; • easily absorbed by plant roots; • provides plants with nitrogen (N).

7.4 Flowchart: The industrial production of fertilisers



Worked example 1

1. Study the diagram below that illustrates the industrial preparation of nitric acid and answer the questions that follow.



1.1 Write down a balanced chemical equation for the formation of product A.
1.2 Name the catalyst used during the reaction in Question 2.1.
1.3 What name is given to the reaction in Question 2.1? Give a reason for this name.
1.4 Write down a balanced chemical equation for the formation of product B.
1.5 Name the products A and B.
1.6 Write down a balanced chemical equation for the formation of product C.
1.7 Name product C.

2. Ammonium nitrate is important for its use in fertilisers and explosives. It can be prepared by the reaction of nitric acid and ammonia.

2.1 Write down a balanced equation for the preparation of ammonium nitrate.
2.2 What kind of fertiliser is ammonium nitrate?
2.3 Which characteristic of ammonium nitrate makes it suitable for use as a fertiliser?
2.4 Which characteristic of ammonium nitrate makes it suitable to be used in explosives?

3. Ammonium sulphate is often used as a fertiliser to supplement nitrogen and sulphur shortages in plants.

3.1 Compile a flow chart that indicates all the industrial steps for the preparation of ammonium sulphate from air, natural gas and sulphur.
3.2 Give balanced equations for all the reactions that take place during the preparation of ammonium sulphate from air, methane and sulphur.

Solutions

1.1 $4NH_3(g) + 5O_2(g) \xrightarrow{Pt} 4NO(g) + 6H_2O(g)$
1.2 Platinum or Rhodium
1.3 Catalytic oxidation of ammonia
1.4 $2NO(g) + O_2(g) \rightarrow 2NO_2(g)$
1.5 A: Nitrogen monoxide B: Nitrogen dioxide
1.6 $3NO_2(g) + H_2O(\ell) \rightarrow 2HNO_3(aq) + NO(g)$
1.7 Nitric Acid

2.1 $HNO_3 + NH_3 \rightarrow NH_4NO_3$
2.2 Primary mineral nutrient
2.3 High nitrogen content per mass
2.4 Nitrogen bonds are easily broken and therefore it decomposes rapidly and easily (explodes).

Answers for 3.1 and 3.2

- $O_2 + N_2$ (air)
- CH_4 (methane)
- S
- To produce:
  $(NH_4)_2SO_4$ (ammonium sulphate)

Step 1: Produce ammonia NH_3 in the Haber process:
N_2 (distilling liquid air) + $3H_2$ (steam reforming of CH_4) $\xrightarrow{Fe}$ $2NH_3$

↓

Step 2: Produce sulphuric acid in the Contact process.

a) $S + O_2$ (from air) + heat $\rightarrow SO_2$ (g)

b) $2SO_2 + O_2 \overset{V_2O_5}{\rightleftharpoons} 2SO_3$ (g)

c) $H_2SO_4 (\ell) + SO_3 (g) \rightarrow H_2S_2O_7 (\ell)$
d) $H_2S_2O_7 (aq) + H_2O \rightarrow 2H_2SO_4 (\ell)$

↓

Step 3: Produce ammonium sulphate:

$2NH_3 (g) + H_2SO_4 (\ell) \rightarrow (NH_4)_2SO_4 (aq)$

7.5 N:P:K fertilisers

As plants need a large amount of the primary mineral nutrients (nitrogen, phosphorus and potassium) and these need to be replenished (replaced) in the soil to make sure that crops grow well to provide enough food, NPK fertilisers that contain a mix of these nutrients, are usually used. They are produced by mixing a nitrogen fertiliser, a phosphorus fertiliser and potassium chloride ($KC\ell$).

The N:P:K (nitrogen : phosphorus : potassium) ratio is printed on the bag.

- The number in brackets indicates what percentage, by mass, of the bag's contents is fertiliser.
- The rest of the contents in the bag (100 minus the number in brackets), is the percentage of the bag's contents that is not fertiliser. This is a combination of inert substances (gypsum, lime and sand) which bind the fertiliser and help to distribute it evenly.

The total mass of the content of the bag is printed on the bag.

Step by step

Step 1. Find the mass of the bag.

Step 2. Find the percentage (%) of fertiliser in the bag (the number in brackets).

26% fertiliser in bag
∴ 74% inert compounds

Step 3. Find the mass of fertiliser in the bag.

$$\text{mass of fertiliser} = \frac{\text{percentage fertiliser}}{100} \times \text{mass of bag}$$

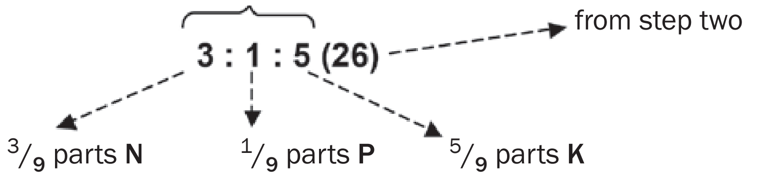
$$\begin{aligned}\text{mass of fertilizer} &= \frac{\text{percentage fertilizer}}{100} \times \text{mass of bag}\\ &= \frac{26}{100} \times 10 \text{ kg} = 2{,}6 \text{ kg}\end{aligned}$$

Step by step (continued)

Refer to the steps on the previous page

Step 4. Find the total number of parts of nutrients in the bag. (Add the numbers representing the ratios of each of the elements, N, P and K.)

Ratio total = 3 + 1 + 5 = 9



Step 5. For each element (N, P and K) find the percentage of the element in the fertiliser:

$$\% \text{ element} = \frac{\text{ratio element}}{\text{total ratio}} \times \% \text{ fertiliser}$$

$$\% \text{ N} = \frac{\text{ratio N}}{\text{total ratio}} \times \% \text{ fertiliser} = \frac{3}{9} \times 26 = 8{,}67$$

$$\% \text{ P} = \frac{\text{ratio P}}{\text{total ratio}} \times \% \text{ fertiliser} = \frac{1}{9} \times 26 = 2{,}89$$

$$\% \text{ P} = \frac{\text{ratio K}}{\text{total ratio}} \times \% \text{ fertiliser} = \frac{5}{9} \times 26 = 14{,}44$$

Step 6. For each element (N, P and K) find the mass of that element in the bag.

$$\text{mass element} = \frac{\text{ratio element}}{\text{total ratio}} \times \frac{\% \text{ fertiliser}}{100} \times \text{mass of bag}$$

$$\text{mass N} = \frac{\text{ratio N}}{\text{total ratio}} \times \frac{\% \text{ fertiliser}}{100} \times \text{mass of bag} = \frac{3}{9} \times \frac{26}{100} \times 10 \text{ kg} = 0{,}87 \text{ kg}$$

$$\text{mass P} = \frac{\text{ratio P}}{\text{total ratio}} \times \frac{\% \text{ fertiliser}}{100} \times \text{mass of bag} = \frac{1}{9} \times \frac{26}{100} \times 10 \text{ kg} = 0{,}29 \text{ kg}$$

$$\text{mass K} = \frac{\text{ratio K}}{\text{total ratio}} \times \frac{\% \text{ fertiliser}}{100} \times \text{mass of bag} = \frac{5}{9} \times \frac{26}{100} \times 10 \text{ kg} = 1{,}44 \text{ kg}$$

The per component totals (0,87; 0,29; 1,44) add up to 2.6kg.

Worked example 2

A bag of fertiliser has the following information on it: 3 : 2 : 3 (26).

1. What information can you deduce from these numbers?
2. Calculate the percentage composition of the fertiliser in the bag.

Solutions

1. It shows the ratio N : P : K.

   $3 + 2 + 3 = 8$ therefore the fertiliser mixture consists of:
   $\frac{3}{8}$ parts N; $\frac{2}{8}$ parts P and $\frac{3}{8}$ parts K
   These nutrients make up 26% of the mass of the bag content.
   The other 74% is made up of gypsum, lime and sand.

2. $\% \text{ N} = \frac{\text{ratio N}}{\text{total ratio}} \times \% \text{ fertiliser} = \frac{3}{8} \times 26 = 9{,}75$

   $\% \text{ P} = \frac{\text{ratio P}}{\text{total ratio}} \times \% \text{ fertiliser} = \frac{2}{8} \times 26 = 6{,}5$

   $\% \text{ K} = \frac{\text{ratio K}}{\text{total ratio}} \times \% \text{ fertiliser} = \frac{3}{8} \times 26 = 9{,}75$

7.6 Excessive use of fertiliser and the environment

The correct application of fertiliser to crops is essential for high quality, fast growing crops but using too much or unnecessary fertiliser has a negative effect on the environment.

- Groundwater is contaminated by fertiliser leaching (spreading by water) into the ground.
- Soil becomes acidic (pH decreases). Many plants do not grow in acidic soil.
- Invasive plants grow excessively while indigenous plants die. Invasive plants are undesirable non-indigenous (foreign) plants that grow too fast and out-compete local plants.
- Fertiliser in dams and rivers leads to “eutrophication”, defined below.
- High nitrate concentrations in drinking water decreases the ability of haemoglobin in the blood to carry oxygen and leads to ‘blue baby syndrome’.

7.6.1 Eutrophication

	In water (dams and rivers)	On land
Causes	• Poor (bad) control of waste products. • Excessive / unnecessary application of fertilisers.	

	• Waste products (urine and faeces) and
	• excessive fertiliser nutrients
	  • leach into ground water and
	  • run into rivers and dams.
		• Poor (bad) farming practises:
		  • Excessive / unnecessary use of fertilisers
		  • Animal waste in feeding and milking stalls contains urea and ammonia and leaches into ground water.

Effects	• Excessive growth of algae; • Algae die; • Bacteria feed on the algae and use oxygen; • Oxygen levels in the water drop; • Fish and other living organisms die.	• Invasive plants grow excessively, indigenous plants die; • Bird and insect species move away disturbing the ecosystems; • Soil erosion increases due to absence of indigenous plants with strong root systems.

Possible solutions	• Strict control over all waste and sewage must be enforced.
	• Waste products:
	  • must be treated and
	  • not allowed to leach into groundwater or
	  • run into rivers and dams.
		• Test soil to determine need for fertiliser – apply correct amount and type;
		• Plant indigenous plants along rivers to prevent erosion and prevent inflow of contaminated water;
		• Conserve natural swamps which break down excess nitrogen nutrients naturally;
		• Control animal waste in feeding and milking stalls.

NB

REMEMBER

An overabundance (excess, too much) of nutrients (N and P) in water leads to:

- the fast and excessive growth of algae and other water plants (this is called ‘algal bloom’) and bacteria
- causing a drop in the oxygen concentration in the water and
- the death of fish and other living organisms in the water.

hint

VOCABULARY

Overabundance / excess:	more than is needed
Shortage:	not enough
Invasive plants:	plants that do not naturally grow in a certain area
Indigenous plants:	plants that grow naturally in (are native to) a certain area
Swamps:	ground that is uncultivated but is usually covered with water
Erosion:	soil and rock is removed from the Earth's surface by wind, rain or water
Stunted growth:	reduced growth leading to smaller, underdeveloped plants

Activity 2

Which ONE of the following is NOT associated with eutrophication in water?

A Dead zones

B Algal bloom

C Depletion of oxygen

D Increased aquatic life

(2)
[2]

Solution

D ✓✓ **[2]**

7.6.2 The effect of a shortage or excess of the primary nutrients (N, P and K) on plants

	N (nitrogen)	P (phosphorus)	K (potassium)
Shortage	• Little growth • Weak stems • Yellow leaves	• Stunted growth • Slow growth • Purple leaves	• Poor quality flowers and fruit (colour and taste) • Leaves have brown or yellow edges
Excess	• Dark green leaves • Poor production of seed and fruit	• Causes shortage of micro nutrients Fe and Zn	• Causes shortage of micro nutrients Mg and Ca • Stunted growth • Poor quality flowers and fruit

7.7 Alternatives to inorganic fertilisers

Although fertilisers are essential for the fast growth of high quality crops, the negative effects of inorganic compounds on the environment must be taken into account. Alternative sources of organic nutrients that can be used to ensure good crops are:

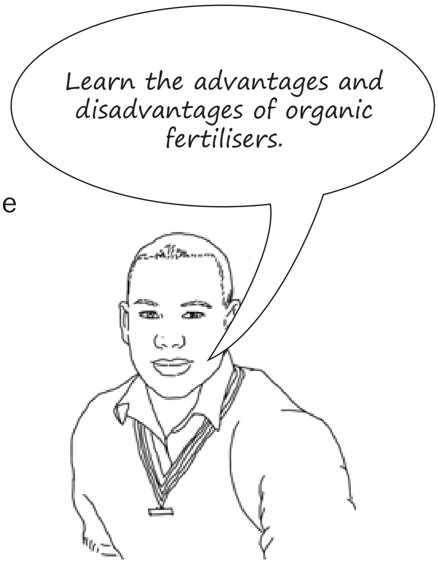
- Bone meal;
- Animal manure;
- Natural plant compost;
- Bat guano (faeces);
- Fish emulsions;
- Kelp meal

Advantages of organic fertilisers:

- Break down and release nutrients more slowly than inorganic fertilisers, so there is less chance of the fertiliser leaching into the soil and causing contamination of groundwater;
- Usually cost less and
- Are often available for free.

Disadvantages of organic fertilisers:

- Not enough is available for large scale usage;
- Provide less nutrients – more has to be used;
- Slow release of nutrients sometimes harms plants;
- Slow release may cause nutrients to be available too late in the plant's growth cycle.



Activity 3

Fertilisers allow farmers to grow crops in the same soil year after year. However, environmental problems, such as eutrophication, are associated with the application of fertilisers.

1. State ONE PRECAUTION that a maize farmer can take to prevent eutrophication. (1)

Nitric acid is an important reactant in the production of ammonium nitrate, a nitrogen-based fertiliser.

2. Write down the name of the industrial process for the production of nitric acid. (1)

3. Write down a balanced equation for the preparation of ammonium nitrate from nitric acid. (3)

[5]

Solutions

1. Use fertilisers sparingly ✓ / Do not over-fertilise ✓
   Make use of precision (computerised) application of fertilisers ✓
   Ensure that water from fields does not run into rivers/dams ✓
   Redirect water from fields into reservoirs/away from rivers/dams ✓ (any one) (1)
2. Ostwald process ✓ (1)
3. HNO_3 ✓ + NH_3 ✓ → NH_4NO_3 ✓ (3)

[5]

Activity 4

The rapidly increasing human population is resulting in an ever-increasing demand for food. To meet this demand, farmers apply fertiliser to the same cultivated land EACH YEAR.

1. Explain why farmers have to apply fertilisers to their land each year. (1)

2. Write down one negative impact that over-fertilisation can have on humans. (1)

3. Sulphuric acid is an important substance used in the manufacture of fertilisers.
The equation below represents one of the steps in the industrial preparation of sulphuric acid.

$$2SO_2(g) + O_2(g) \rightleftharpoons 2SO_3(g) \qquad \Delta H < 0$$

3.1 Write down the name of the process used to prepare sulphuric acid in industry (1)
3.2 Write down the name or the formula if the catalyst used in 2.3.1 (1)
3.3 Is the forward reaction endothermic or exothermic? Give a reason for your answer. (1)
3.4 Write down the name or formula of the fertiliser formed when sulphuric acid reacts with ammonia. (2)

[7]

Solutions

1. Fertilisers replenish nutrients depleted by the growing of crops ✓ (1)

2. Damage to crops/soil ✓ resulting in small or no harvest/ less income. Excessive fertiliser seeps into groundwater and contaminates drinking water ✓ or runs into rivers and/or dams and causes eutrophication ✓ which may result in less income ✓/famine/starvation ✓/poor quality drinking water ✓/fewer recreation areas/✓ environmental damage/✓ death of wild animals ✓ (any one) (1)

3.1 Contact process ✓ (1)

3.2 V_2O_5 ✓ vanadium pentoxide ✓ (any one) (1)

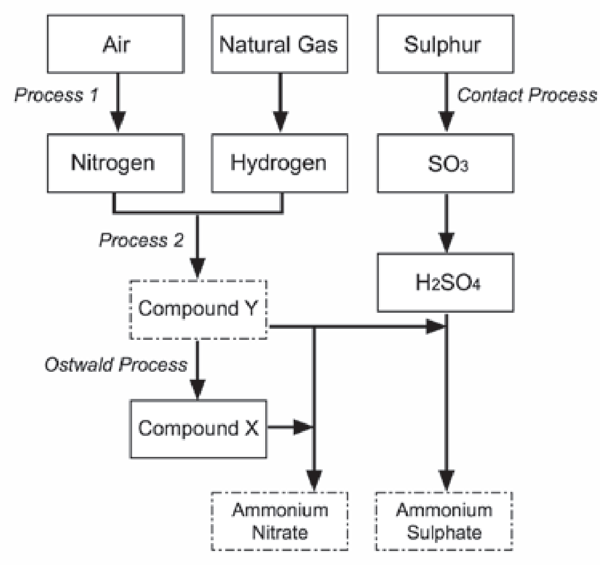
3.3 Exothermic as $\Delta H < 0$ ✓ (1)

3.4 $(NH_4)_2SO_4$ ✓✓ **OR** / Ammonium ✓ sulphate ✓ (2)

[7]

Activity 5

Ammonia, ammonium nitrate and ammonium sulphate are three important nitrogen-containing fertilisers. The flow diagram below shows how these fertilisers are produced in industry.



1. Use the information in the flow diagram above and write down the following:

- **1.1** Name Process 1 (1)
- **1.2** Balanced equation for Process 2 (3)
- **1.3** Name or Formula for compound X (1)
- **1.4** Balanced equation for the preparation of ammonium sulphate using sulphuric acid and compound Y (3)
- **1.5** Name or Symbol of the primary nutrient in ammonium sulphate (1)

2. Write down one positive impact of fertilisers on humans (1)

3. Write down two negative impacts of the use of ammonium nitrate as fertiliser, on humans. (2)

[12]

Solutions

1.1 Fractional distillation of liquid air ✓ (1)

1.2 $N_2 + 3H_2 \rightarrow 2NH_3$ (reactants ✓ products ✓ balance ✓) (3)

1.3 Nitric acid / HNO_3 ✓ (1)

1.4 $H_2SO_4 + 2NH_3 \rightarrow (NH_4)_2SO_4$ (reactants ✓ products ✓ balance ✓) (3)

1.5 Nitrogen / N ✓ (1)

2. Enhance growth of crops/plants ✓ to produce more food for humans ✓ food security for humans ✓ production / application of fertiliser ✓ results in job creation selling of fertilisers ✓ stimulates the economy ✓ (any one) (1)

3. (Excessive) nitrates in water (eutrophication) ✓ can result in blue baby syndrome or cancer ✓ (Excessive) nitrates/ammonium ions in water can result in poor quality drinking water ✓ or death of fish ✓ or less food ✓ or fewer recreational facilities ✓ or famine due to killing plants / crops from the excess ✓ or excessively changing the pH of the soil and thereby reducing the food production ✓ (any two) (2)

[12]

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