WJEC
CBAC

AS/A LEVEL
GCE in Chemistry

REVISION AID

UNIT 4
A Level

by

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A Level

UNIT CH4 Spectroscopy and Organic Chemistry (Analysing and building molecules)

This unit builds on the foundation ideas of spectroscopy and basic organic chemistry introduced at AS level and goes on to explore these concepts in more detail.

It also explores the use of these topics in structure elucidation, in synthesis and in industrial and environmental applications.

TOPIC 9 Spectroscopy

TOPIC 10 Isomerism and aromaticity

TOPIC 11 Organic compounds containing oxygen

11.1 **Alcohols and phenol.**

11.2 **Aldehydes and ketones.**

11.3 **Carboxylic acid and derivatives.**

TOPIC 12 Organic compounds containing nitrogen

TOPIC 13 Organic synthesis and analysis

TOPIC 14 The process of how science works

Topic 9 Spectroscopy

Spectroscopic techniques are invaluable tools in the determination of structure. Mass spectrometry has already been encountered in the AS units. At A level infrared and nmr spectroscopy are encountered.

Candidates should be able to:

(a) *recall the energy gradation across the electromagnetic spectrum from u.v. to visible to i.r. spectra;*

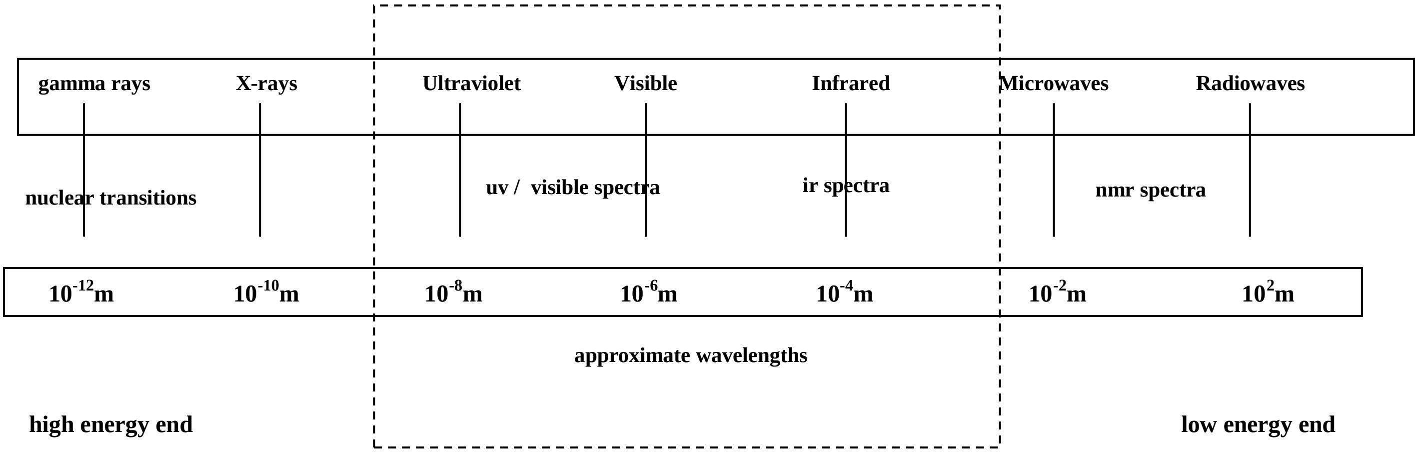
(b) *appreciate that energy levels can be split by a magnetic field, that certain nuclei, including 1H, possess intrinsic spin, and that measurements of the magnitudes of the interactions between the nuclear spin and the magnetic field are the basis of nuclear magnetic resonance spectroscopy;*

(c) *explain why some substances are coloured in terms of the wavelengths of visible light absorbed;*

(d) *explain the meaning of the term chromophore and give examples of chromophores in organic species, e.g. – N = N – in conjugated systems, including azo dyes.*

Students should recall the nature of the electromagnetic spectrum. The region enclosed by the dotted rectangle is specifically mentioned in **Topic 9.**

A simplified electromagnetic spectrum



(b) Nuclear Magnetic Resonance

The fundamental particles that make up atoms may be regarded as spinning charged particles. Nuclear magnetic resonance is concerned with the spin properties of the nucleus.

If the number of protons and the number of neutrons are both even then the nucleus has no overall spin.

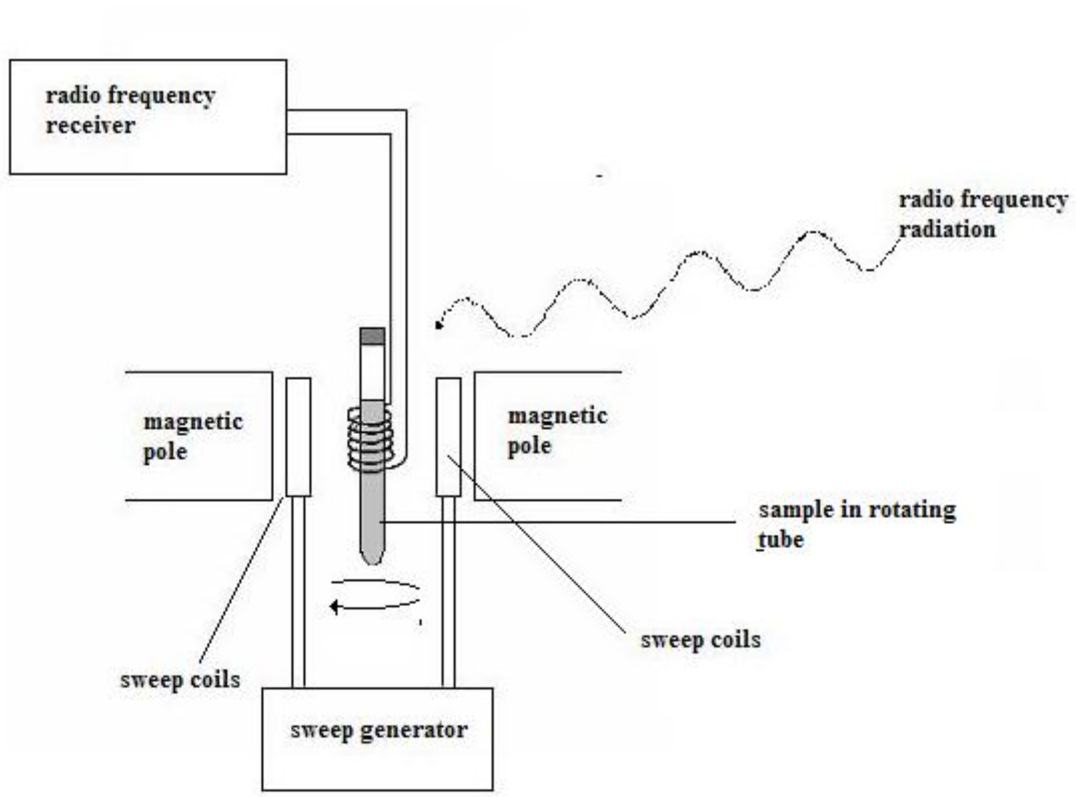
If the number of protons plus the number of neutrons is odd, then the nucleus has half integer spin.

If the number of protons and the number of neutrons are both odd, then the nucleus has integer spin.

In the absence of a magnetic field the spin energy levels are the same but in the presence of a magnetic field, the energy levels split.

The most common form of nmr is proton nmr. The ${}^{1}_{1}H$ atom has a nuclear spin of ½ and such hydrogen atoms occur in most organic compounds. In the presence of a magnetic field the spin energy level splits to +½ and –½.

The basics of a nuclear magnetic spectrometer are shown below.



The sample is held in a spinning tube between the poles of a powerful magnet. The magnetic field can be varied by means of current-carrying coils. Gradual variation of the magnetic field is called sweeping. The sample is subjected to radio frequency electromagnetic radiation and a receiver can detect absorption of radiation by the sample for a given magnetic field strength and a fixed radio frequency. All factors are linked to a computer and recorder.

Although all ${}^{1}_{1}H$ atoms are the same, the absorption depends on the environment of the hydrogen atom. The magnetic field at the nucleus is not the same as the applied magnetic field because the charged electrons also interact with the applied magnetic field. The difference between the two is called the nuclear shielding.

Topic 10

Candidates should be able to:

(*a*) *give the systematic names of all simple compounds, including benzene derivatives, containing the functional groups occurring in this Unit;*

(b) understand the term stereoisomerism as embracing both E–Z and optical isomerism;

(c) explain what is meant by a chiral centre, recall that this gives rise to optical isomerism, and be able to identify chiral centres in given molecules, and understand what is meant by an enantiomer;

(d) recall that enantiomers rotate plane-polarised light in opposite directions and that equimolar amounts of enantiomers form racemic mixtures;

(e) describe the structure of, and bonding in, benzene;

(f) calculate the delocalisation or resonance energy of benzene from given enthalpy data;

(g) describe and classify the nitration and halogenation reactions of benzene as electrophilic substitution, and recall the mechanism for these reactions;
(The equation for the formation of NO_2^+ *is not required.)*

(h) describe the Friedel-Crafts alkylation of benzene;

(i) compare benzene and alkenes with respect to benzene's resistance to addition and explain this resistance in terms of π *electron delocalisation;*

(j) compare the ease of alkaline hydrolysis of chloroalkanes and chlorobenzene and explain the difference in terms of the C – Cl bond strength, and rationalise the greater strength of the C – C1 bond in the latter case;

Nomenclature

(a) Systematic nomenclature.

Because of the large number of organic compounds it is necessary to devise a way of naming them that leaves no ambiguity. Many organic compounds have been known for a long time and have trivial names that pre-date systematic nomenclature.

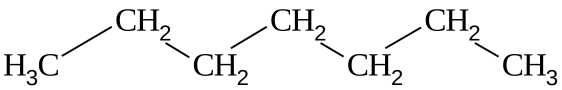
Acetic acid, CH_3COOH, which is found in vinegar, has the systematic name **ethanoic acid**.
Acetone, C_3H_6O, sometimes used as nail varnish remover, has the systematic name **propanone**.

Naming hydrocarbons.

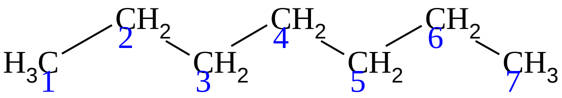
Organic compounds have a carbon skeleton. Compounds are named in terms of this carbon skeleton and the individual carbon atoms are assigned a number to identify them.

Alkanes.

An alkane in which the carbon atoms form a continuous chain is called a straight chain molecule.

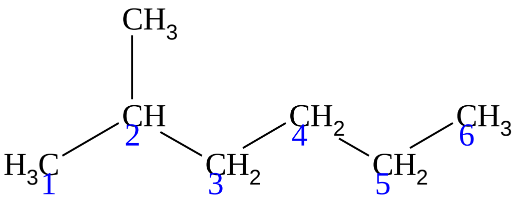


heptane



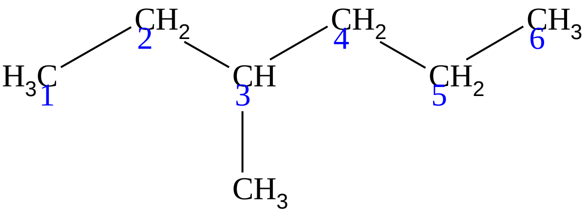
The seven carbon atoms numbered

One isomer of heptane is 2-methylhexane



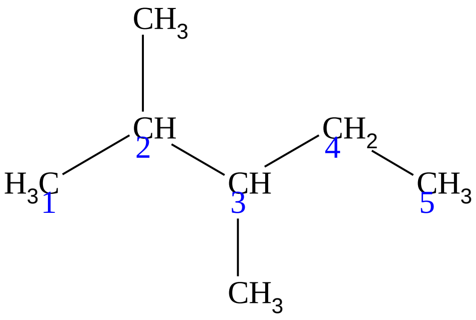
The $-CH_3$ group is called the methyl group as it is derived from methane, CH_4. In the molecule above, the methyl group is substituted for a hydrogen atom on the second carbon atom.

Another isomer is 3-methylhexane



4-methyl hexane does not exist because if we number the hexane chain from the other end it would be the same as 3-methylhexane above. See rules below.

When there is more than one methyl group attached to the chain we use the prefixes *di-* , *tri-* etc.



2,3-dimethylpentane

Rules

- Look for the longest continuous carbon chain.
- Base the name on the straight-chain alkane with the same number of carbons.
- Look for the shorter carbon branches and the names of those straight-chain alkanes.
- State the number of identical branches by adding *di-* (two), *tri-* (three), *tetra-* (four), etc.
- Number the positions of the branches on the longest chain so that the arithmetic total of the numbers used is the lowest.
- Keep alphabetical order of branch name.

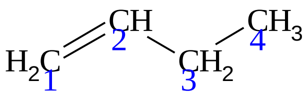
Naming alkenes

Like alkanes the structure is examined for the longest straight-chain carbon chain.

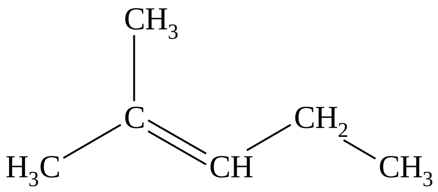
The name is based on the hydrocarbon with the same number of C-atoms as the longest continuous carbon chain that contains the double bond.

The lowest number is used to show the position of the double bond.

The ending “ene” replaces the ending “ane” in the alkanes.



but-1-ene

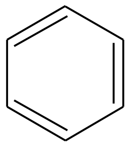


2-methylpent-2-ene

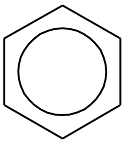
Aromatic hydrocarbons

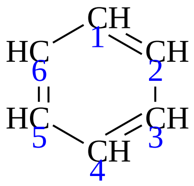
Compounds based on the benzene ring are called aromatic hydrocarbons. The name originates from the odours of such compounds but now has a more sophisticated meaning.

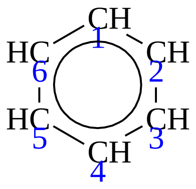
Benzene is a six membered ring which can be represented as



or

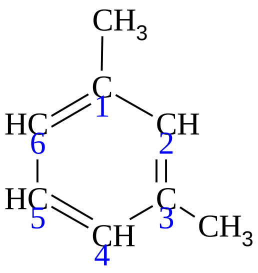


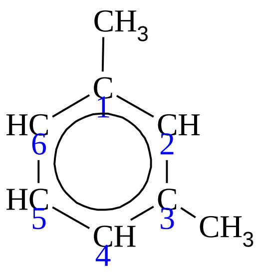


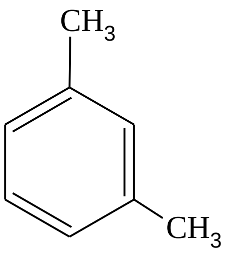


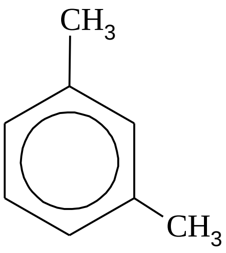
see later

Derivatives are named by numbering the ring.







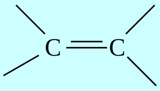
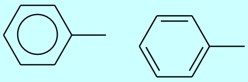
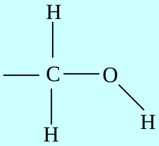
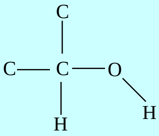
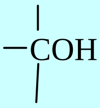
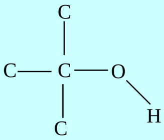
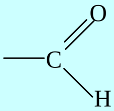
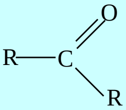
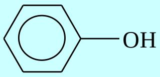
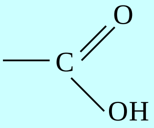
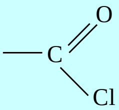


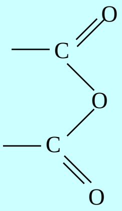
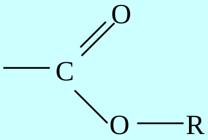
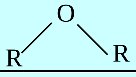
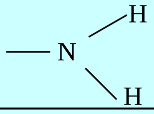
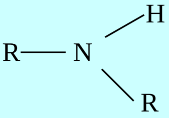
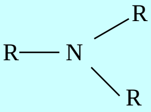
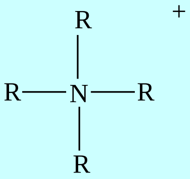
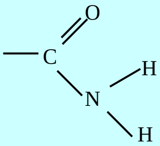
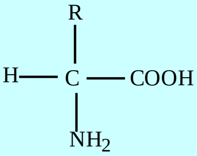
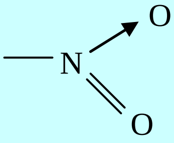
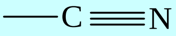
1,3-dimethylbenzene

Functional Groups

Atoms and groups of atoms other than hydrogen which are attached to carbon atoms are known as functional groups.

Functional Groups

Functional Group		Type of compound	Prefix in name	Suffix in name
>C=C<		alkene		ene
C_6H_5-		arene, aromatic compounds	phenyl-	benzene
-CH_2OH		primary alcohol	hydroxy-	-ol
>CHOH		secondary alcohol	hydroxy-	-ol
 COH		tertiary alcohol	hydroxy-	-ol
-CHO		aldehydes		-al
>CO		ketones	oxo-	-one
Ar-OH		phenol any OH attached to a benzene ring is a phenolic group	hydroxy-	-ol
-CO_2H		carboxylic acid		-oic acid
-COCl		acyl or acid chloride	-oyl chloride	acid or acyl chloride

$-(CO)_2O$		acid anhydrides		anhydride
$-CO_2R$		ester		-oate
R-O-R		ether	oxy-	
$-NH_2$		primary amine	amino-	amine
R_2NH		secondary amine	amino-	amine
R_3N		tertiary amine	amino-	amine
R_4N^+		quaternary ammonium ion		
$-CONH_2$		amide	amido-	amide
$RCH(NH_2)COOH$		α-amino acid		
$-NO_2$		nitro compounds	nitro-	
-CN		nitriles	cyano-	nitrile

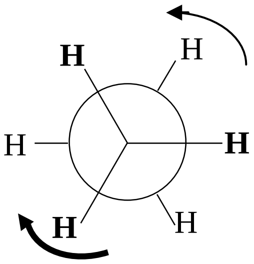
-Cl	-Cl	chloro compounds	chloro-	-chloride
-Br	-Br	bromo compounds	bromo-	-bromide
-I	-I	iodo compounds	iodo-	-iodide

(b) **STEREOISOMERISM**

This occurs with compounds with the same molecular and structural formulae but which have a different arrangement of their atoms in space.

E-Z isomerism

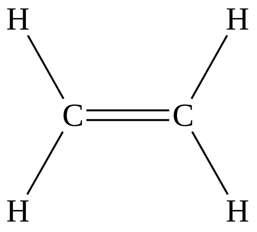
With an **alkane** such as ethane, C_2H_6, there is free rotation about the carbon-carbon single bond.

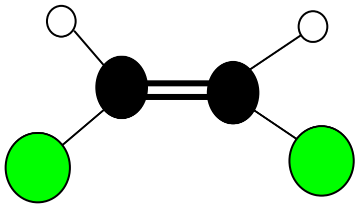


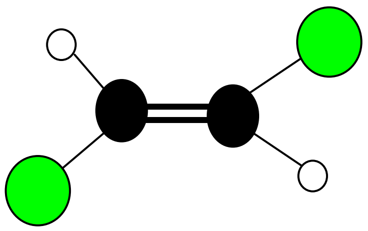
Viewed along the carbon – carbon bond, the three hydrogen atoms of each methyl group can rotate with respect to each other.

In an **alkene** such as ethene, C_2H_4, the double bond prevents this rotation.

There is no rotation around the carbon-carbon double bond and the molecule is confined to a planar shape. This means that in compounds such as 1,2-dichloroethene, represented by the ball and stick diagrams below, two forms are possible. This are described as E-Z isomers.







The rules for assigning E-Z nomenclature are known as CIP rules after the chemists who developed the system, Cahn, Ingold and Prelog.

The first step is to look at the two groups at the end of the double bond and rank the two groups in terms of the atomic number of the atoms concerned. The atom with the higher atomic number takes precedence (higher priority). This is done for both ends of the double bond. If the higher priority groups are on the same side of the double bond, then it is the **Z** isomer (from the German ***zusammen*** which is together). If they are on opposite sides then it is the E isomer(from the German ***entgegen*** which is opposite).

Examples

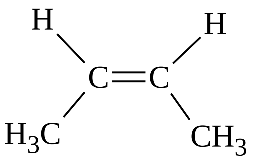
but-2-ene

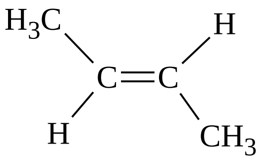
Look at the left hand end of the double bond. C has a higher priority than H.

Look at the right hand end of the double bond. C has a higher priority than H.

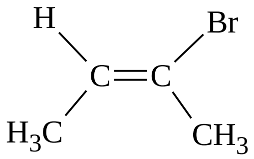
The carbons are on the same side of the double bond and so this is

(Z) - but-2-ene and **(E) – but-2-ene**.





Consider the molecule of 2-bromo-but-2-ene.



Look at the left hand end of the double bond. C has a high priority than H.

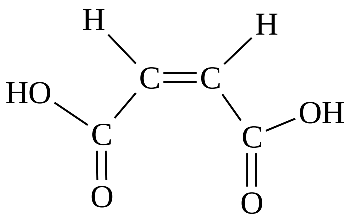
Look at the right hand end of the double bond. Br has a high priority than C.

The higher priority atoms are on opposite sides of the bond and this is **(E) - 2-bromo-but-2-ene.**

[Note in *cis/trans* isomerism this would be the *cis* isomer.]

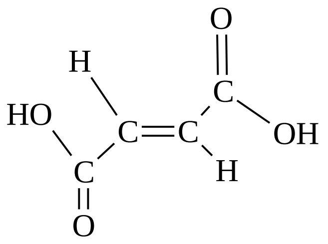
The E and Z isomers may have different and physical properties.

Consider the two butenedioic acids.



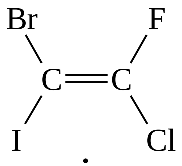
(Z) – butenedioic acid

trivial name, maleic acid,
b.p. 130 ^{o}C
forms an anhydride on heating

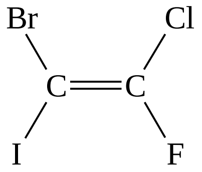


(E) – butenedioic acid

trivial name, fumaric acid
b.p. 200 ^{o}C sublimes
does not form an anhydride



i



ii

Consider the following two structures

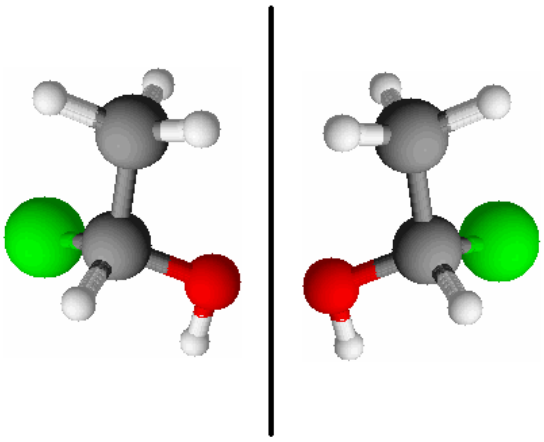
Two different molecules as there is no free rotation about the carbon-carbon double bond.

Looking at the left hand end of **i**, I has higher priority than Br and at the right hand side Cl has higher priority than F. The higher priority atoms are on the same side of the double bond so structure **i** is the **Z- isomer** and similarly structure **ii** is the **E –isomer**.

Optical isomerism

This occurs when the isomers have the same molecular formula and same structural formula but have a different effect on plane polarised light. The isomers are non-superimposable mirror images. This property is known as ***chirality*** and the isomers are said to be ***chiral***.

Optical isomerism arises mainly from molecules which have four different atoms or groups of atoms attached to a tetrahedral carbon atom. The carbon atom is said to be an **asymmetric carbon atom**, since the molecule does not possess a plane or axis of symmetry. A ball and stick model shows the mirror image relationship and the fact that the isomers cannot be superimposed upon each other. Such isomers are described as ***optical isomers* or *enantiomers***.

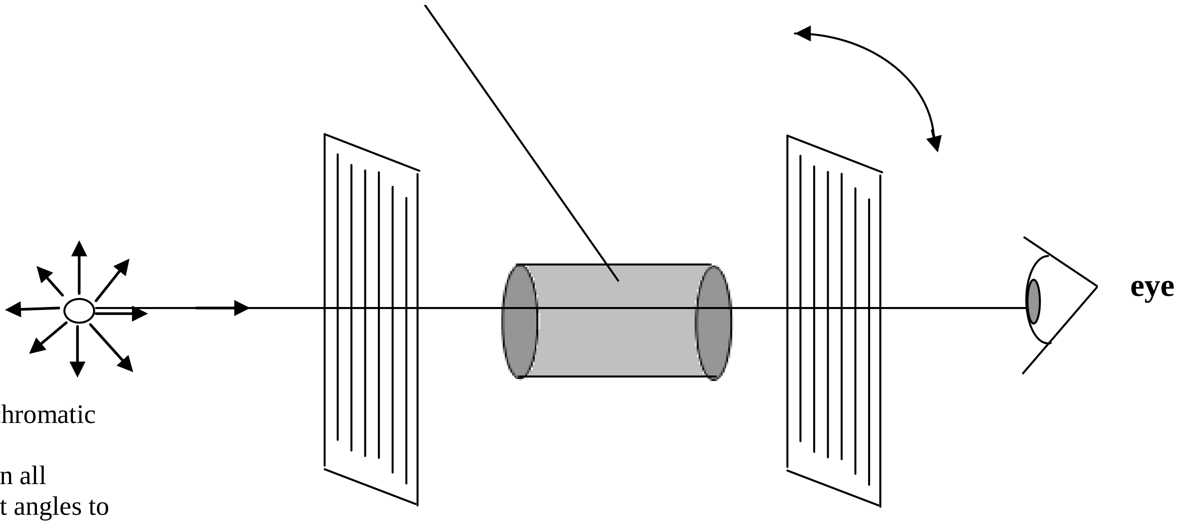


mirror line

The isomers of organic compounds of this type, in the liquid state or in solution, have the ability to rotate the plane of polarised light either to the left (laevorotatory) or to the right(dextrorotatory). They are said to be ***optically active*** and are given the prefix *l*- or *d*- for the laevorotatory and dextrorotatory forms respectively. The amount of rotation can be measured by a polarimeter.

An equimolar mixture of the two optically active forms is optically inactive and is called a **racemic mixture** or **racemate**. Separation of a racemate into its component enantiomers is called ***resolution***.

A diagram of a simple polarimeter



Cell containing a solution of an optically active compound. The compound rotates the plane of polarised light.

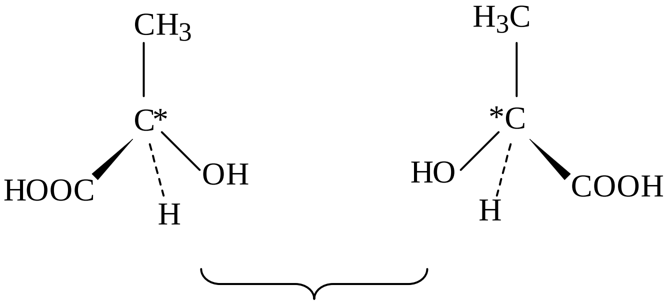
Source of monochromatic light
With vibrations in all directions at right angles to the direction of propagation.

The polarizer which allows only light vibrations in one direction at right angles to the direction of propagation through

The analyser which has to be rotated to restore the original illumination before the compound was inserted in the instrument.

Examples of optical isomers.

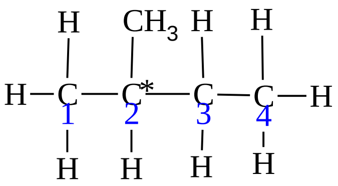
2-hydroxy propanoic acid.



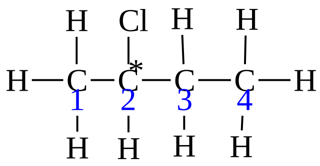
Mirror images

* indicates asymmetric carbon atom or chiral centre

2-Substituted butane molecules have an asymmetric carbon.



2-methylbutane



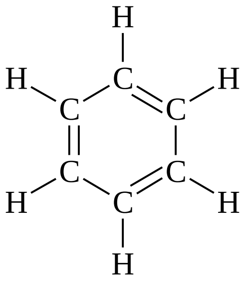
2-chlorobutane

* indicates the asymmetric carbon atom or chiral centre

(e) **Bonding in benzene.**

Benzene, C_6H_6 is an important molecule

Benzene is a ring of six carbon atoms in a planar regular hexagon. The structure was initially solved by Kekulé as



This is called the Kekulé structure of benzene

Although this formula explains some of the properties of benzene it does not explain all its reactions or its stability towards certain reagents.

The modern view is that the double bonds hold no fixed positions but that all the p electrons from each of the six carbon atoms overlap to form a ring of π-electrons.

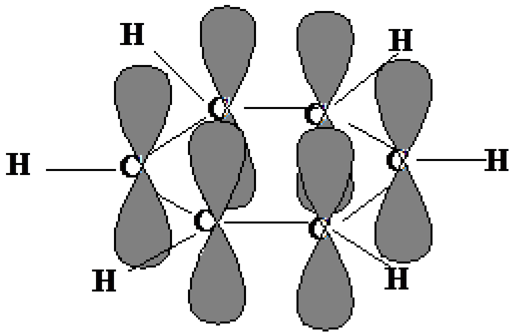


Diagram showing the p-orbitals at right angles to the hexagon of carbon atoms.

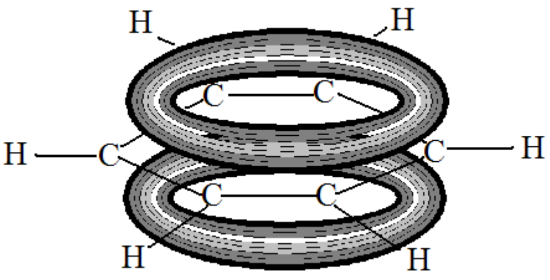
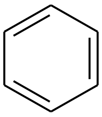
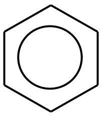


Diagram showing the π-orbital, a ring above and below the plane of carbon atoms. The π-electrons are said to be delocalised. i.e. any one of the π-electrons cannot be assigned to a particular atom.

For this reason the benzene ring is represented as



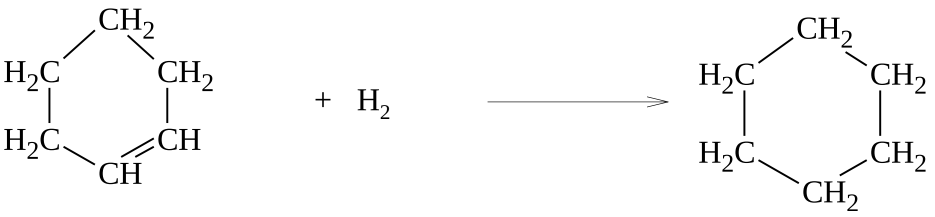
or



Kekulé structure or with the internal ring

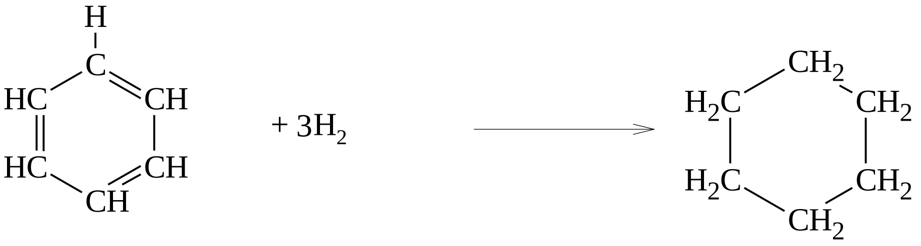
Physical evidence shows all the atoms of benzene to lie in a plane and all the carbon-carbon bonds are of equal length which would not be true if single and double bonds were present.

The enthalpy change of hydrogenation of cyclohexene



cyclohexane

is approximately -120 kJ mol^{-1} and it might be expected that for the Kekulé structure the enthalpy change of hydrogenation would be of the order of -360 kJ mol^{-1}.
However, the enthalpy change for



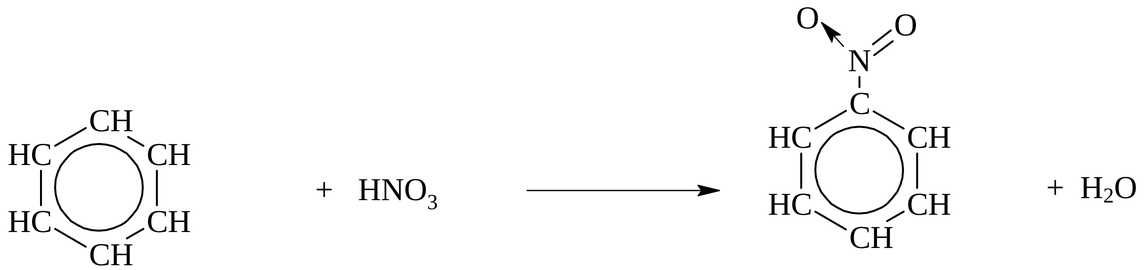
is – 208 kJ mol^{-1} .

This means that benzene is more stable than expected, by approximately150 kJ mol^{-1}.
This energy difference arises from the delocalisation of the π-electrons and is called the *delocalisation energy* or *stabilisation energy*. An older term was the *resonance energy*.

For this reason, in writing formulae, the hexagon with the delocalised ring is preferred to the Kekulé structure.

As in the alkenes, the π-electrons provide a region of high electron density.
This means that benzene should be susceptible to attack by electrophiles.
Unlike the alkenes, benzene undergoes substitution reactions.

A typical substitution reaction is nitration which can be represented by



nitrobenzene

The reaction conditions are

- Reflux at a temperature below 55 °C
- Use a mixture of concentrated nitric and sulfuric acids (nitrating mixture)

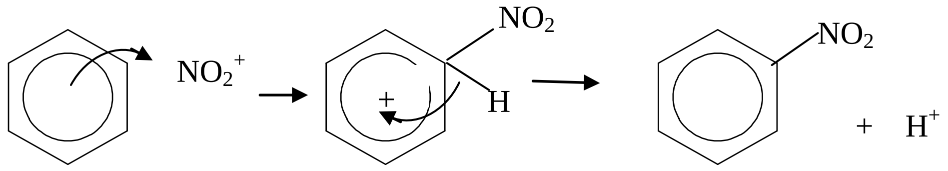
The nitrating mixture produces the nitryl cation or nitronium ion.

$2H_2SO_4 + HNO_3 \rightarrow 2HSO_4^- + H_3O^+ + NO_2^+$

nitryl cation

This equation is not required by the specification, see Topic 10(g)

The reaction then involves interaction of the π-electrons of the benzene ring with the NO_2^+ electrophile. The intermediate structure is called a Wheland intermediate. (after G. Wheland)

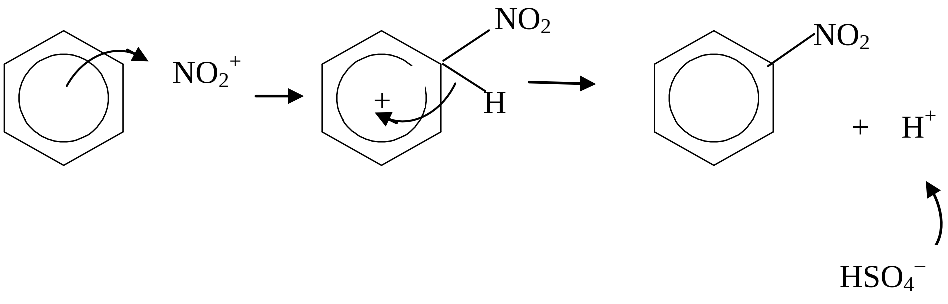


Wheland intermediate

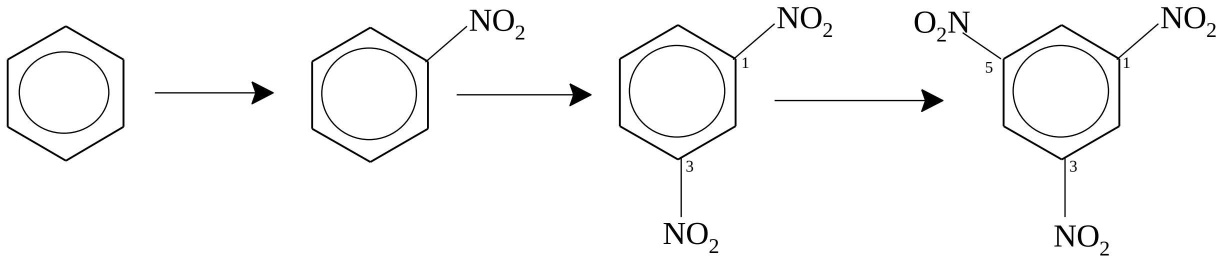
the bonding pair of electrons between carbon and hydrogen shifts into the ring to restore delocalisation as a proton is lost.

This reaction mechanism is called **electrophilic substitution**.

The ejected proton will react with any nucleophiles present and reaction with the hydrogensulfate ion will form H_2SO_4.



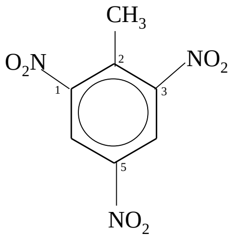
At higher temperatures further nitration occurs.



1,3-dinitrobenzene

1,3,5-trinitrobenzene

The trinitro- derivative is explosive and can be compared to 2-methyl-1,3,5-trinitrobenzene (old name trinitrotoluene or TNT)



2-methyl-1,3,5-trinitrobenzene

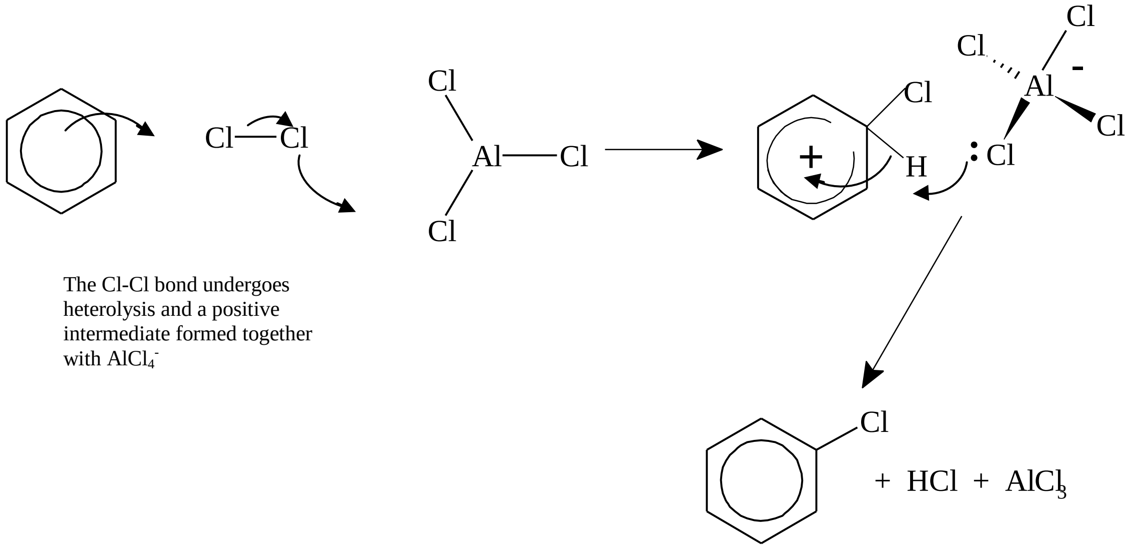
TNT

Chlorination.

Chlorine may be substituted into the benzene ring under the following reaction conditions

- Absence of light
- Room temperature
- Anhydrous conditions
- In the presence of another substance called a halogen carrier, e.g. aluminium chloride.

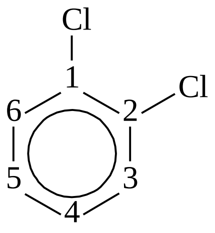
Aluminium chloride, $AlCl_3$, is electron deficient, the aluminium having only six valency electrons around the aluminium. The reaction mechanism is thought to involve the formation of $[AlCl_4]^-$. The mechanism is electrophilic substitution.



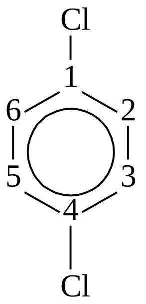
The Cl-Cl bond undergoes heterolysis and a positive intermediate formed together with $AlCl_4^-$

chlorobenzene

Further substitution gives a mixture of 1,2-dichlorobenzene and 1,4 –dichlorobenzene



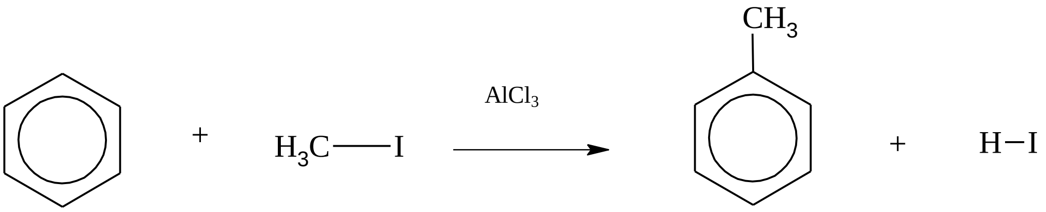
1,2-dichlorobenzene



1,4-dichlorobenzene

(h) The Friedel-Crafts Reaction

When benzene is treated with iodomethane, CH_3I, in the presence of aluminium chloride at room temperature and in anhydrous conditions, methylbenzene is formed.

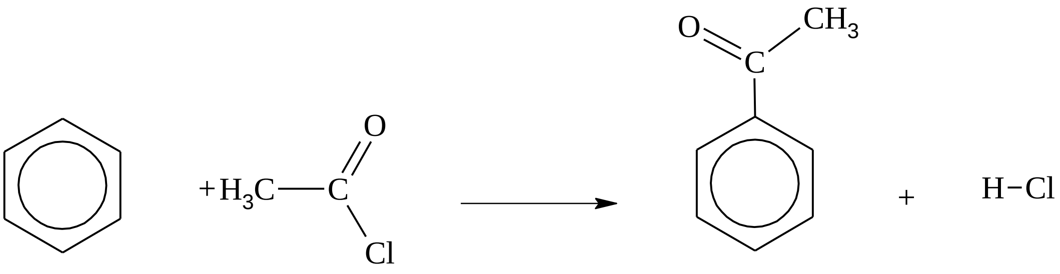


Iodomethane methylbenzene

This is another electrophilic substitution reaction. The reaction is sometimes called *alkylation* as it is a means of introducing an alkyl group (C_nH_{2n+1}–) into an benzene ring.

It will work with halogenoalkanes of formula $C_nH_{2n+1}X$ where X is halogen.

If an acyl halide is used then a ketone is formed.



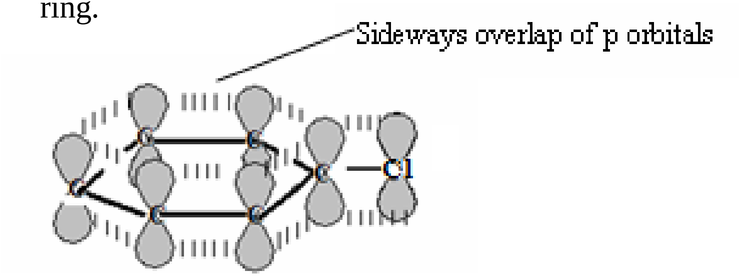
ethanoyl chloride phenylethanone

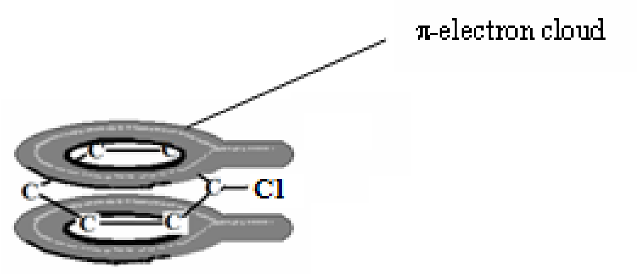
Although benzene takes part in some addition reactions, such reactions occur much less readily than in the alkenes. This can be explained by saying that if there were addition across a double bond in benzene then delocalisation would be lost and the system lose stability.

(j) Aromatic halogen compounds are far more resistant to hydrolysis than halogenoalkanes.

When the halogen atom is attached to a benzene ring, it is far less reactive than when in a halogenoalkane.

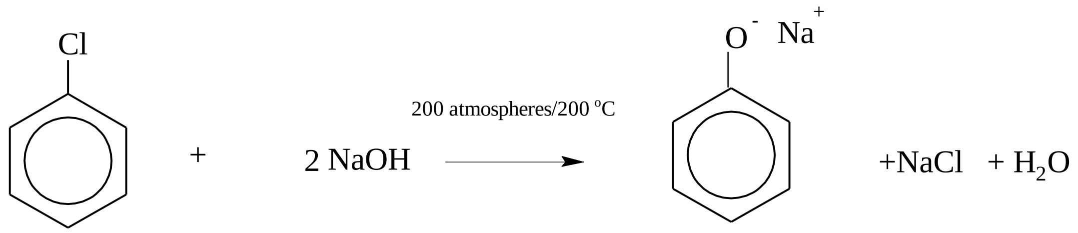
The reason is that the p-orbital of the halogen atom can enter into the delocalised π-electrons of the ring.



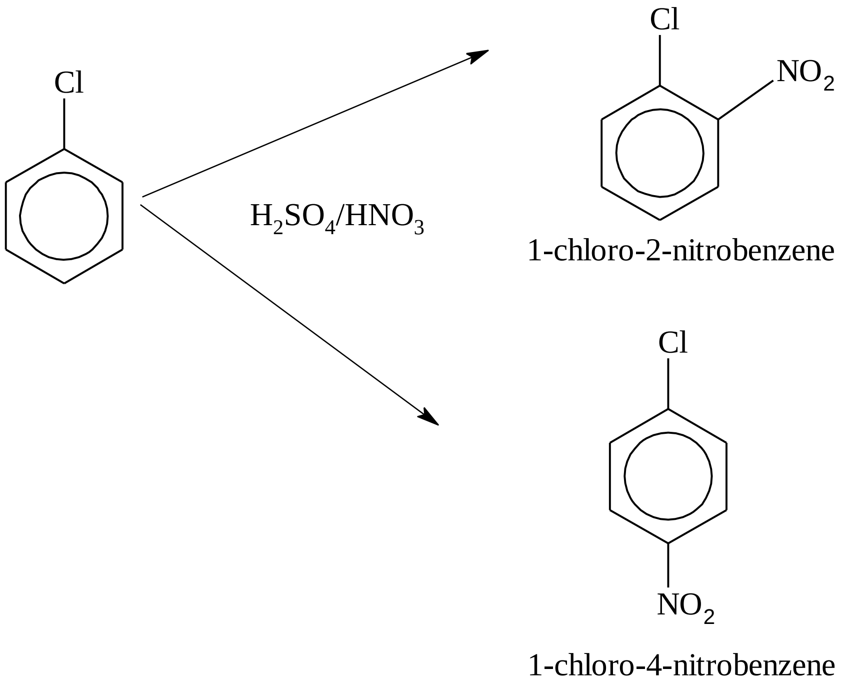


The result is that the halogen atom attached to the ring is not easily substituted since delocalisation must be destroyed.

It can only be replaced by –OH under drastic conditions.



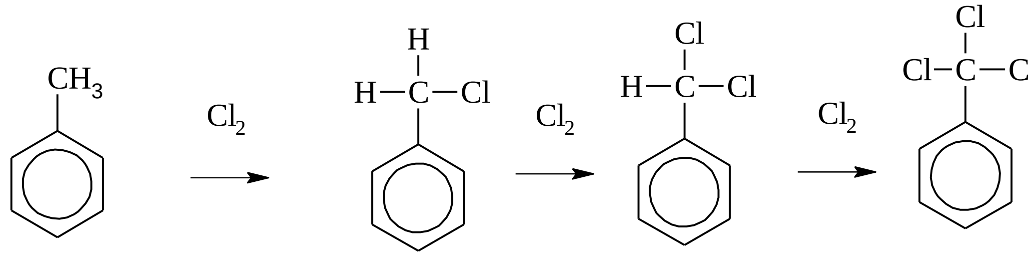
The aromatic ring of chlorobenzene may be chlorinated, nitrated etc. The product is a mixture of the 2- and 4- isomers.



Aromatic compounds with halogen in the side-chain.

Any carbon chain attached to the benzene ring is called a side-chain.

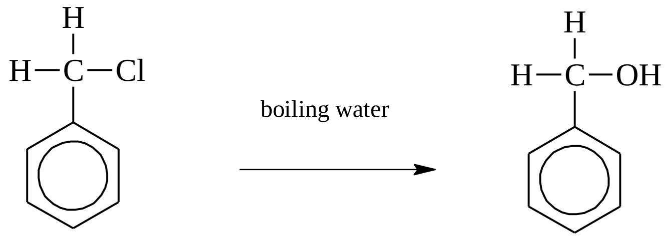
Methylbenzene can be chlorinated when chlorine is passed into boiling methylbenzene in the presence of light. (Free radical conditions.)



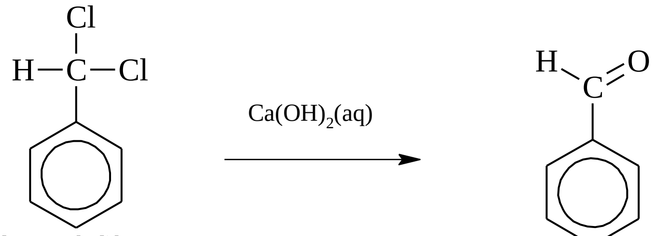
(chloromethyl)benzene (dichloromethyl)benzene (trichloromethyl)benzene

The chlorine atoms in these compounds are readily susceptible to substitution reactions.

For example, they are easily hydrolysed.



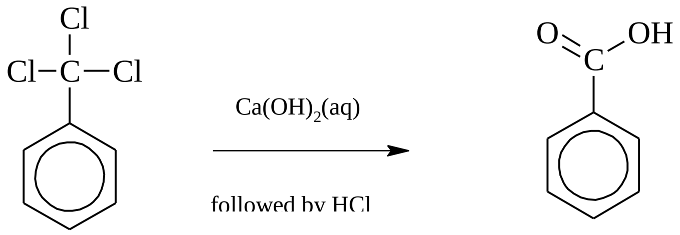
(chloromethyl)benzene phenylmethanol



(dichloromethyl)benzene

benzaldehyde
or benzenecarbaldehyde

Two –OH groups on the same carbon atom is called a gem-diol and eliminates a molecule of water to form the aldehyde.



(trichloromethyl)benzene

benzoic acid

or benzenecarboxylic acid

Each chlorine atom is replaced by –OH, this is unstable and eliminates water to form the carboxylic acid.

The lack of reactivity of halogen bound to the benzene ring is one cause of the persistence of some insecticides in the environment.

The classic case is that of DDT, which is also fat soluble and accumulates in the food chain. Its use is now strictly controlled.

Remember that halogen in a side chain of an aromatic compound is much more reactive than halogen directly bonded to a carbon atom in the benzene ring. The bond strength of the latter is greatly increased by participation in delocalisation as described above.

TOPIC 11 Organic compounds containing oxygen

Candidates should be able to:

(a) *describe the methods of forming primary and secondary alcohols from halogenoalkanes and carbonyl compounds ;*

(b) *recall:*

  (i) *the reactions of primary and secondary alcohols with hydrogen halides, ethanoyl chloride and carboxylic acids (to give sweet smelling esters);*

  (ii) *the dehydration reaction (elimination) of alcohols;*

(c) *describe the oxidation reactions of primary and secondary alcohols;*

(d) *show an awareness of the use of ethanol as a biofuel;*

(e) *explain the acidity of phenol and describe its reactions with bromine and with ethanoyl chloride;*

(f) *recall the colour reaction of some phenols with* $FeCl_3$ *solution and the use of this test to distinguish phenols from alcohols.*

Topic 11.1 Alcohols and phenol.

(a) **Methods of forming alcohols from halogenoalkanes.**

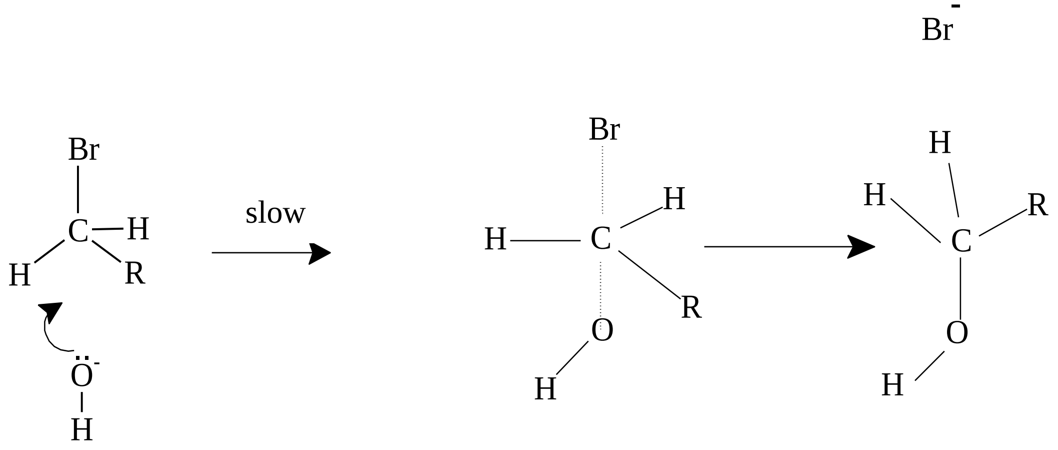
When iodomethane is warmed with **aqueous** sodium hydroxide, the corresponding alcohol is formed.

$$C_2H_5I + NaOH \rightarrow C_2H_5OH + NaI$$

Kinetic studies show that the reaction is second order overall, first order with respect to both the halogen compound and the hydroxide ion. (see kinetics Unit 5)

The mechanism is referred to as being S_N2. (Nucleophilic substitution by a bimolecular process)

e.g.



Nucleophilic attack
By the hydroxide ion

Formation of a transition state in which a partial bond is forming between the carbon and the oxygen atom and the carbon bromine bond is breaking.

Formation of product with the bromide ion leaving

Secondary halogenoalkanes are also hydrolysed by warm aqueous sodium hydroxide.

$$C_2H_5CHBrCH_3 \quad + \quad NaOH \rightarrow C_2H_5CH(OH)CH_3 \quad + \quad NaBr$$

2-bromobutane butan-2-ol

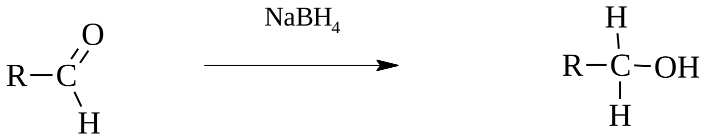
Formation of alcohols from carbonyl compounds

Reduction

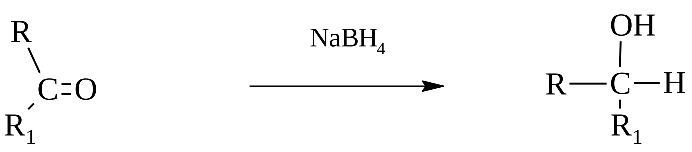
The carbonyl group may be reduced by a number of reagents, e.g. lithium tetrahydridoaluminate(III), sodium tetrahydridoborate(III), sodium and ethanol, zinc and ethanoic acid.

Sodium tetrahydridoborate(III) is very convenient because it can be used in aqueous media whereas lithium tetrahydridoaluminate(III) must be used in anhydrous conditions and involves a solvent such as ethoxyethane.

Examples



a primary alcohol



a secondary alcohol

(b) (i) Reactions of alcohols with hydrogen halides

The general reaction is

$$ROH + HX \rightarrow RX + H_2O$$

$$X = \text{-Cl, -Br or –I.}$$

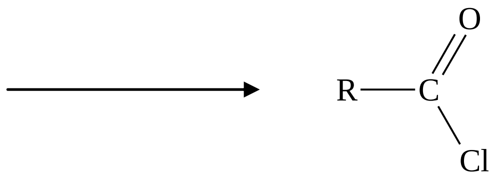
This is the basis of the **Lucas test** to distinguish primary, secondary and tertiary alcohols.
The test is based on the relative stabilities of carbocations.

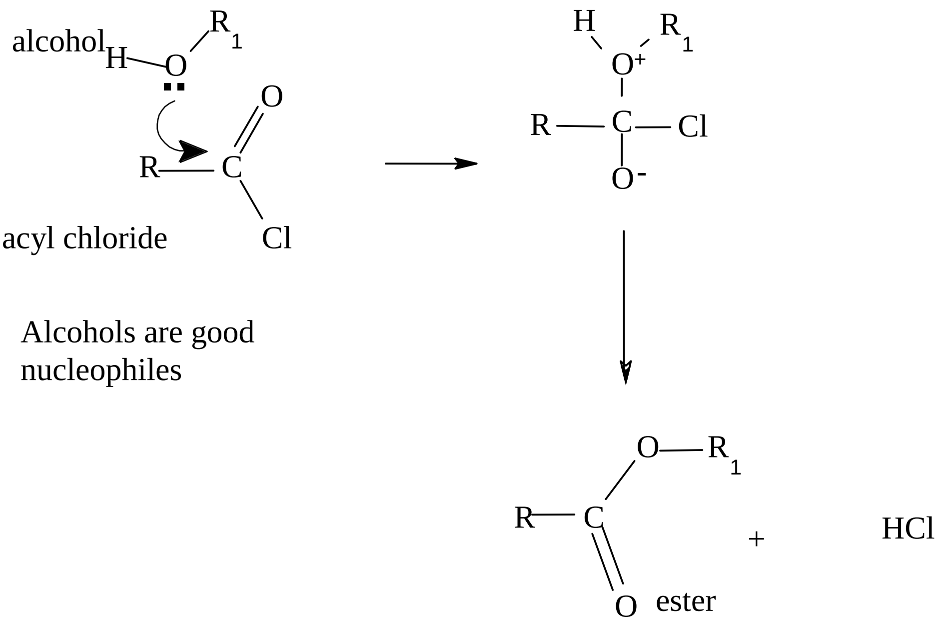
The alcohol is treated with anhydrous zinc chloride (a catalyst) in concentrated hydrochloric acid.

Tertiary alcohols react quickly to form the tertiary chloride compound, $R_3C\text{-}Cl$. This is insoluble and appears almost instantly as cloudiness in the solution.
The secondary alcohol will give some cloudiness after some time but the primary alcohol gives no indication of reaction.

The specification only refers to primary and secondary alcohols.
Reactions with acyl chlorides, such as ethanoyl chloride, CH_3COCl.

Acyl or acid chlorides have the general formula





The result is a sweet smelling compound called an ester.

Example

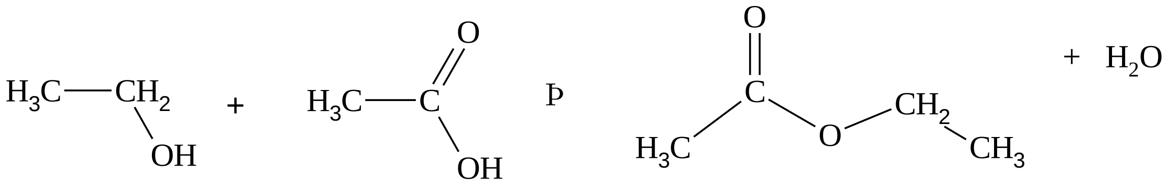
$$CH_3COCl \ + \ C_2H_5OH \ \rightarrow \ CH_3COOC_2H_5 \ + \ HCl$$

ethanoyl chloride ethanol ethyl ethanoate

Reaction with carboxylic acids.

Alcohols react with carboxylic acids in the presence of a small amount of concentrated sulfuric acid to form esters. This reaction is often called *esterification*.

$$ROH \ + \ R_1COOH \ \square \ R_1COOR \ + \ H_2O$$



ethanol ethanoic acid ethyl ethanoate

The concentrated sulfuric acid acts as a catalyst. Its function is to protonate the carboxylic acid and the resulting positive species undergoes nucleophilic attack by the alcohol. Elimination of a proton and a molecule of water results in the formation of the ester.

Another method uses anhydrous hydrogen chloride as the catalyst (Fischer-Speier Method).

(ii) **Elimination reactions of alcohols**

When ethanol is heated with an excess of concentrated sulfuric acid to 180 ^{o}C, ethene is formed by elimination of a molecule of water.

$$C_2H_5OH \xrightarrow[\substack{\text{concentrated } H_2SO_4 \\ 180\ ^{o}C}]{} C_2H_4 \ + \ H_2O$$

The same reaction can be achieved by passing ethanol vapour over aluminium oxide or porous pot above 300 ^{o}C.

Alcohols may also be dehydrated by treated with hot concentrated phosphoric acid.

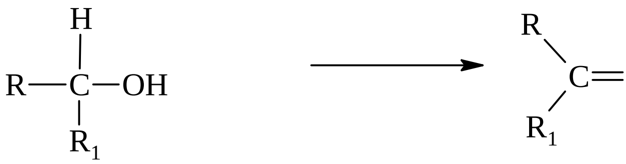
(c) **Oxidation of alcohols.**

The usual reagent for oxidising alcohols is aqueous potassium or sodium dichromate and aqueous sulfuric acid.

Primary alcohols are oxidised to aldehydes and carboxylic acids; secondary alcohols are oxidised to ketones. Tertiary alcohols are resistant to oxidation but under severe conditions may yield carboxylic acids containing fewer carbon atoms than the parent alcohol.

Primary $$\underset{}{RCH_2OH} \rightarrow \underset{\text{aldehyde}}{RCHO} \rightarrow \underset{\text{carboxylic acid}}{RCOOH}$$

Secondary



ketone

The oxidation of the primary alcohol can be considered as a two-stage process. To obtain the aldehyde, mild conditions must be used with the aldehyde distilled off as it forms. Complete oxidation of a primary alcohol to the carboxylic acid may be avoided.

More vigorous conditions result in the acid.

$$\left.\begin{array}{l} Cr_2O_7^{2-} + 14H^+ + 6e^- \rightarrow 2Cr^{3+} + 7H_2O \\ RCH_2OH \rightarrow RCHO + 2H^+ + 2e^- \end{array}\right\} \text{Half-equations}$$

$$Cr_2O_7^{2-} + 8H^+ + 3RCH_2OH \rightarrow 3RCHO + 2Cr^{3+}\ 7H_2O$$

$$\left.\begin{array}{l} Cr_2O_7^{2-} + 14H^+ + 6e^- \rightarrow 2Cr^{3+} + 7H_2O \\ RCH_2OH + H_2O \rightarrow RCOOH + 4H^+ + 4e^- \end{array}\right\} \text{Half-equations}$$

$$2Cr_2O_7^{2-} + 16H^+ + 3RCH_2OH \rightarrow 3RCOOH + 4Cr^{3+}\ 11H_2O$$

A similar redox equation can be constructed for a secondary alcohol being oxidised to a ketone.

Primary, secondary and tertiary alcohols may be distinguished by their reactions with acidified dichromate.

Aldehydes and ketones may be obtained by passing the alcohol vapour over a copper catalyst at 500 ^oC.

$$RCH_2OH \xrightarrow{Cu/500\ ^oC} RCHO + H_2$$

$$R_2CHOH \xrightarrow{Cu/500\ ^oC} R_2CO + H_2$$

(d) Ethanol can be used as a biofuel which is carbon neutral. For many years ethanol has been blended with petrol to form a fuel called “Gasohol”.

In growing, plants utilise the process of photosynthesis to form carbohydrates.

e.g.

$$6CO_2 + 6H_2O \xrightarrow[\text{chlorophyll}]{\text{sunlight}} C_6H_{12}O_6 + 6O_2$$

The carbohydrate material from plants such as starch, sugars etc. may be fermented using enzymes from the microorganism, yeast.

e.g. Starch, $(C_6H_{10}O_5)_n$ is hydrolysed to form the disaccharide maltose, $C_{12}H_{22}O_{11}$, which changes under the influence of enzymes from yeast at about 35 ^{o}C to form ethanol and carbon dioxide.

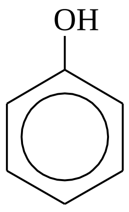
$$C_{12}H_{22}O_{11} + H_2O \rightarrow 2C_6H_{12}O_6$$

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2$$

Combustion of the ethanol forms water and carbon dioxide. The carbon dioxide simply replaces that used in photosynthesis to form the plant carbohydrate.

(e) **Phenol**

Phenol itself is a toxic crystalline compound, C_6H_5OH. Skin contact with phenol must be avoided.

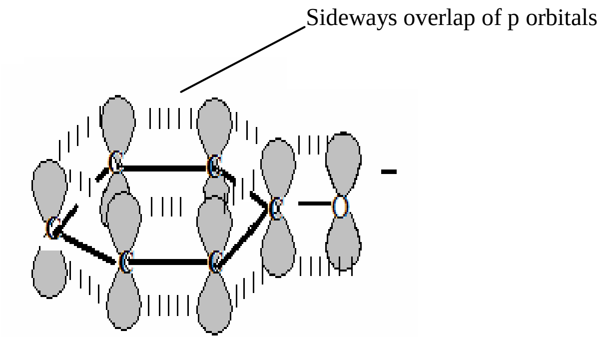


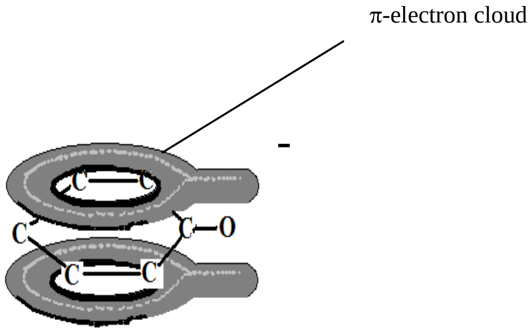
phenol

In aqueous solution, phenol is acidic, sometimes called *carbolic acid*. This contrasts with the alcohols which are neutral in aqueous solution..

$$C_6H_5OH + H_2O \rightleftharpoons \underbrace{C_6H_5O^-}_{\text{phenoxide ion}} + H_3O^+$$

The phenoxide ion is stabilised by incorporation of the p-orbital of the oxygen atom into the delocalised π-electrons of the ring.





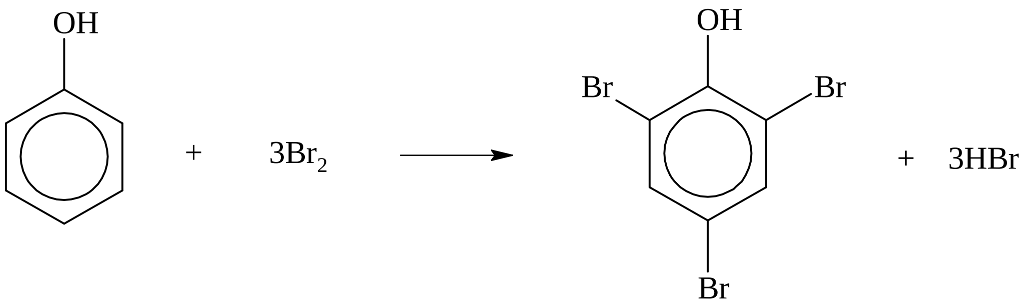
Some reactions of phenol

Phenol, although sparingly soluble in water, reacts with aqueous sodium hydroxide.

$$C_6H_5OH + NaOH \rightarrow \underset{\text{Sodium phenoxide}}{C_6H_5ONa} + H_2O$$

The presence of the –OH group activates the benzene ring to electrophilic reagents.

Substitution takes place in the 2 and 4 positions. With bromine or bromine water the 2,4,6-tribromo derivative is obtained.



2,4,6-tribromophenol

The trichloro- derivative can also be formed. This may be used as an antiseptic, TCP.

2,4,6-tribromophenol forms as a whitish precipitate when aqueous phenol is treated with bromine water.

The –OH group in phenol differs from the –OH group in an alcohol in that it cannot be esterified by reaction with a carboxylic acid and concentrated sulfuric acid.

It will react with an acyl chloride to form an ester.

$$C_6H_5OH + CH_3COCl \rightarrow \underset{\text{phenyl ethanoate}}{CH_3COOC_6H_5} + HCl$$

(f) The –OH group attached to a benzene ring is called a **phenolic** group. Such groups often react withm aqueous iron(III) chloride to form an intensely coloured complex, violet, blue or green. Phenol itself gives an intense violet colour. Alcohols do not give such a colour with aqueous iron(III) chloride.

Topic 11.2 Aldehydes and ketones

Candidates should be able to:

(a) *describe the formation of aldehydes and ketones by the oxidation of primary and secondary alcohols respectively;*

(b) *describe how aldehydes and ketones may be distinguished by their relative ease of oxidation using Tollens' reagent and Fehling's reagent ;*

(c) *recall the use of $NaBH_4$ to reduce aldehydes and ketones and state the organic products formed*

(d) *describe the reaction of aldehydes and ketones with 2,4-dinitrophenylhydrazine reagent as a nucleophilic addition-elimination (condensation) reaction and explain the use of this reaction in showing the presence of a carbonyl group and in identifying specific aldehydes and ketones by determining the melting temperatures of the purified products;*

(e) *describe and understand the mechanism of the addition of HCN to carbonyl compounds as an example of a nucleophilic addition reaction ;*

(f) *describe how the triiodomethane (iodoform) test is carried out and explain its use in detecting CH_3CO – groups or their precursors.*

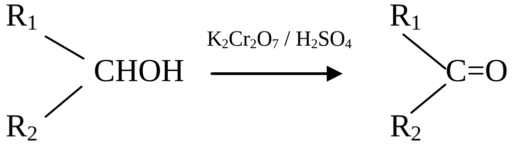
(a) Aldehydes and ketones are formed by the oxidation of primary and secondary alcohols respectively with acidified aqueous sodium or potassium dichromate(VI). See Topic 11.1 above.

The formation of the aldehyde requires mild conditions to prevent complete oxidation to the carboxylic acid.

The reactions can be written

$$RCH_2OH \xrightarrow{K_2Cr_2O_7\ /\ H_2SO_4} RCHO + H_2O$$

and



$$R_1R_2CHOH \xrightarrow{K_2Cr_2O_7\ /\ H_2SO_4} R_1R_2C{=}O$$

(b) Aldehydes and ketones may be distinguished by the resistance of ketones to oxidation.

Two common reagents are Fehling’s solutions and Tollens’ reagent.

Fehling’s solutions are

Solution 1 aqueous copper(II) sulfate

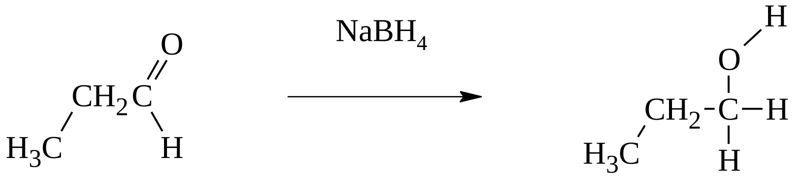
Solution 2 sodium potassium tartrate (potassium sodium 2,3-dihydoxybutanoate) dissolved in aqueous sodium hydroxide

The substance under test is warmed with equal volumes of the above solutions. If an aldehyde is present, a reddish colour will develop as copper(I) oxide, Cu_2O, is formed.
Ketones do not give this reaction.

Tollens' reagent is an ammoniacal solution of silver nitrate, it contains the diamminesilver(I) ion, $[NH_3)_2Ag]^+$. The reagent should always be freshly prepared and unused solution together with the used test solutions destroyed with dilute nitric acid after use. This prevents the possible formation of explosive silver compound, silver fulminate.
When a small amount of an aldehyde is added to cold Tollens' reagent and the mixture gently warmed, a black precipitate of silver is formed or a silver mirror is seen on the inside of the test tube.
Ketones do not give this reaction.

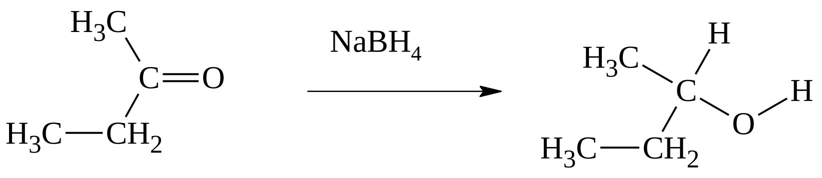
(c) **Reduction of the carbonyl group**

The carbonyl group may be reduced by a number of reagents, e.g. lithium tetrahydridoaluminate(III), sodium tetrahydridoborate(III), sodium and ethanol, zinc and ethanoic acid.
Sodium tetrahydridoborate(III), $NaBH_4$, is very convenient because it can be used in aqueous media whereas lithium tetrahydridoaluminate(III) must be used in anhydrous conditions and involves a solvent such as ethoxyethane.



propanal

propan-1-ol
a primary alcohol

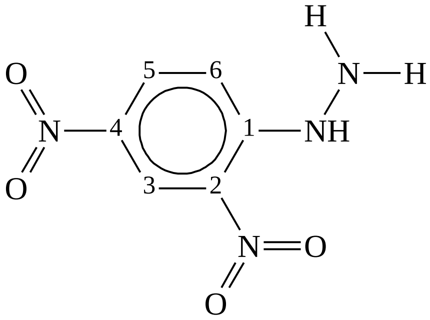


butan-2-ol
a secondary alcohol

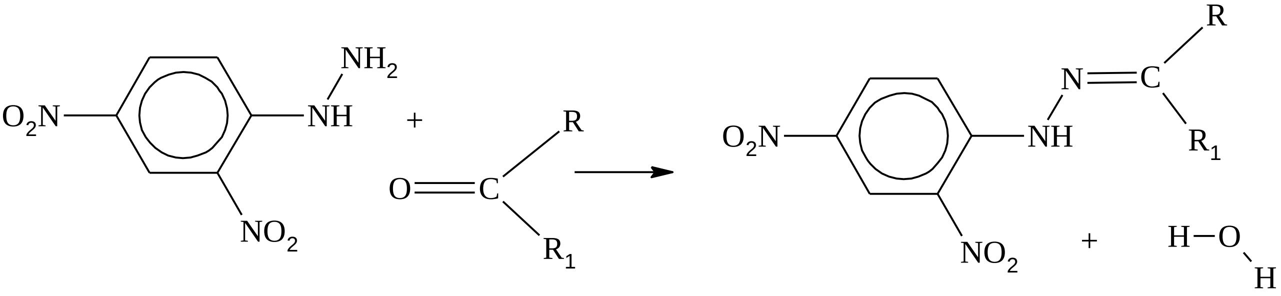
(d) **Addition-elimination (condensation) reactions.**

In these reactions the carbonyl undergoes nucleophilic attack but the adduct loses a small molecule, usually water.

One of the most useful reagents is 2, 4-dinitrophenylhydrazine reagent. This is a solution of 2,4-dinitrophenylhydrazine in a suitable solvent. When the carbonyl compound reacts with this reagent the result is a yellow or orange solid (the corresponding hydrazone). These derivatives may be isolated and purified and the original carbonyl compound identified from the melting point of the 2,4-dinitrophenylhydrazone that is formed.



2,4 - dinitrophenylhydrazine



The product is called a 2,4 – dinitrophenylhydrazone.

If R_1 or R_2 is hydrogen then the reactant is an aldehyde.

Examples of the melting points of 2,4-dinitrophenylhydrazine derivatives of common carbonyl compounds.

Carbonyl compound	**Melting point of the 2,4-dinitrophenylhydrazone / °C**
ethanal	168
benzaldehyde (benzenecarbaldehyde)	237
salicyladehyde	252 decomposes
propanone	126
butanone	115

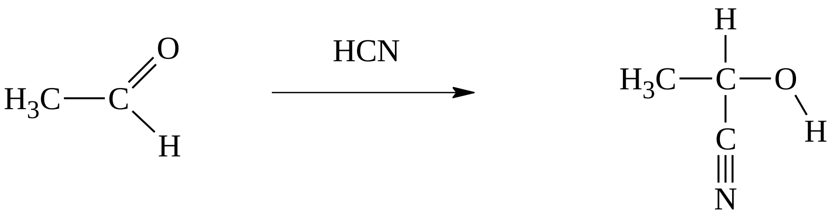
(e) **Nucleophilic addition of HCN**

Carbonyl compounds will add on a molecule of hydrogen cyanide, HCN. The rate is slow but is greatly increased by addition of alkali or cyanide ions.

Alkali will neutralise some of the HCN molecules giving a higher concentration of cyanide ions.

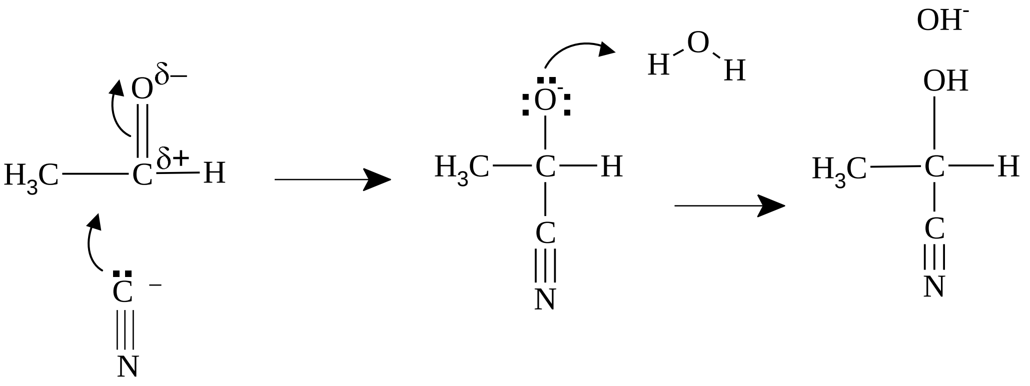
$$HCN + OH^- \ \square\ CN^- + H_2O$$

e.g. $CH_3CHO + HCN \rightarrow CH_3CH(OH)CN$



2-hydroxypropanenitrile

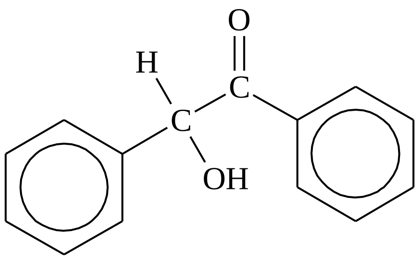
The mechanism for this reaction is *nucleophilic addition*.



Nucleophilic attack by cyanide ion at the carbon atom of the polar carbonyl group

The resulting negative ion gains a proton from water (solvent) or any other available molecule such as HCN

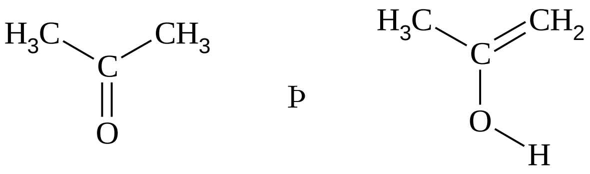
Benzenecarbaldehyde, benzaldehyde, C_6H_5CHO does not react with cyanide ions in this way. When it is refluxed with ethanolic potassium cyanide, the product is $C_6H_5CH(OH)COC_6H_5$.



The haloform reaction.

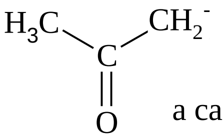
This is a reaction which is given by methyl ketones of the form CH_3CO-X and alcohols which can be oxidised to methyl ketones. e.g., ethanol, CH_3CH_2OH and propan2-ol, $CH_3CH(OH)CH_3$.
A useful diagnostic test for methyl ketones is the iodoform reaction.
Iodoform is triiodomethane, CHI_3. It is a yellow, insoluble compound with a characteristic antiseptic smell.

The procedure is to add the compound to **either** iodine and aqueous sodium hydroxide **or** aqueous potassium iodide and aqueous sodium chlorate(I), NaClO, if a yellow precipitate of triiodomethane is formed then the methyl ketone group is present.
It is possible for a methyl ketone to exist in the enol state.

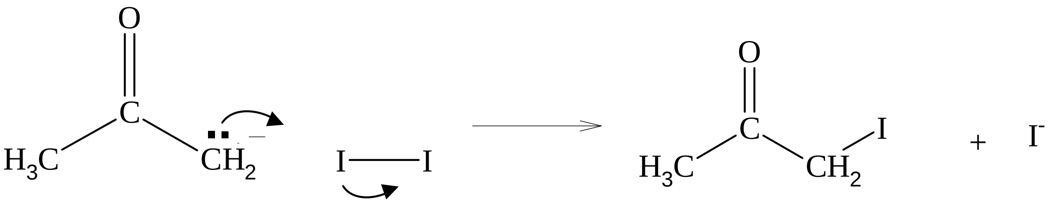


ketone enol

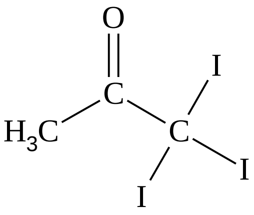
In the presence of alkali, th from the e gative ion, a carbanion.
This negative ion will react with iodine



a carbanion



This then undergoes further iodination to form



In the presence of alkali $CH_3COCI_3 + OH^- \rightarrow CH_3COO^- + CHI_3$

triiodomethane

Topic 11.3 (a) (i)

Candidates should be able to:

(a) *(i)* *describe the physical properties of lower carboxylic acids (volatility and solubility) and relate these to the presence of hydrogen bonding;*

(ii) *discuss and show understanding of the relative acidities of carboxylic acids, phenol, alcohols and water, and appreciate that carboxylic acids liberate* CO_2 *from carbonates and hydrogencarbonates but that phenol does not;*

(iii) *recall that phenols in aqueous solution give colour reactions with iron(III) chloride solution;*

(b) *recall the following listed processes and apply knowledge of them to the elucidation of organic problems:*

(i) *the formation of carboxylic acids from alcohols and aldehydes ;*

(ii) *the formation of aromatic carboxylic acids by the oxidation of methyl sidechains with alkaline MnVII and subsequent acidification;*

(iii) *methods of converting the acids to esters and acid chlorides, and the hydrolyses of these compounds;*

(iv) *the behaviour of acids on reduction with* $LiAlH_4$*; acid decarboxylation and its use in structure determination;*

(c) *recall the following listed processes and apply knowledge of them to the elucidation of organic problems:*

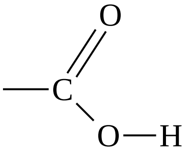
(i) *methods of converting carboxylic acids to amides;*

(ii) *formation of nitriles from halogenoalkanes;*

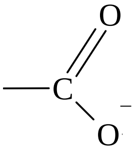
(iii) *the reduction of nitriles with* $LiAlH_4$ *and the hydrolysis of nitriles and amides;*

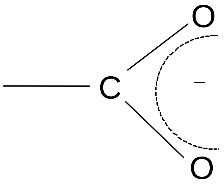
(d) *recall the industrial importance of ethanoic anhydride and polyesters.*

The carboxyl group,-COOH, is



The carboxylate ion,-COO$^-$, is or

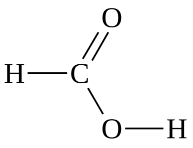




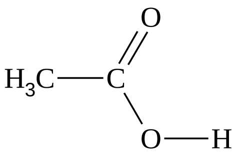
The arc indicates delocalised electrons. The two oxygen atoms are identical.

The alkanoic acids

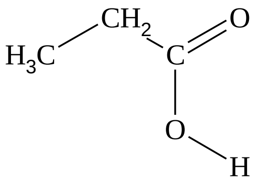
The first four members are



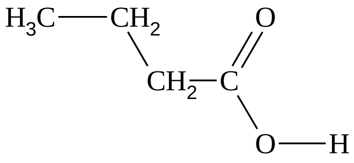
methanoic acid



ethanoic acid



propanoic acid



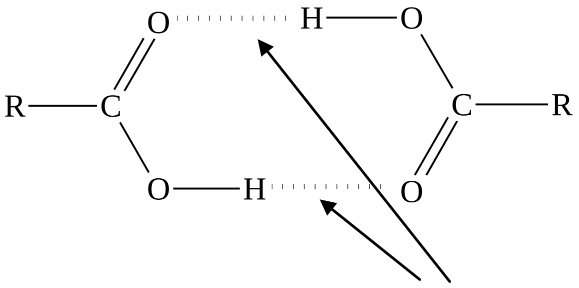
butanoic acid

These acids are weak acids although they are much stronger than phenol. They liberate carbon dioxide from aqueous sodium carbonate or aqueous sodium hydrogencarbonate. Phenol does not.

Acid	HCOOH methanoic acid	CH_3COOH ethanoic acid	CH_3CH_2COOH propanoic acid	$CH_3CH_2CH_2COOH$ butanoic acid
pK_a at 298K	3.75	4.76	4.87	4.82
b.p/^oC	101	118	141	154
solubility in water	very soluble	very soluble	soluble	not soluble

The boiling points of these acids are higher than would be expected from their molar masses.

The reason is that there is extensive hydrogen bonding within the liquids. Evidence shows that carboxylic acids often form dimers through hydrogen bonding.



Hydrogen bonds

The solubility in water is favoured by hydrogen bonding between the carboxyl group and water molecules but as the carbon chain lengthens, its hydrophobic nature reduces the solubility in water.

(ii) The pK_a values above show that the acids become weaker as molar mass increases.

$$pK_a = -\log K_a$$

The pK_a value for phenol is approximately 10. i.e. $K_a = 10^{-10}$ mol dm^{-3}

Since the value of K_w for water is 10^{-14} mol^{2}dm^{-6} at 298K, the order of acidity is

carboxylic acid > phenol> water.

The pK_a values for carbonic acid, H_2CO_3, and the hydrogencarbonate ion, HCO_3^-, are 6.37 and 10.32 respectively. It follows that carboxylic acids are strong enough to release carbon dioxide from aqueous sodium carbonate and aqueous sodium hydrogencarbonate but phenol will not, since it is not a strong enough acid.

(iii) It must be remembered that phenol gives a violet coloration with aqueous iron(III) chloride. When neutral aqueous iron(III) chloride is added to an aqueous solution of the ammonium salt of a lower carboxylic acid, a reddish brown colour is observed. If repeated with benzoic acid a buff coloration is observed.

(b) (i) Carboxylic acids are formed from alcohols and aldehydes by oxidation with aqueous potassium or sodium dichromate(VI) acidified with sulfuric acid.

$$CH_3CH_2CH_2OH \xrightarrow{K_2Cr_2O_7 \,/\, H_2SO_4} CH_3CH_2COOH + H_2O$$

This redox reaction may be balanced from the ion/electron half equations

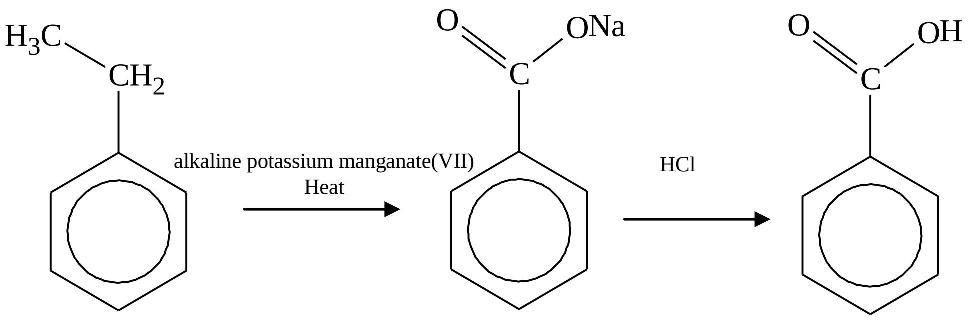
$$Cr_2O_7^{2-} + 14H^+ + 6e^{v} \rightarrow 2Cr^{3+} + 7H_2O$$

$$CH_3CH_2CH_2OH + H_2O \rightarrow CH_3CH_2COOH + 4H^+ + 4e^-$$

for the aldehyde

$$CH_3CH_2CHO + H_2O \rightarrow CH_3CH_2COOH + 2H^+ + 2e^-$$

Aromatic carboxylic acids may be formed by the oxidation of a side chain of an aromatic compound by heating with alkaline potassium manganate(VII). The product is a salt of the acid since the conditions are alkaline and the mixture must be acidified with hydrochloric acid to release the free acid.

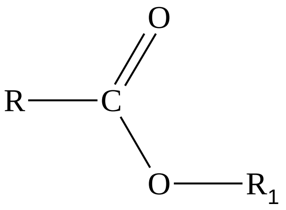


ethylbenzene sodium benzenecarboxylate benzenecarboxylic acid

Benzenecarboxylic acid is almost insoluble at room temperature and can be filtered from the reaction mixture and purified by recrystallisation from hot water.

(iii) Esters

Esters are sweet smelling compounds of general formula $RCOOR_1$.

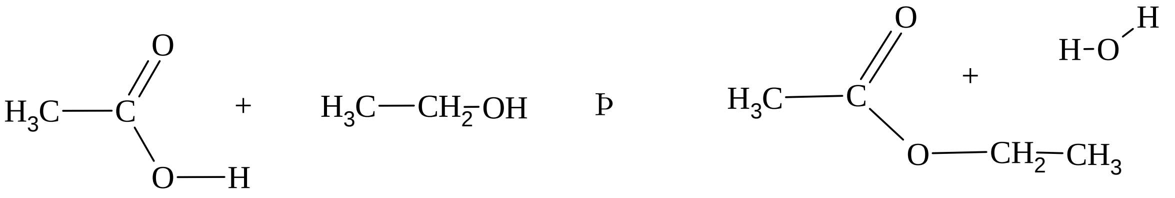


They are prepared by heating a carboxylic acid and an alcohol in the presence of an acid catalyst such as concentrated sulfuric acid.

$$RCOOH + R_1OH \rightarrow RCOOR_1 + H_2O$$

$$CH_3COOH + C_2H_5OH \rightarrow CH_3COOC_2H_5 + H_2O$$

ethanoic acid ethanol ethyl ethanoate



ethyl ethanoate

Sometimes it is more convenient to use dry hydrogen chloride as the catalyst. This is called the *Fischer-Speier* method.

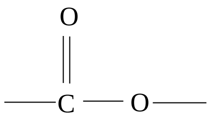
Alternatively, the alcohol may be treated with an acid chloride. *(see below*).

When esters are heated with dilute mineral acids such as hydrochloric and sulfuric acids, they are hydrolysed.

$$RCOOR_1 + H_2O \xrightarrow{H^+} RCOOH + R_1OH$$

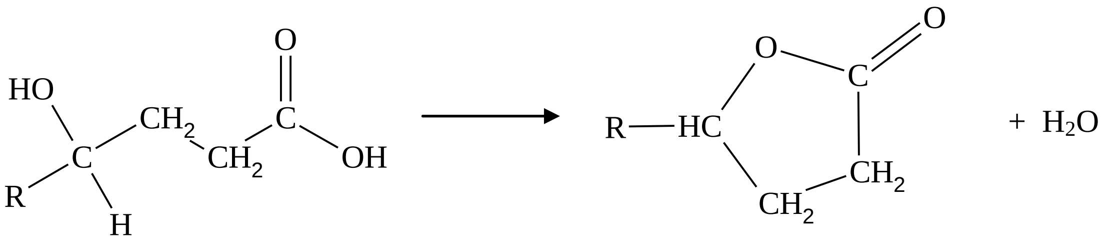
$$RCOOR_1 + NaOH \rightarrow RCOONa + R_1OH$$

Notice that alkaline hydrolysis gives the sodium salt of the carboxylic acid.



The ester group

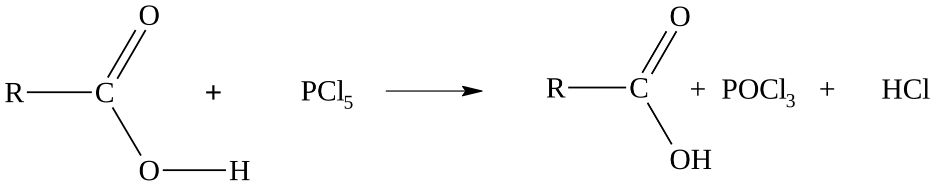
Sometimes it is possible to form an **internal** ester from some hydroxyacids.



The ring structure of such an ester is broken on hydrolysis.

Acid chlorides

The reaction between carboxylic acids and phosphorus pentachloride yields acid or acyl chlorides.



An acid chloride

e.g $CH_3COOH + PCl_5 \rightarrow CH_3COCl + POCl_3 + HCl$

ethanoyl chloride

Alternative reagents are phosphorus trichloride and sulphur dichloride oxide.

$3CH_3COOH + PCl_3 \rightarrow 3CH_3COCl + H_3PO_3$

$CH_3COOH + SOCl_2 \rightarrow CH_3COCl + SO_2 + HCl$

Acid chlorides are extremely reactive and are acylating reagents. This means they are reagents which can introduce the RCO- group into a molecule.

Ethanoyl chloride, CH_3COCl is more reactive than benzenecarbonyl chloride (benzoyl chloride), C_6H_5COCl.

Ethanoyl chloride is readily hydrolysed by water

$$CH_3COCl + H_2O \rightarrow CH_3COOH + HCl$$

When a bottle of ethanoyl chloride is opened, misty fumes of hydrogen chloride are seen as the compound reacts with atmospheric water vapour.

Benzoyl chloride reacts much more slowly than ethanoyl chloride.

(iv) Reduction by lithium tetrahydridoaluminate(III), $LiAlH_4$.

$$R.COOH \xrightarrow{LiAlH_4} RCH_2OH$$

Sometimes written for simplicity as

$$R.COOH + 4[H] \rightarrow RCH_2OH + H_2O$$

This reagent will not reduce any carbon-carbon double bonds in the carbon chain of the acid.

It is important to note that unlike aldehydes and ketones, carboxylic acids **are not** reduced by sodium tetrahydridoborate(III).

Decarboxylation.

If a carboxylic acid or its sodium salt is strongly heated with sodalime, a carbon atom is removed.

$$CH_3CH_2COOH + 2NaOH \rightarrow C_2H_6 + Na_2CO_3$$

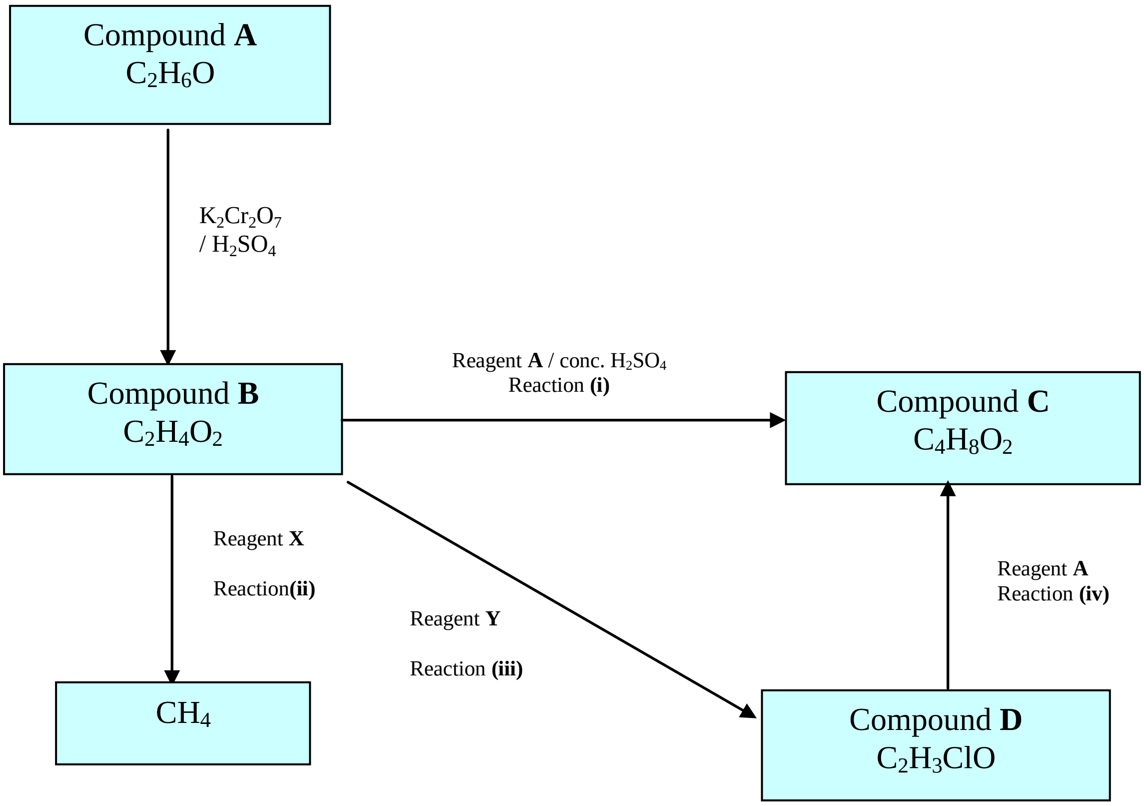
This reaction is called *decarboxylation*

$$CH_3CH_2COONa + NaOH \rightarrow C_2H_6 + Na_2CO_3$$

All the reactions in **Topic 11.3(b)** may be used in examination questions for students to elucidate structures in organic problems.

A straightforward example is shown below.

Study the following reaction scheme.



Write full displayed structural formulae for compounds **A, B C** and **D**.

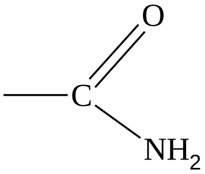
Identify reagents **X** and **Y**.

Write balanced equations for reactions **(i), (ii), (iii)** and **(iv).**

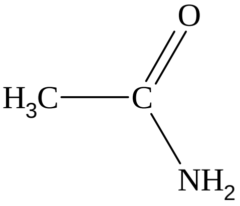
(c) (i) Conversion of carboxylic acids to amides.

Amides

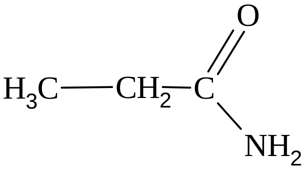
The amide or amido- group is



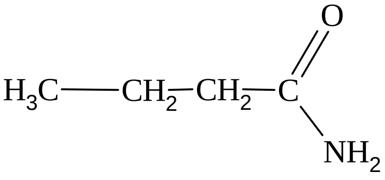
Aliphatic amides are



ethanamide

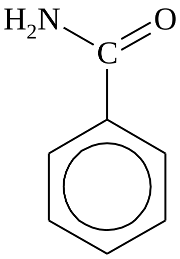


propanamide



butanamide

The simplest aromatic amide is



benzamide

or benzenecarboxamide

Amides maybe formed from carboxylic acids by a variety of methods.

- By dehydration of the ammonium salt of the acid.

Excess of the acid is refluxed with ammonium carbonate for several hours.

$$(NH_4)_2CO_3 + RCOOH \rightarrow RCOONH_4 + CO_2 + H_2O$$

The excess acid prevents

$$RCOONH_4 \rightarrow RCOOH + NH_3$$

The ammonium salt dehydrates on heating

$$RCOONH_4 \rightarrow RCONH_2 + H_2O$$

- Via the acid chloride

$$RCOOH + PCl_5 \rightarrow RCOCl + POCl_3 + HCl$$

$$RCOCl + NH_3 \rightarrow RCONH_2 + HCl$$

- Via the ester

The carboxylic acid can be converted to an ester. Esters react with ammonia to form amides (ammonolysis).

e.g. $CH_3COOC_2H_5 + NH_3 \rightarrow CH_3CONH_2 + C_2H_5OH$

(ii) Formation of nitriles.

Nitriles.

The nitrile group is $—C{\equiv}N$

CH_3CN is called ethanenitrile. The name is based on the hydrocarbon with the same number of carbon atoms. C_6H_5CN is cyanobenzene or phenyl cyanide

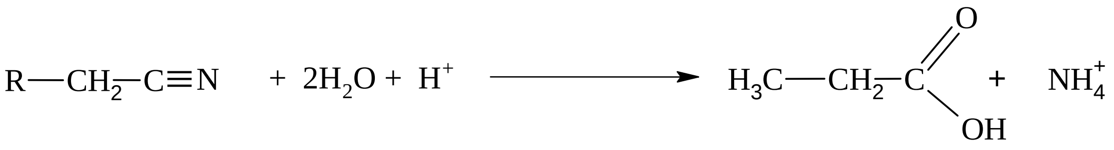
A cyanide ion can be introduced into a halogenoalkane by nucleophilic substitution or into a carbonyl compound by nucleophilic addition. Both these methods provide a means of increasing the length of a carbon chain in an organic molecule.

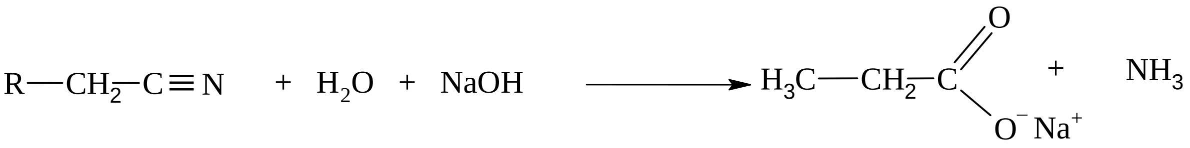
The halogenoalkane is refluxed with ethanolic potassium cyanide.

$$RCH_2I + KCN \rightarrow RCH_2CN + HI$$

Reactions of nitriles

Nitriles are hydrolysed by both aqueous strong acids (HCl and H_2SO_4) and by aqueous sodium hydroxide.





Note that nitriles evolve ammonia when heated with aqueous sodium hydroxide.

This also true of amides.

$$CH_3CONH_2 + NaOH \rightarrow CH_3COONa + NH_3$$

Primary amines, RCH_2NH_2, do not give ammonia with NaOH

Nitriles may be reduced to primary amines by lithium tetrahydridoaluminate(III).

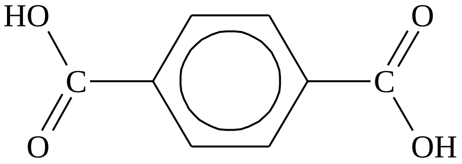
$$R—CH_2—C{\equiv}N \xrightarrow{LiAlH_4} R—CH_2—CH_2—NH_2$$

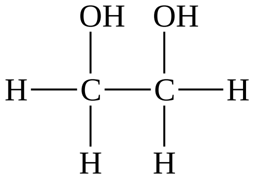
a primary amine

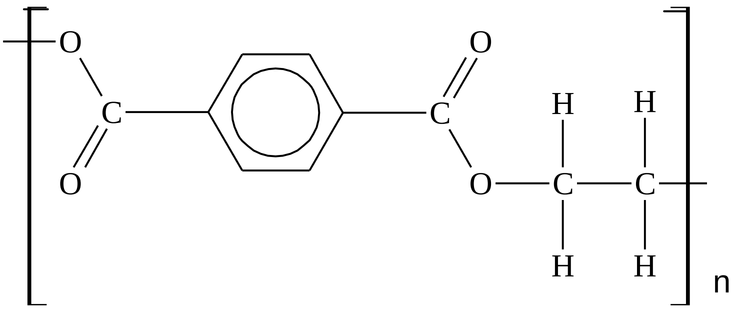
(d) Polyesters

The ester linkage is important in polyesters such as Terylene. In this polymer the carboxyl groups of 1.4-benzenedicarboxylic acid combine with the –OH groups of ethane-1,2-diol.

e.g.



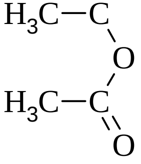




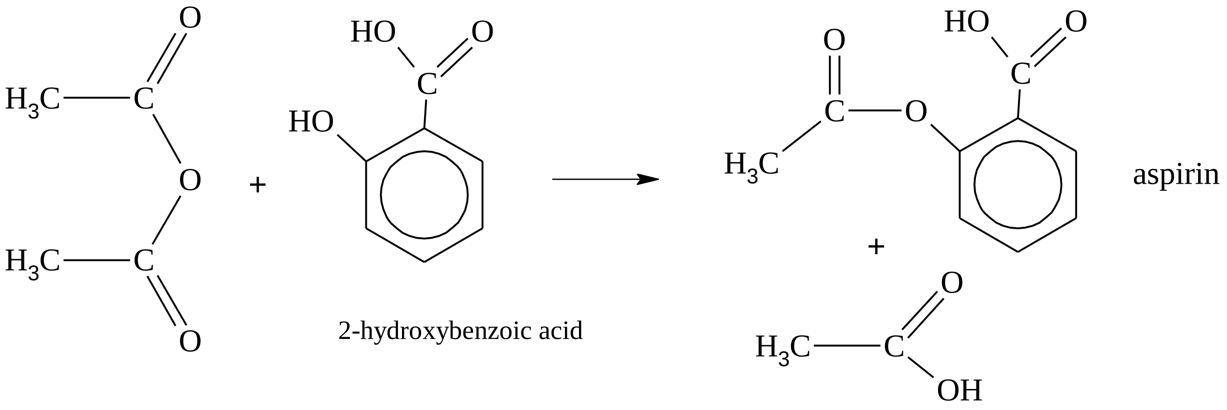
In the manufacture of Terylene the two monomers are heated. (details given later)
In some processes the dimethyl ester of 1,4-benzenedicarboxylic acid is used.
There are many different types of polyester. Their structures depend upon the monomers used.
The diols may be ethane-1,2-diol or 1,2-diydroxypropane and the dicarboxylic acids, 1,4-benzenedicarboxylic acid, 1,6-hexanedioic acid and 1,10-decanedioic acid.

Polyesters are used in the textile industry either as a spun fibre or blended with natural fibres such as cotton to form polycotton fibres.

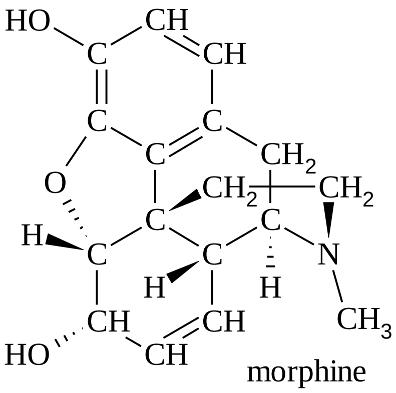
Ethanoic anhydride

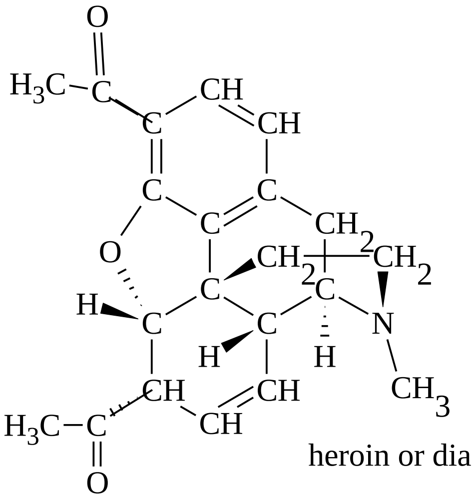


This is an important acylating agent which introduces the CH_3CO- group into compounds.
e.g. it is used to react with 2-hydroxybenzoic acid to form aspirin.



In recent times, concern has been shown about supplies of ethanoic anhydride; especially for the illegal manufacture of heroin. Morphine has two –OH groups which can be ethanoylated (acetylated) to form a diethanoyl derivative called diacetyl morphine. Diacetyl morphine is also known as *diamorphine* or *heroin.*


morphine


heroin or diamorphine

Topic 12 Organic compounds containing nitrogen.

Candidates should be able to:

(a) describe the preparation of primary aliphatic and aromatic amines from halogenoalkanes and nitrobenzenes respectively;

(b) recall that, and explain why, amines are basic;

(c) recall the ethanoylation reaction of primary amines using ethanoyl chloride;

(d) compare the reaction of primary aliphatic and aromatic amines with cold nitric(III) acid (nitrous acid), describe the coupling of benzenediazonium salts with phenols such as naphthalen-2-o1 and aromatic amines and the importance of this reaction for azo dyes; recall the role of the –N=N– chromophore in azo dyes and be aware that this group links two aromatic rings;–

(e) recall the general formulae of α-amino acids and discuss their amphoteric and zwitterionic nature;

(f) write down the possible dipeptides formed from two different α-amino acids;

(g) understand the formation of polypeptides and proteins and have an outline understanding of primary, secondary and tertiary protein structure;

(h) show an awareness of the importance of proteins in living systems, e.g. as enzymes;

(i) recall in outline the mode the synthesis and the industrial importance of polyamides and understand the similarity of the peptide linkage to that in naturally occurring proteins.

(a) Primary amines.

Aliphatic primary amines may be prepared from halogenoalkanes.

The halogenoalkane (usually the iodide) is heated with an ethanolic solution of ammonia in a sealed tube immersed in boiling water.

$$RCH_2I + NH_3 \rightarrow RCH_2NH_2 + HI$$

Since the amine is basic, the salt is formed $RCH_2NH_3^+ I^-$.

Also there will be some $(RCH_2)_2NH$ and $(RCH_2)_3N$

Alternatively the halogenoalkane may be converted to the nitrile which may be subsequently reduced to the primary amine.

$$RCH_2I + KCN \rightarrow RCH_2CN + KI$$

$$RCH_2CN \xrightarrow[\text{lithium tetrahydridoaluminate(III)}]{} RCH_2CH_2NH_2$$

Note this is a synthetic method to introduce another carbon atom into the carbon chain.

Preparation of the aromatic primary amine, phenylamine, $C_6H_5NH_2$.

The laboratory preparation of phenylamine involves the reduction of nitrobenzene with tin and concentrated hydrochloric acid. The mixture is heated and the phenylamine produced forms phenylammonium hexachlorostannate(IV).

$$2C_6H_5NO_2 + 18HCl + 3Sn \rightarrow (C_6H_5NH_3^+)_2[SnCl_6]^{2-} + 2[SnCl_6]^{2-} + 4H_2O + 4H^+$$

Sodium hydroxide is then added to release phenylamine.

$$(C_6H_5NH_3^+) + OH^- \rightarrow C_6H_5NH_2 + H_2O$$

The phenylamine is then removed by steam distillation and purified by extraction with ethoxyethane and final distillation.

(b) The basic nature of amines.

All amines are basic because the nitrogen atom caries a non-bonding pair of electrons which can accept a proton.

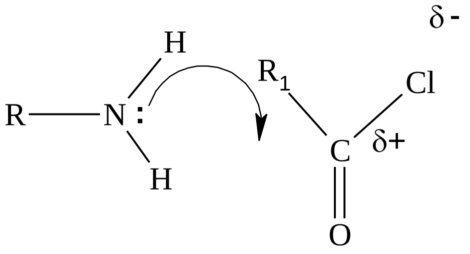
$RNH_2 + H_2O \text{ Þ } RNH_3^+ + OH^-$ Some pK_b values are

Ammonia	NH_3	4.75	$K_b = 1.78 \times 10^{-5}$
Ethylamine	$C_2H_5NH_2$	3.27	$K_b = 5.37 \times 10^{-4}$
phenylamine	$C_6H_5NH_2$	9.35	$K_b = 4.47 \times 10^{-10}$

So ethylamine is a stronger base than ammonia which in turn is stronger than phenylamine.

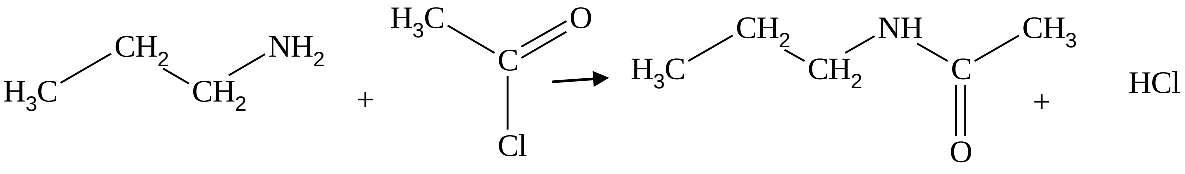
(c) Primary amines react with ethanoyl chloride to form substituted amides.

The amines are nucleophiles which will attack the positive centre in an acid chloride.



The resulting intermediate then loses a proton and a chloride ion to give R-NHOC-R_1 which is a substituted amide.

e.g.



propylamine N-propyl ethanamide

Note the nomenclature. Using "N" indicates that the alkyl group is attached to the nitrogen atom.

(d) **Reaction with nitrous acid**

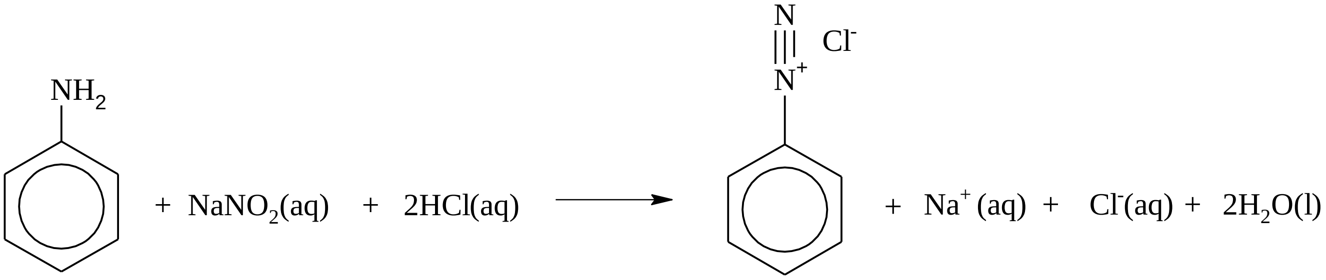
Nitrous acid is always prepared from sodium nitrite (sodium nitrate(III)) and hydrochloric acid when required.

Aliphatic primary amines give an almost quantitative yield of nitrogen gas. The reaction is complex and a mixture of organic products is usually formed.

At room temperature, phenylamine also yields gaseous nitrogen and phenol.

$$C_6H_5NH_2 + HNO_2 \rightarrow C_6H_5OH + N_2 + H_2O$$

If the temperature is below 10 ^{o}C, then another reaction takes place and the product is aqueous benzenediazonium chloride.



benzenediazonium chloride

The conditions for the reaction are

- The temperature must be below 10 ^{o}C. The reaction is exothermic so temperature control is important. At temperatures near to 0 ^{o}C , the reaction is very slow.
- There must be an excess of nitrous acid so that all the amine is converted. Benzenediazonium chloride can couple with unused phenylamine. For every mole of phenylamine used there must be more than two moles of HCl and just over one mole of sodium nitrite.

The product is not isolated as pure benzenediazonium chloride is explosively unstable.

Diazonium compounds are useful intermediates in the synthesis of organic compounds.

1. If aqueous benzenediazonium chloride is warmed above 10 ^{o}C, phenol is formed

$$C_6H_5N_2Cl(aq) + H_2O(l) \rightarrow C_6H_5OH(aq) + NaCl(aq) + N_2(g)$$

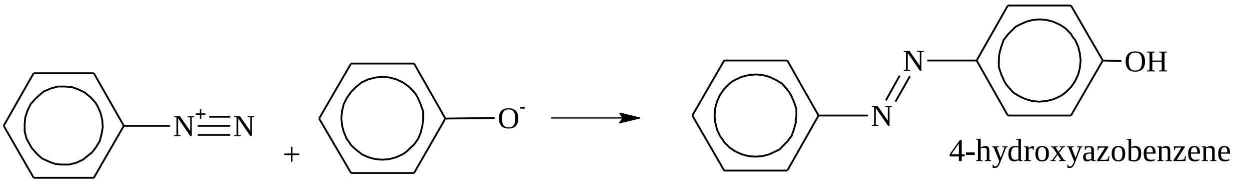
2. Iodobenzene is formed when aqueous benzenediazonium chloride is warmed with aqueous potassium iodide.

$$C_6H_5N_2Cl(aq) + KI(aq) \rightarrow C_6H_5I(l) + KCl(aq) + N_2(g)$$

4. Coupling reactions.

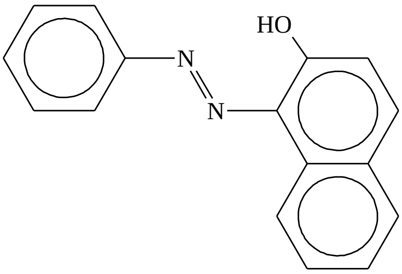
Benzenediazonium chloride reacts with phenols and amines to form coloured compounds called azo dyes.

- With phenol, in alkaline solution, the reaction below takes place.



This is the reason that in the preparation of benzenediazonium chloride the temperature must not rise above 10 ^{o}C otherwise a coupling reaction make take place.

The product is yellow. The colour arises from the overlap of π-electrons from the –N=N- bond and the π-electrons of the two benzene rings. Such an extended electron system is known as a conjugated system. Such systems absorb electromagnetic radiation. When this absorption takes place in the visible region of the spectrum, the electron system is known as a *chromophore.*



(b) An alkaline solution of naphthalen-2-ol also couples with benzenediazonium chloride to form an insoluble red dye.

(Knowledge of this reaction demanded by the specification).

- The reaction with phenylamine to give $C_6H_5\text{-N=N-NH-}C_6H_5$ as a yellow precipitate.

$$C_6H_5N_2Cl \ + \ C_6H_5NH_2 \ \rightarrow \ C_6H_5\text{-N=N-NH-}C_6H_5 \ + \ HCl$$

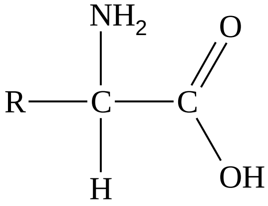
In the presence of strong acid the product undergoes an isomeric change to $C_6H_5\text{-N=N-}C_6H_5\text{-}NH_2$

Knowledge of this reaction demanded by the specification).

(e) **2-amino acids (α – amino acids)**

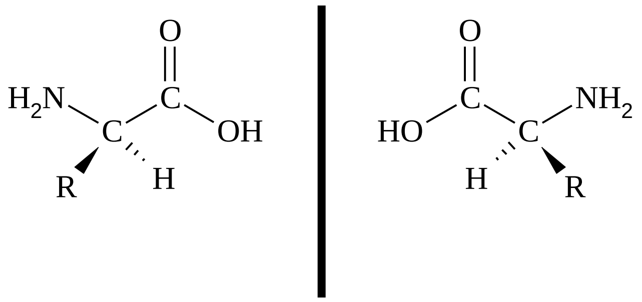
Amino acids are bifunctional compounds containing an amino group, $-NH_2$, and a carboxyl group, -COOH.

The most important amino acids are α-amino acids, with general formula



These are important compounds since they are derived from proteins by hydrolysis.

All except the 2-aminoethanoic acid, glycine, exhibit optical isomerism.

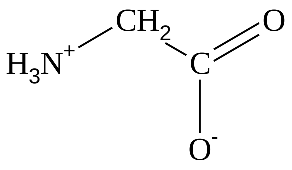


mirror line

Human proteins are formed from twenty α-amino acids. Some of these acids are known as *essential* amino acids. The essential amino acids are obtained through diet whereas the non-essential amino acids can be synthesised by biochemical processes within the body. The essential amino acids are obtained by the hydrolysis of animal or vegetable protein in digestion.

The amino acids derived from proteins are all chiral in the same sense.

2-Aminoethanoic acid has a melting point over 200 ^{o}C but a molar mass of only 75 g mol^{-1}.
The reason is that, by migration of a proton from the carboxyl group, the amino acid exists as



The zwitterion of glycine

Amino acids in this ionic form are called **zwitterions**.

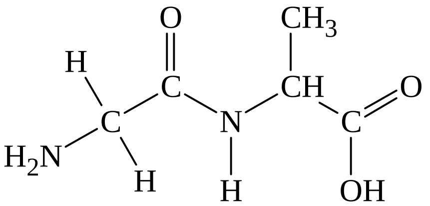
Amino acids are amphoteric since the carboxyl group acts as an acid and the amino group acts as a base.

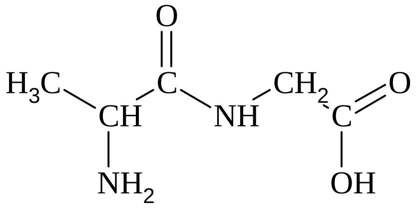
The carboxyl group will form esters and can be decarboxylated.

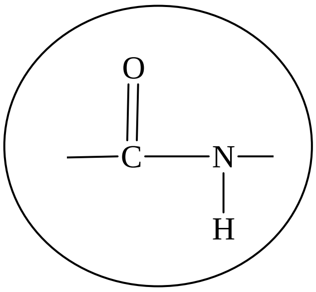
The amine group will react with nitrous acid and with acid chlorides.

(f) Two amino acids so linked is called a dipeptide.

Glycine, $CH_2(NH_2)COOH$ and alanine,$CH_3CH(NH_2)COOH$ can form two dipeptides.





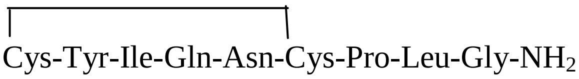


the peptide link

(g) Proteins contain a sequence of a-amino acids joined by an amide (or peptide) link.

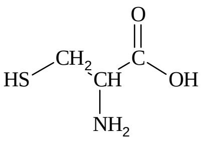
Proteins are naturally occurring polymers containing a large number of α-amino acid units smaller sequences of α-amino acid units are usually called polypeptides.

The hormone, oxytocin, responsible for contraction of the uterus in childbirth is a polypeptide. It is a polypeptide made up of eight amino acid units. The two cysteine units count as one since they are linked via the sulphur atoms and called cystine.

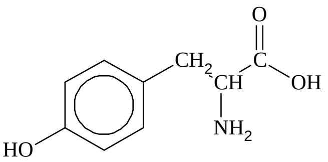


Cys-Tyr-Ile-Gln-Asn-Cys-Pro-Leu-Gly-NH_2

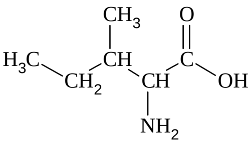
The abbreviations in this formula are shown below.



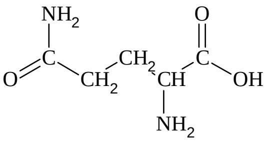
Cysteine (Cys)*



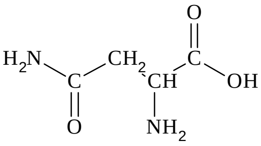
Tyrosine (Tyr)



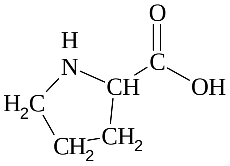
Isoleucine (Ile)



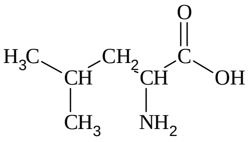
Glutamine (Gln)



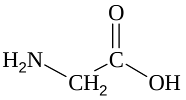
Asparagine (Asn)



Proline (Pro)



Leucine (Leu)

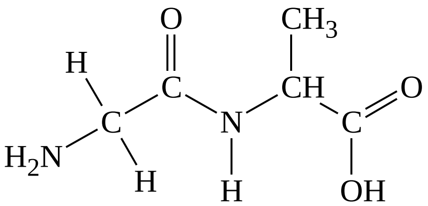


Glycine (Gly)

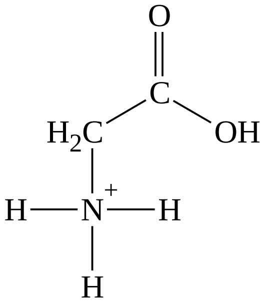
* Note that two cysteine units can join by means of a disulphide bridge -S-S- to form cystine as in oxytocin above.

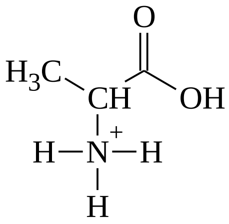
Proteins and polypeptides are hydrolysed by both acids and alkalis. The hormone, insulin, which is used by diabetics, cannot be taken orally since it would be hydrolysed in the digestive system before it could become effective in treating the condition.

When the dipeptide

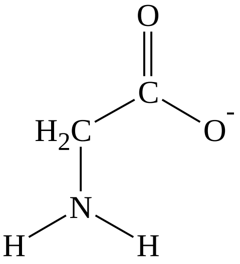


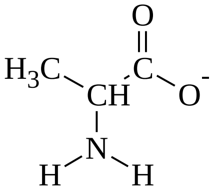
is hydrolysed by acid the products are





If hydrolysed by alkali the products are





(g) The structures of proteins.

Primary structure.

This is simply the sequence of a-amino acids forming the protein chain. If the protein contains cysteine units in the chain which form disulphide links, the disulphide bridges are still part of the primary structure.

Secondary Structure

The secondary structure is concerned with how parts of the protein can fold up to form an α **-helix** which is held in shape by hydrogen bonds involving the peptide links or a **β-pleated sheet** in which the amino acids form a shape like a piece of paper stabilised by hydrogen bonds between amino acids in different polypeptide chains.

Tertiary Structure

This refers to the protein as a whole and is the way in which the α-coils and β-pleated sheets of the protein fold with respect to each other.

Visit http://www.nature.com/horizon/proteinfolding/background/importance.html

(h) Protein is an essential component of a healthy diet. The functions of proteins are numerous. They are necessary for structural functions in living organisms e.g. in nails, feathers, hair skin and the collagen of cartilage. Proteins are enzymes, the biological catalysts.

Some proteins and some polypeptides are hormones e.g. oxytocin and insulin.

(i) Polyamides

These are very useful polymers with uses as fibres in textiles, filaments such as fishing lines and as small light gears in small electric motors.

Nylon-6.6 was first manufactured in 1940.

It is made from 1,6-diaminohexane, and hexanedioic acid

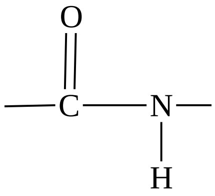
$$nH_2N(CH_2)_6NH_2 + nHOOC(CH_2)_4COOH \rightarrow [-OC(CH_2)_4CONH(CH_2)_6NH-]_n + n\,H_2O$$

It is a condensation polymer.

It may be made in the laboratory by adding aqueous 1,6-diaminohexane to a solution of hexanedioyl chloride, $ClOC(CH_2)_4COCl$, in tetrachloromethane. The polymer forms at the interface of the two immiscible liquids and may be drawn out of the mixture. (The nylon rope trick.)

Note that the linkage between the monomers in nylon 6.6 is the amide link hence the nylons are classified as polyamides.

This amide linkage is the same as the peptide link in proteins and polypeptides.



$$-\overset{\overset{\large O}{\|}}{C}-\underset{\underset{\large H}{|}}{N}-$$

There are a number of Nylons depending on the monomers used.

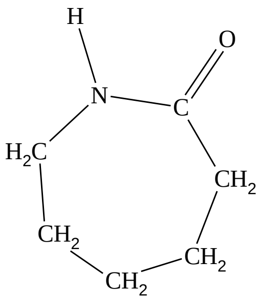
nylon 6.10

$NH\text{-}(CH_2)_6\text{-}NH\text{-}CO\text{-}(CH_2)_8\text{-}CO\text{-}NH\text{-}(CH_2)_6\text{-}NH\text{-}CO\text{-}(CH_2)_8\text{-}CO\text{-}$

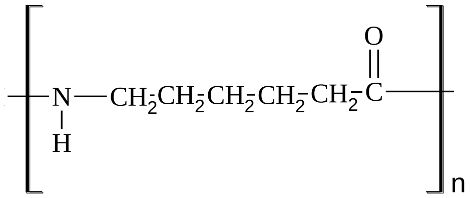
nylon 6.8

$NH\text{-}(CH_2)_6\text{-}NH\text{-}CO\text{-}(CH_2)_6\text{-}CO\text{-}NH\text{-}(CH_2)_6\text{-}NH\text{-}CO\text{-}(CH_2)_6\text{-}CO\text{-}$

Nylon 6 is manufactured from a single monomer, caprolactam. When this molecule polymerises, the ring opens, and the molecules join up in a continuous chain.



caprolactam
6 carbon atoms



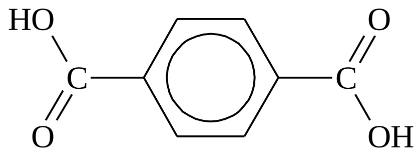
$$\left[\underset{\displaystyle H}{\underset{|}{N}} - CH_2CH_2CH_2CH_2CH_2 - \overset{\displaystyle O}{\overset{\|}{C}} \right]_n$$

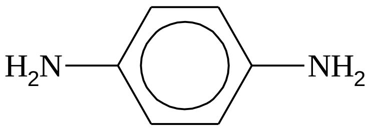
Nylon-6

Another interesting polyamide is Kevlar.

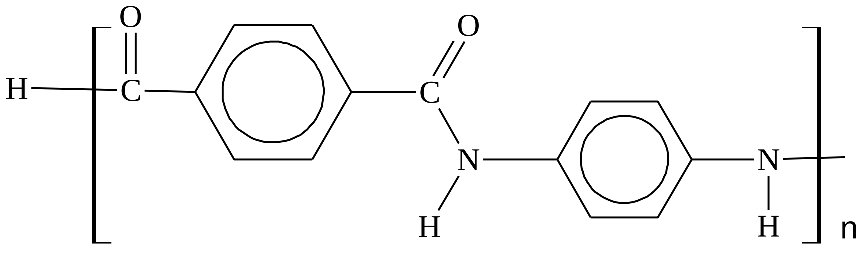
Kevlar has a polyamide structure similar to nylon-6,6 but instead of the amide links joining chains of carbon atoms together, they join benzene rings.

The two monomers are benzene-1,4-dicarboxylic acid and 1,4-diaminobenzene.





The amino and carboxyl groups can eliminate water to form the polymer with the repeat unit



Kevlar is a very tough polymer which is used in body armour. Its properties are very different from the ordinary Nylons which have carbon chains.

TOPIC 13 Organic Synthesis and Analysis

Candidates should be able to:

(a) *derive empirical formulae from elemental composition data and deduce molecular formulae from these results plus additional data such as titration values, gas volumes, mass spectrometric molecular ion values and gravimetric results;*

(b) *use given mass spectral data to elucidate the structure of simple organic molecules (up to and including C8 molecules, with one chlorine atom);*

(c) *interpret given simple infrared spectra using characteristic group frequencies (supplied in cm-1) : O–H(str), N–H (str), C≡N (str), C=O (str) and N–H (bend) [str = stretch] and use these to identify groupings in organic molecules;*

(d) *understand that n.m.r. spectra can give information regarding the environment and number of equivalent hydrogen atoms in organic molecules and use such supplied information in structure determination;*

- * *Candidates will be supplied with simplified n.m.r. spectra of relevant compounds and with a table listing the approximate positions of commonly encountered resonances. They may also be supplied with an indication of the relative peak areas of each resonance and with a note that the splitting of any resonance into n components indicates the presence of n-1 hydrogen atoms on one* ***adjacent*** *carbon, nitrogen or oxygen atom. Questions may be set showing spectra at low resolution where splitting is not shown.*

(e) *outline the general reaction conditions and basic techniques of manipulation, separation and purification used in organic chemistry, and recall the essential safety requirements during these operations;*

(f) *understand the use of melting temperatures as a determination of purity;*

(g) *propose sequential organic conversions by combining a maximum of three reactions in the specification;*

(h) *deduce percentage yields in preparative processes;*

- *(i) show understanding of the wide applicability of spectroscopic techniques to analytical problems in industry, medicine and the environment;*

(j) *understand and be able to explain and exemplify the distinction between condensation polymerisation and addition polymerisation;*

(k) *give, as examples of important industrial and processes, the outline chemistry and any necessary conditions of the manufacture of polyesters (e.g. PET) and polyamides (e.g. Nylon 6 and 6,6) starting from compound(s) containing the respective two functional groups;*

(l) *outline the uses of thin layer chromatography (TLC), gas chromatography and highperformance liquid chromatography (HPLC) in analysis (details of the theory of chromatography and of the methods used are not required) and be able to find the composition of mixtures by use of retardation factor (Rf), retention time and peak area.*

(a) Derivation of empirical formula

The specification requires candidates to derive empirical formula form elemental composition data. This data may be given as percentage composition, by mass or as actual gravimetric data.
All methods involve finding the ratio of the numbers of moles of each kind of atom in the compound.
To determine molecular formula extra information is required. This may be molar mass, molecular ion mass spectrum data, volumetric analysis data or gaseous volume data from which molar mass may be evaluated.

Example

An organic compound has the following percentage composition, by mass.
C 63.97; H 4.49; Cl 31.54:
The mass spectrum of the compound shows two peaks in the molecular ion region with m/z values of 112 and 114 with heights in the ratio of 3:1.
Identify the compound and explain the molecular ion region of the mass spectrum.

element	% by mass	A_r	% / A_r	Ratio of number of moles of atoms
C	63.97	12.0	5.33	6.00
H	4.49	1.01	4.44	5.00
Cl	31.54	35.5	0.888	1.00

Empirical formula is C_6H_5Cl

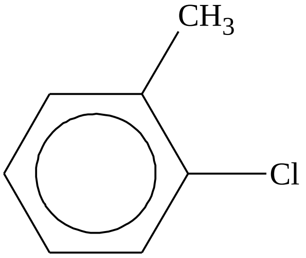
Empirical formula mass = 112.5 g mol^{-1}

Molecular formula is C_6H_5Cl, the two molecular ion peaks correspond to $C_6H_5{}^{35}Cl$ at 112 and $C_6H_5{}^{37}Cl$ at 114, the chlorine isotopes being in the ration 3:1.

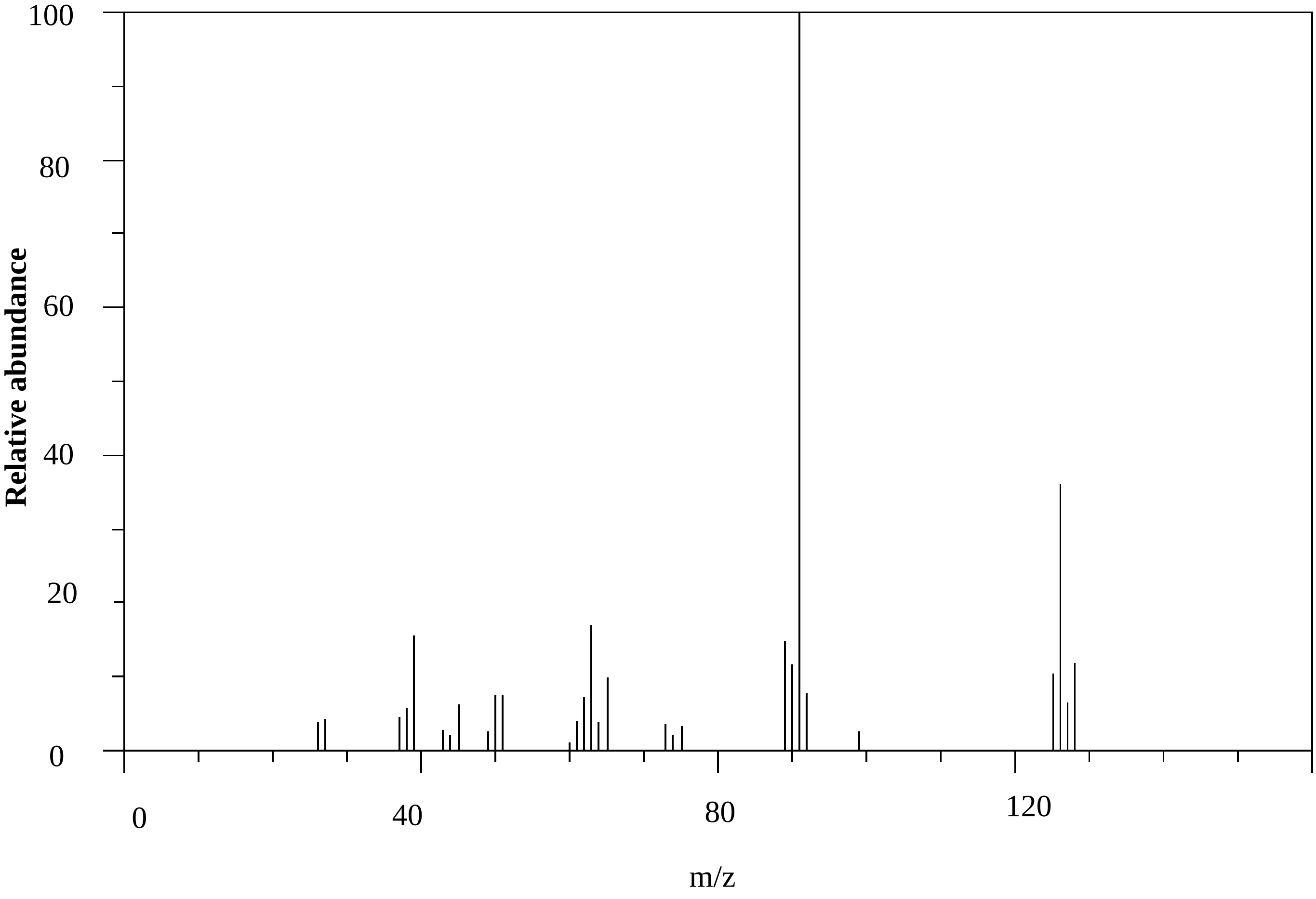
(b) ***Use of mass spectra in the determination of structure, limited containing up to and including eight carbon atoms per molecule and no more than one chlorine atom.***

When organic molecules are introduced into the mass spectrometer, the high speed electrons not only ionise the molecules but also fragment them. The fragmentation pattern is often a clue to the structure of the compound.

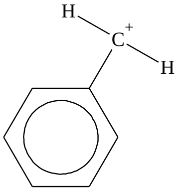
The diagram below shows the simplified mass spectrum of 1-chloro-2-methylbenzene



1-chloro-2-methylbenzene

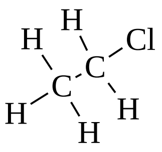


The base peak is at m/z = 91 which suggests

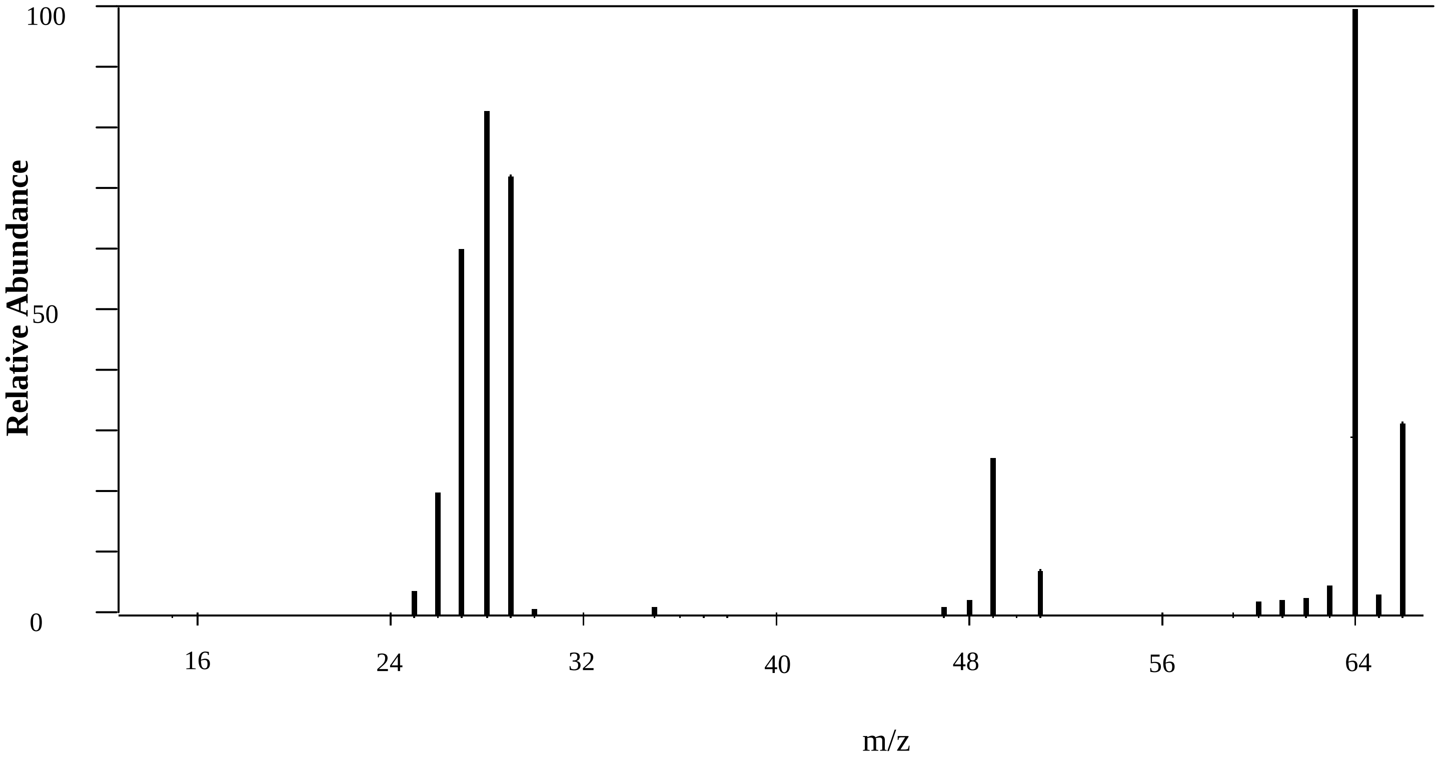


The peaks at m/z at 126 and 128 are molecular ion peaks $CH_3C_6H_4{}^{35}Cl$ and $CH_3C_6H_4{}^{37}Cl$ and are in the ratio 3:1. Candidates should be able to familiarise themselves with mass spectra.

A simplified mass spectrum of chloroethane is shown below.



chloroethane



Once again we notice the two molecular ion peaks at 64 and 66 in an approximate 3:1ratio. These are due to $[C_2H_5Cl]^+$ ions for the two isotopes of chlorine.

The peaks at 49 and 51 are due to the fragmentation $[C_2H_5Cl]^+ \rightarrow \cdot CH_3 + {}^+CH_2Cl$

Other fragmentations which can be deduced are

$[C_2H_5Cl]^+ \rightarrow \cdot H + {}^+CHClCH_3$ peaks at 63 and 65

$[C_2H_5Cl]^+ \rightarrow \cdot Cl + {}^+CH_2CH_3$ peak at 29

$[C_2H_5Cl]^+ \rightarrow HCl + [C_2H_4]^+$ peak at 28

For mass spectra visit

http://webbook.nist.gov/chemistry/

(c) For interpretation of infrared absorption spectra, candidates will be supplied with the following data.

Infrared Spectroscopy characteristic absorption values

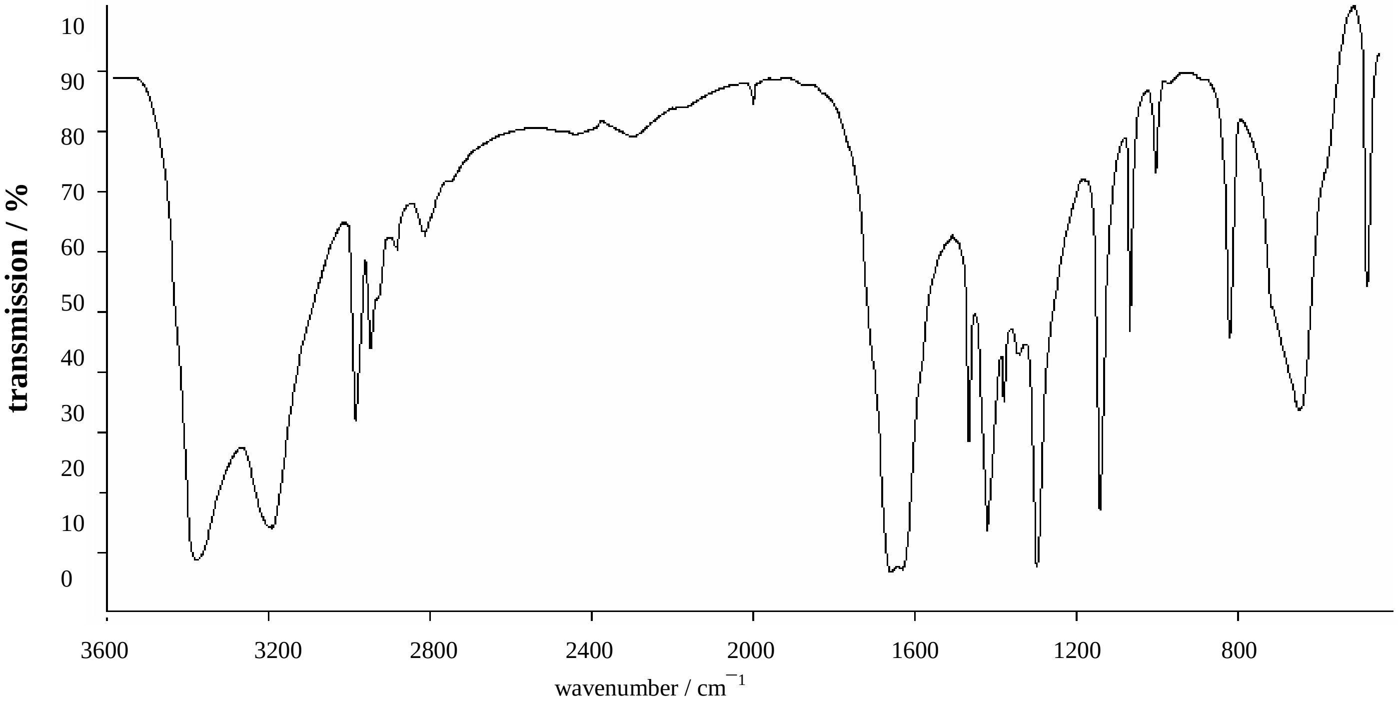
Bond	**Wavenumber/cm^{-1}**
C- Br	500 to 600
C-Cl	650 to 800
C-O	1000 to 1300
C=C	1620 to 1670
C=O	1650 to 1750
C≡N	2100 to 2250
C-H	2800 to 3100
O-H	2500 to 3550
N-H	3300 to 3500

Infrared spectra

Infrared data is available from a small quantity of the compound and gives a good spectrum very quickly.

Example

A compound has molecular formula C_3H_7NO and the infrared absorption spectrum below.



Suggest a structure for this compound. What extra IR information would be useful to be more certain?

One approach.

Possible bonds are

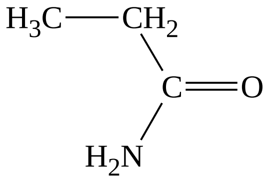
C-H 2800 – 3100 cm^{-1} (*2850 – 3000 cm^{-1} is the C-H stretching frequency with saturated carbon)*

C=O approx 1650 cm^{-1} in spectrum *(this is the C=O stretching frequency in amides)*

N-H 3000 -3500 cm^{-1} *(the N-H stretching frequency in the –NH_2 group is 3300-3400 cm^{-1})*

The candidates are not expected to know the information in italics

Could be

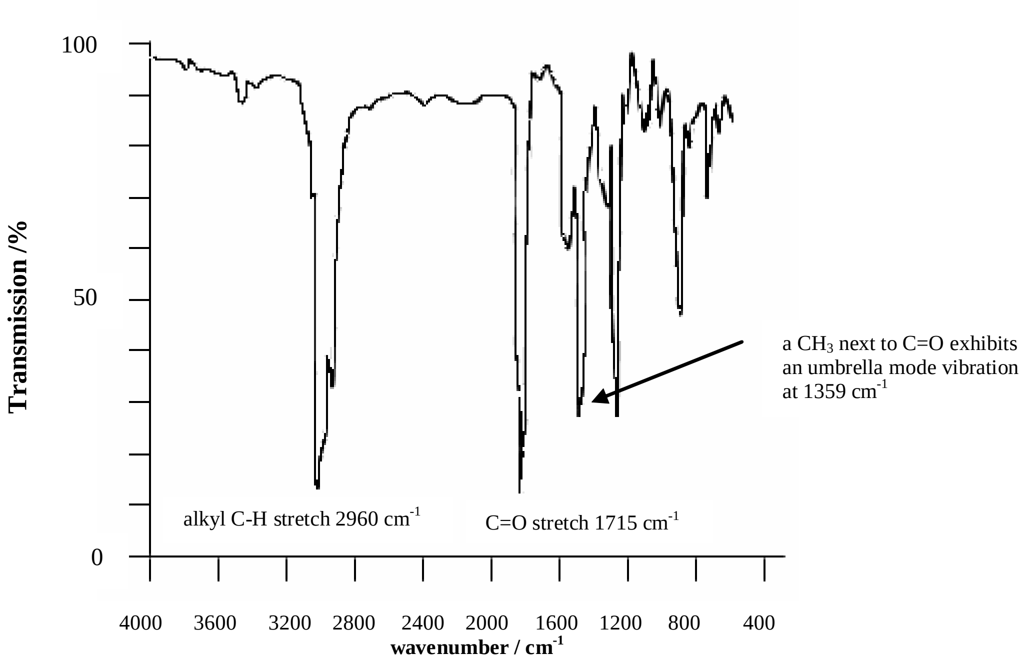


No information on absorption of C-N bond or C-C bond is given and would be desirable.

Infrared spectrum of hexan-2-one

The infrared absorption spectrum of hexan-2-one is shown below.

Note some special features.



(d) Nuclear Magnetic Resonance spectra.

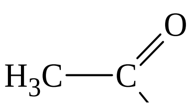
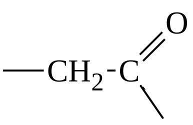
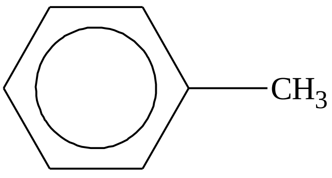
Some aspects of nuclear magnetic resonance have been dealt with in Topic 9(b).

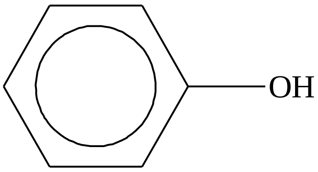
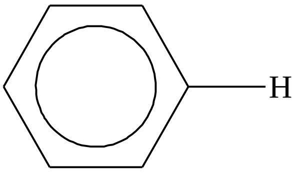
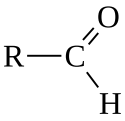
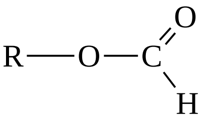
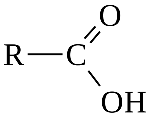
The most common NMR is proton NMR. This usually employs a radio frequency of 60 Mhz and an magnetic field of about 1.41 Tesla. In nuclear magnetic resonance, the frequency of the radiation absorbed by a nucleus depends upon its environment in the molecule. Different types of protons in an organic molecule absorb radiation of different frequencies. To find these absorptions, the radio frequency is kept constant and the magnetic field varied by the sweep coils.

The absorptions are compared with the standard tetramethylsilane, TMS, which has twelve identical hydrogen atoms $(CH_3)_4Si$. TMS is assigned a chemical shift, δ, value of zero. The shift values of other absorptions are measured in ppm.

Candidates will be supplied with the information following .

Typical proton chemical shift values (δ) relative to TMS = 0

Type of proton	**Chemical shift (ppm)**
$-CH_3$	0.1 to 2.0
$R-CH_3$	0.9
$R-CH_2-R$	1.3
$CH_3-C\equiv N$	2.0
 $H_3C-C(=O)-$	2.0 to 2.5
 $-CH_2-C(=O)-$	2.0 to 3.0
	2.2

R-CH_2-Halogen	3.3 to 4.3
-O-CH_3, -OCH_2-R, -O-CH=C<	3.5 to 4.0
R-OH	4.5 *
CH_2=C<	4.8
	7.0 *
	7.3
 $\mathrm{R-C(=O)H}$  $\mathrm{R-O-C(=O)H}$	9.8*
 $\mathrm{R-C(=O)OH}$	11.0 *

* variable figure dependent on concentration and solvent

Low resolution NMR

- the number of peaks gives the number of different environments the hydrogen atoms occur in
- the ratio of the areas under the peaks gives the ratio of the numbers of hydrogen atoms in the different environments

  e.g. the ratio of the areas under the three peaks of low resolution NMR for ethanol are 3:2:1
- information of the environments of the hydrogen atoms is obtained from the values of the chemical shifts of the peaks

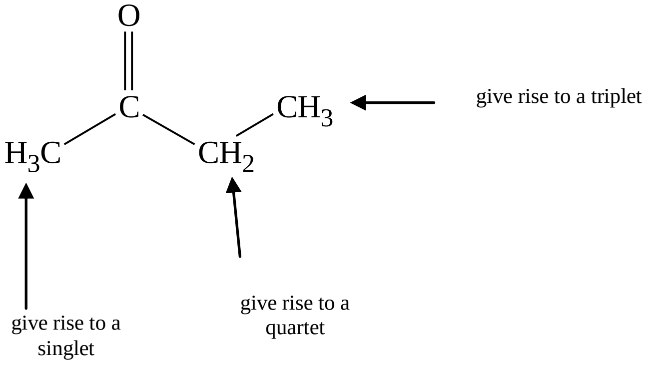
High resolution NMR

In high resolution NMR the peaks are often split due to spin coupling.
The amount of splitting gives information about the number of hydrogen atoms attached to the carbon atom adjacent to the one being considered.

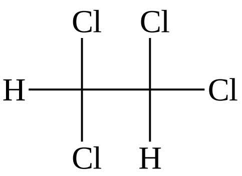
The number of peaks in the cluster is one more than the number of hydrogen atoms on the adjacent carbon atom. This is the (n+1) rule. Note that this is stated differently in the specification. *"...note that the splitting of any resonance into n components indicates the presence of n-1 hydrogen atoms on one* ***adjacent*** *carbon, nitrogen or oxygen atoms."*

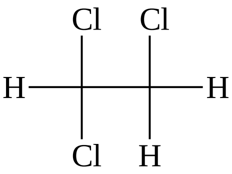
i.e. a single peak (a singlet) is due to hydrogen atoms adjacent to a carbon carrying no hydrogen atoms
a doublet is due to hydrogen atoms adjacent to a carbon carrying one hydrogen atom, -CH-
a triplet is due to hydrogen atoms adjacent to a carbon carrying two hydrogen atoms, $-CH_2-$
A quartet is due to hydrogen atoms adjacent to a carbon carrying three hydrogen atoms, $-CH_3-$
Hence NMR for ethanol has a triplet, a quartet and a single peak.

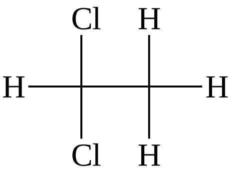
Butan-2-one

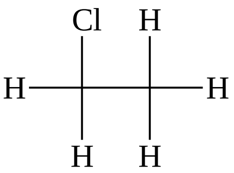


Look at the following

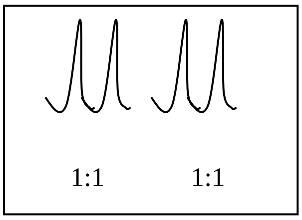


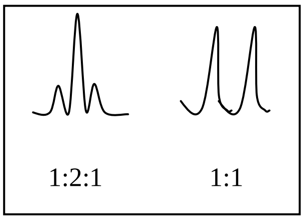


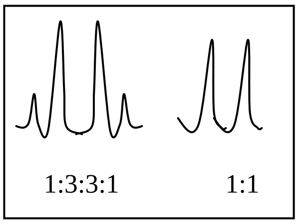


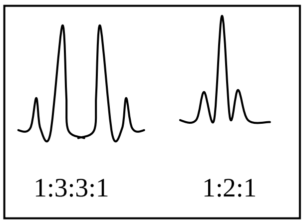


Spectra for the hydrogen atoms in each of the molecules







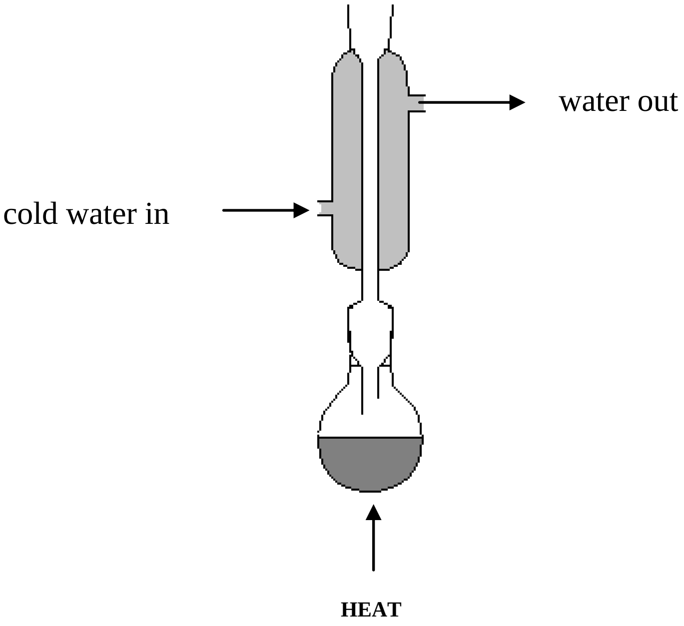


(e) Basic practical techniques

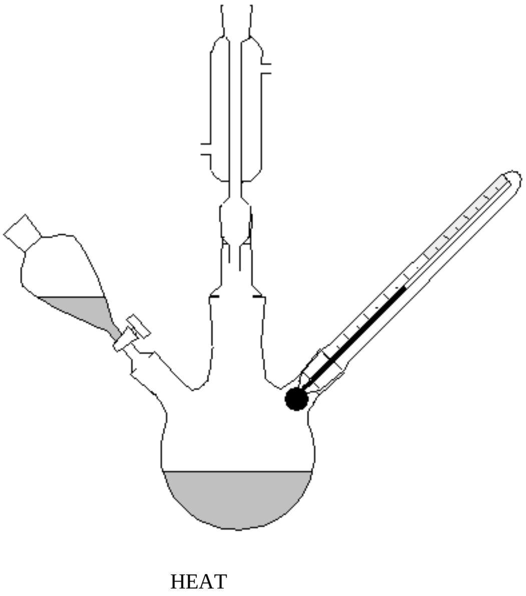
Reflux

Many organic compounds are volatile and when heated would escape to the atmosphere before reaction is complete and the products if volatile would be lost.

To contain the compounds when heating a reaction mixture, the process of reflux is used.



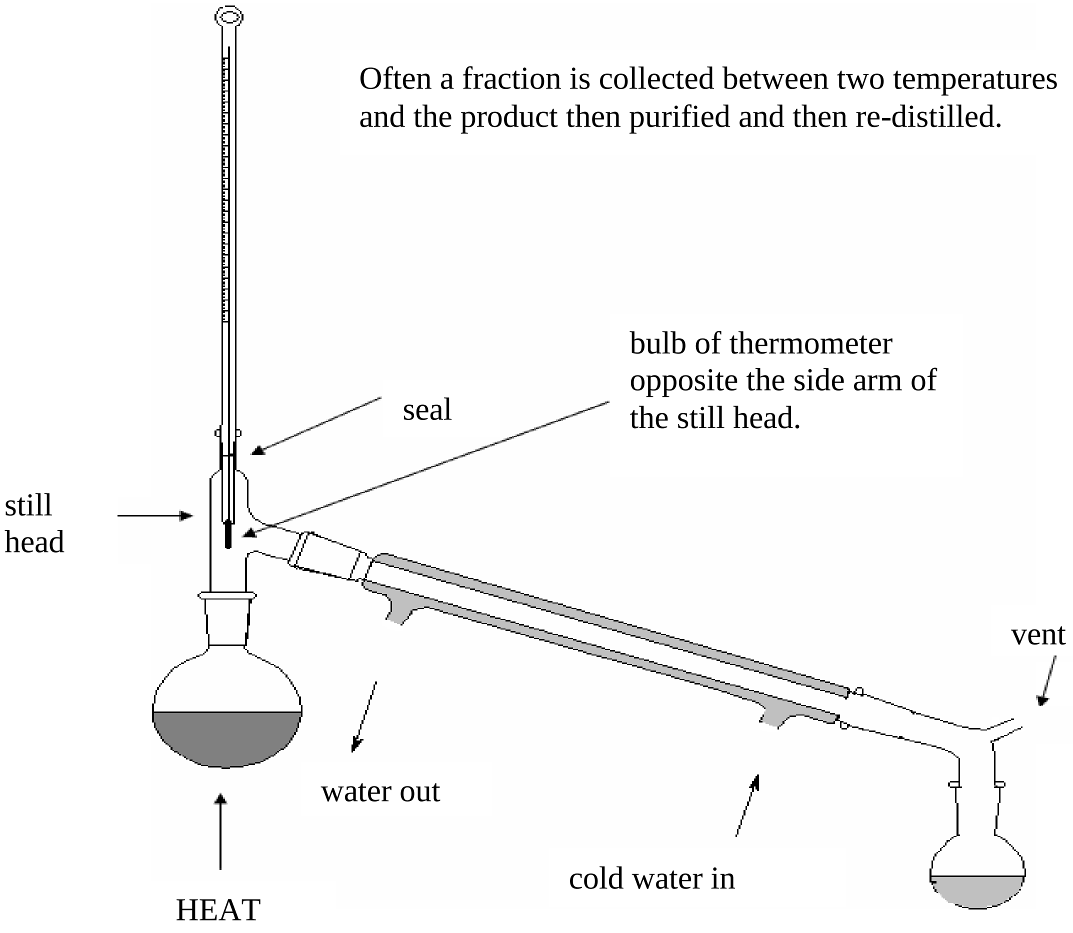
By cooling the vapours from the reacting mixture, the chemicals are contained within the reaction flask as they condense and run back.



Reflux with addition for reactions

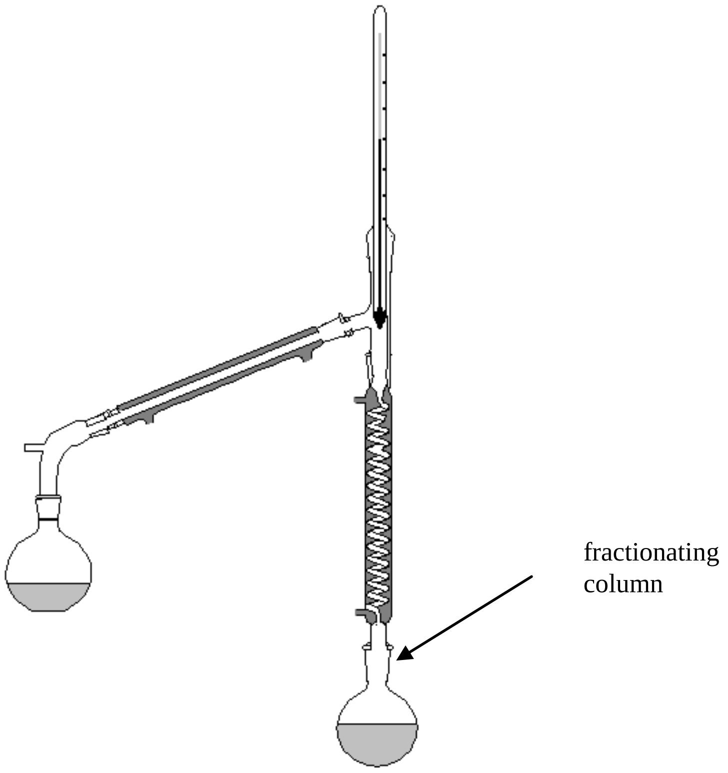
Modern glassware has interchangeable ground glass joints. Care should be taken to avoid these joints sticking. One method is to use a small length of plumber's PTFE tape between the two surfaces. This does not impair the seal but does prevent sticking.

Simple distillation

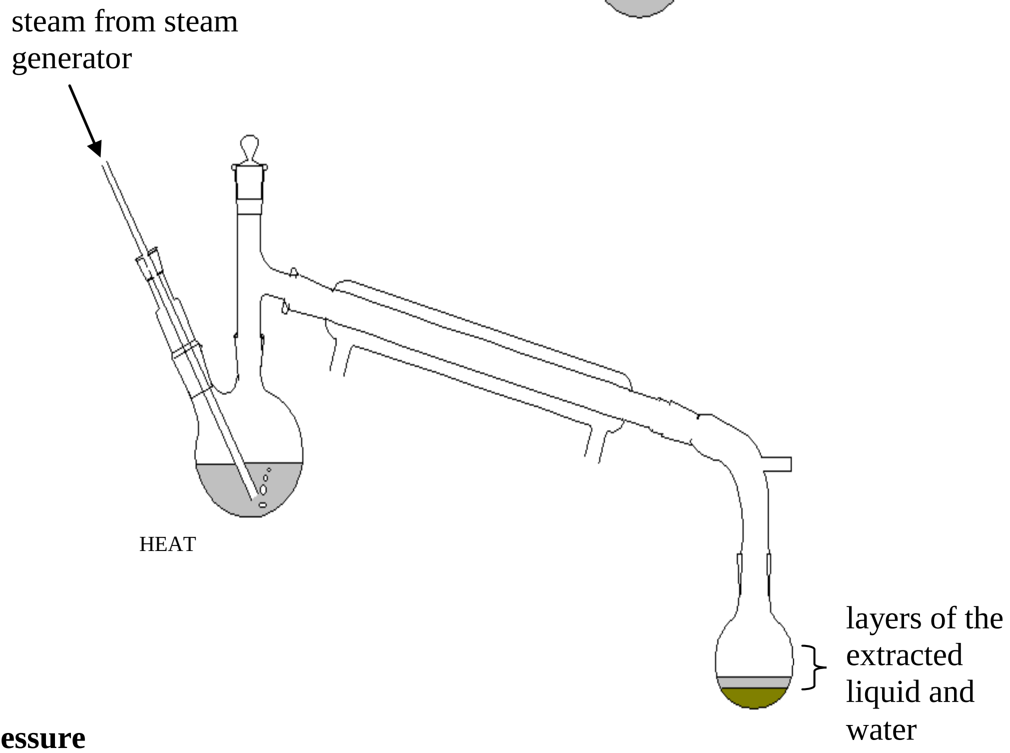

Often a fraction is collected between two temperatures and the product then purified and then re-distilled.

Fractional distillation

Fractionating columns vary in design and efficiency. The fractionating column provides surfaces on which the components can condense and then re-evaporate. The lower the boiling point of the component the higher up the column until it eventually distils over. The collecting flask can be changed as various fractions distil.



Steam Distillation



Steam distillation is used to remove insoluble high boiling point liquids from reaction mixtures. It is particularly useful for compounds that may decompose or change near their boiling points. The liquid forms an insoluble layer with the condensed steam in the receiver.

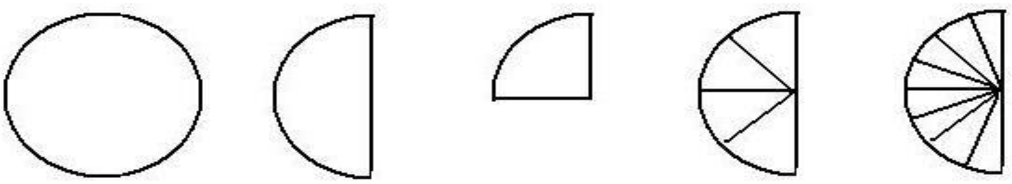
Distillation under reduced pressure

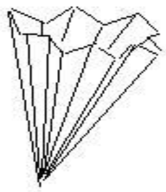
Some compounds may decompose or change at temperatures near their boiling points.
It is therefore advisable to distil such compounds under reduced pressure. A liquid boils when its vapour pressure equals the external pressure. The technique involves connecting the distillation apparatus to a vacuum pump while carrying out the distillation.

Filtration

This technique is used to remove solids from liquid mixtures.

Simple filtration involves a filter funnel and filter paper. Faster filtration is used with a fluted funnel and paper.

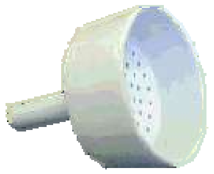




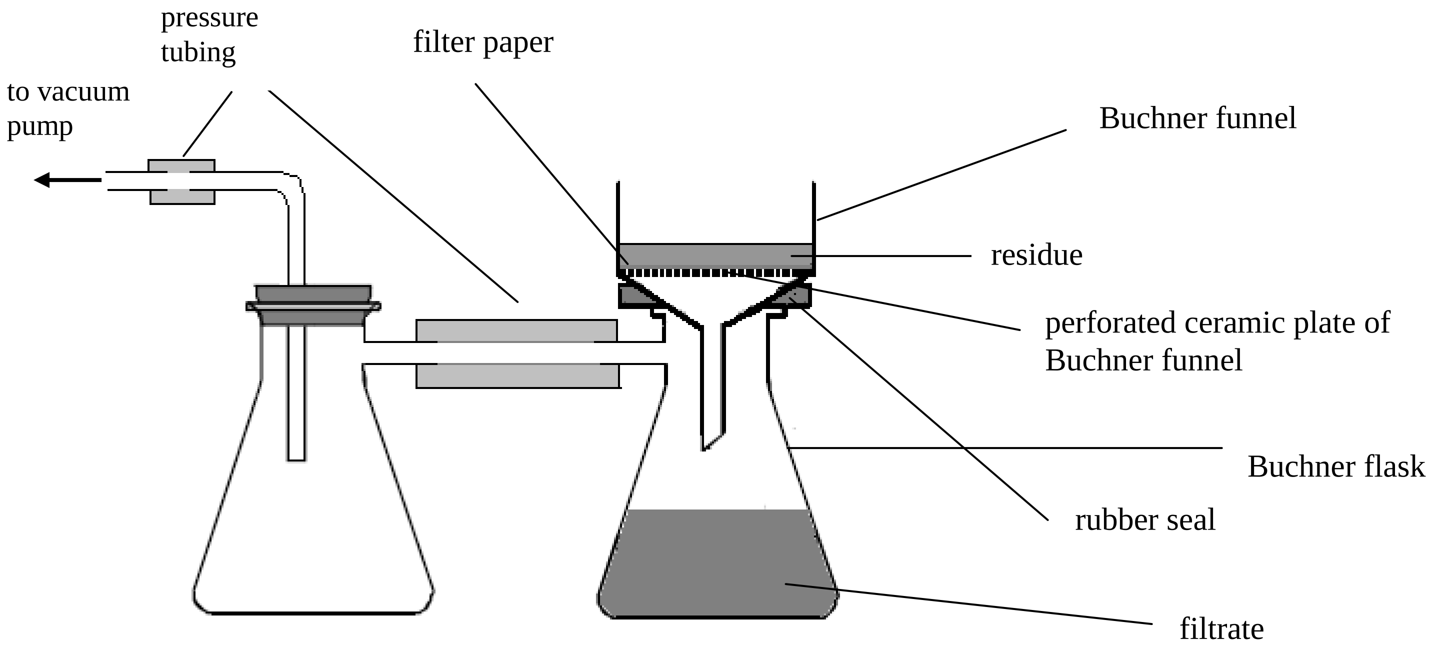
Fold the filter paper as shown then open out and place in the funnel

Better filtration results are obtained by vacuum filtration.

The most common method is to use a Buchner funnel attached, via a splash back flask, to a water vacuum pump.



A porcelain Buchner funnel



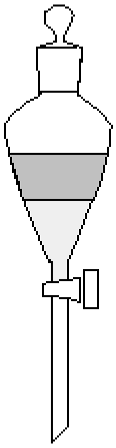
For smaller amounts of solid, a similar device called a Hirsch funnel is used. The principles are exactly the same as with a Buchner funnel.

Recrystallisation

This technique is used to purify solids. The principle is to find a solvent which will dissolve both the compound and the impurities when hot but which dissolves much less of the compound when cold. The stages are

- find a suitable solvents by trial and error or reference to the literature
- dissolve the specimen in the minimum volume of hot solvent
- filter hot, if necessary, to remove insoluble impurities
- allow to cool
- filter the compound at the pump
- wash the residue and dry
- recrystallise if necessary

Separation of immiscible liquids



This is effected with a separating funnel.
If used in solvent extractions, successive extractions with several small volumes of solvent are more efficient than using the same total volume in one single extraction.

When carrying out any of the above techniques, the usual health and safety considerations must be borne in mind.

Many organic compounds are flammable and care must be observed with naked flames. When solvents such as ethoxyethane are being distilled there should be no naked flames on the bench or in the vicinity. Heating is best carried out with a hot water bath prepared elsewhere. The toxicity of compounds must be remembered and fume cupboards used as appropriate. Whenever possible preparations should be carried out on as small a scale as possible.

(f) Melting points.

Pure compounds have sharp melting points. In organic chemistry in the laboratory we consider a compound which melts over a range of 1 – 2 ^oC to be quite pure. There is a variety of apparatus in which to carry out such a determination. They usual require a small quantity of the compound to be introduced to fine capillary tube sealed at one end. The tube is then heated in the apparatus and the sample viewed. It is important to make sure that temperature rises slowly especially near the melting temperature, no more than 2 ^oC per minute.

Determination of a sharp melting point denotes purity and the value can be used to eliminate many other compounds. Another useful technique is the method of mixed melting points. If the identity of a compound is suspected, then a small sample can be mixed with a known sample of that compound.
If the two are identical then there should be no change in the value of the melting point. If they are not identical then the one will behave as an impurity in the other, the melting point may be lowered and lose its sharpness.

Melting points may be used to identify carbonyl compounds from the meting points of their purified 2,4-dinitrophenylhydrazone derivatives.

(g) The specification demands that candidates can put together up to three chemical reactions from the course of study to carry out sequential conversions in an organic synthesis or degradation.
A synthesis involves building up a larger molecule from smaller ones and a degradation involves forming simpler compounds from a more complicated one.
In synthesis it may be necessary to increase the length of a carbon chain and this may be done by addition of inorganic carbon in the form o the –CN group.
This can be done by the electrophile substitution of a halogenoalkane with ethanolic KCN or by the nucleophilic addition of HCN to a carbonyl compound.
Subsequent treatment of the cyano-compound may involve

- acid hydrolysis $\text{-CN} \rightarrow \text{-COOH}$

or

- reduction $\text{-CN} \rightarrow \text{-CH}_2\text{NH}_2$

Other reactions which should be remembered are:

ethanoylation reaction CH_3COCl	with alcohols, phenols and amines
esterification	of alcohols
reduction	of acids and alcohols
oxidation of	aldehydes, alcohols ad aromatic side-chains
hydrolysis of	esters, halogenoalkanes
electrophilic substitution	of the benzene ring
polymerisations	
catalytic hydrogenation	of carbon-carbon double bonds
coupling reactions of diazonium compounds	

In degradations molecules are usually split by hydrolysis or by decarboxylation.

(h) The calculation of yields in preparative processes has been dealt with elsewhere as well as atom economy.

The yields in organic chemistry are very variable often due to the possibility of side reactions.
To determine the yield it is necessary to determine the mass of purified product from a known mass of a reagent which is not in excess.

From the starting mass the maximum theoretical mass of product can be calculated and then this compared with the actual mass of purified product.

Example

23.5 g of the purified 2,4-dinitrophenylhydrazone derivative of propanal were obtained from 7.5 g of the aldehyde when treated with excess 2,4-dinitrophenylhydrazine reagent. Calculate the yield.

$C_2H_5CHO + (NO_2)_2C_6H_3NHNH_2 \rightarrow (NO_2)_2C_6H_3NHN{=}CHC_2H_5 + H_2O$

one mole one mole

58 g 253

7.5 g would give a maximum yield of $(253 \times 7.5)/58 = 82.1$

Percentage yield $= (23\text{-}5 \times 100) / 82.1 = 28.6\ \%$

(i) Candidates to show an understanding of the wide range of spectroscopic techniques which can be applied to analysis in industry, medicine and the environment. Analysis in industry employs the whole spectrum of analytical techniques.

Mass spectrometry is used in the pharmaceutical and related industries often in tandem with Gas Liquid Chromatography to gain knowledge of complex biochemical mixtures. New uses for mass spectrometry have been found in modern forensic science.

In industry, uv-visible spectroscopy is used for quick and reliable applications.

- the measurement of concentrations of chromophores in solution
- determining the presence of impurities in coloured samples
- use in following the kinetics of a reaction

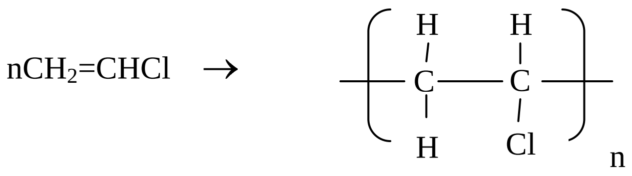
Infrared spectroscopy is quick and reliable and is a valuable analytical tool. A sophisticated infrared technique called Fourier transform infrared is capable of distinguishing diamond gemstones from counterfeit ones.

The use of NMR in industry is ever widening.
In agriculture, moisture and oil content of seeds and feeds can be measured, the components of some fertilisers. In the chemical industry routine moisture analyses are carried out by NMR.
In medicine all spectroscopic techniques are used from time to time but in recent years Nuclear Magnetic Resonance Imaging has been shown most helpful. Using NMR a whole body can be imaged and information derived from the scan about pathological and physiological abnormalities.
NMR has also been used in the study of body fluids and in following the metabolic pathways of medicinal drugs.

All these techniques and applications can be accesses by using an internet search engine.

(j) The difference between addition and condensation polymers has already been touched upon **(Topic 11.3(d) Topic 12)**.

Addition polymers are formed from monomers without the elimination of any other molecules. Examples of such polymers are those formed from derivatives of ethene.
e.g. poly(chloroethene). The monomer is chloroethene $CHCl{=}CH_2$

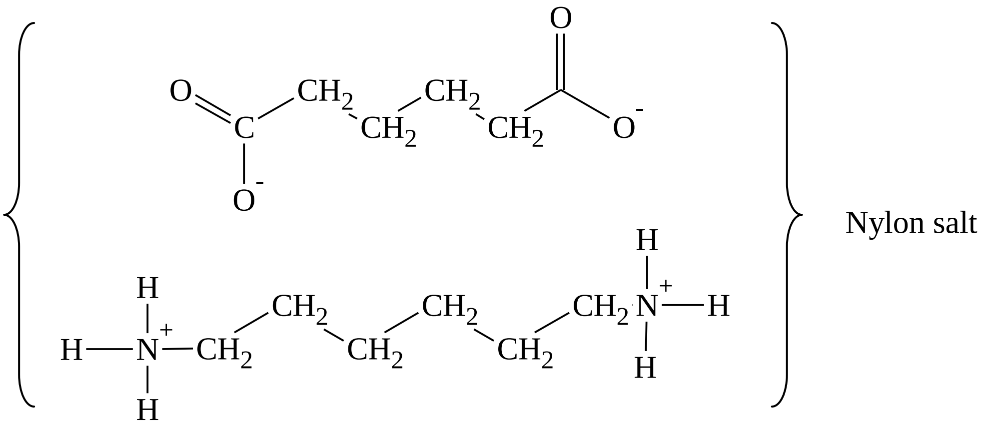


$$nCH_2{=}CHCl \rightarrow \left[-\overset{H}{\underset{H}{C}}-\overset{H}{\underset{Cl}{C}}- \right]_n$$

In condensation polymers, the joining of the monomers accompanied by the elimination of a small molecule. **e.g. the formation of Nylon 6,6**

$$nClOC(CH_2)_4COCl \ + \ nH_2N(CH_2)_6NH_2 \rightarrow \left[OC(CH_2)_4CONH(CH_2)_6NH \right]_n \ + 2nHCl$$

(k) Manufacture of PET see previously page 37. The chemistry of the manufacture of Nylon 6,6 and Nylon 6 has been discussed on page 46
One method for the manufacture of nylon 6,6 involves the starting materials of adipic acid (hexanedioic acid) and hexamethylenediamine (1,6-diaminohexane). These are allowed to react in the presence of water to form "Nylon salt" solution in which the two molecules neutralise each other by proton transfer.

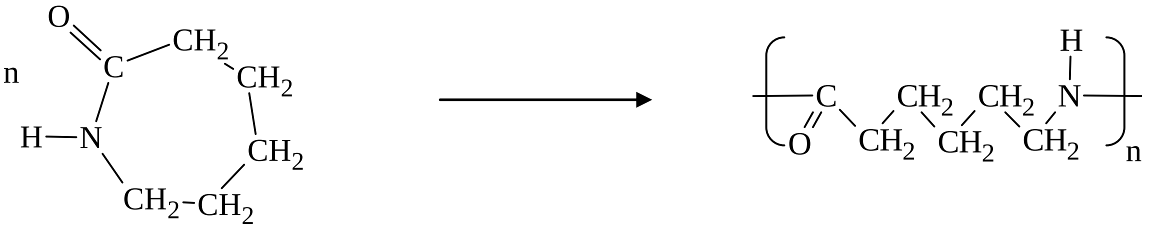


The reaction mixture is heated to around 130 °C when polymerisation occurs and water is removed. The product is a molten melt which can be turned in chips for fibre manufacture.

A second method uses the nitrile of hexanedioic acid, 1,6-diaminohexane and steam at a high temperature and pressure in the presence of an oxygen-containing phosphorus catalyst.

Nylon 6

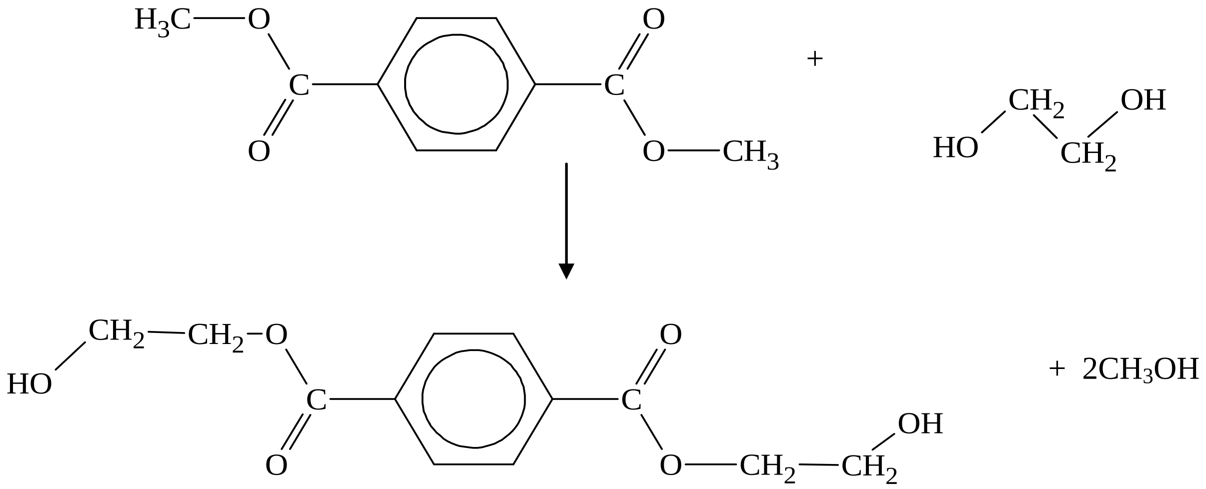
Caprolactam is heated to about 250 °C with up to 10% water. This causes opening of the ring and subsequent polymerisation.



The polyester, Terylene or poly(ethyleneterephthalate), PET.

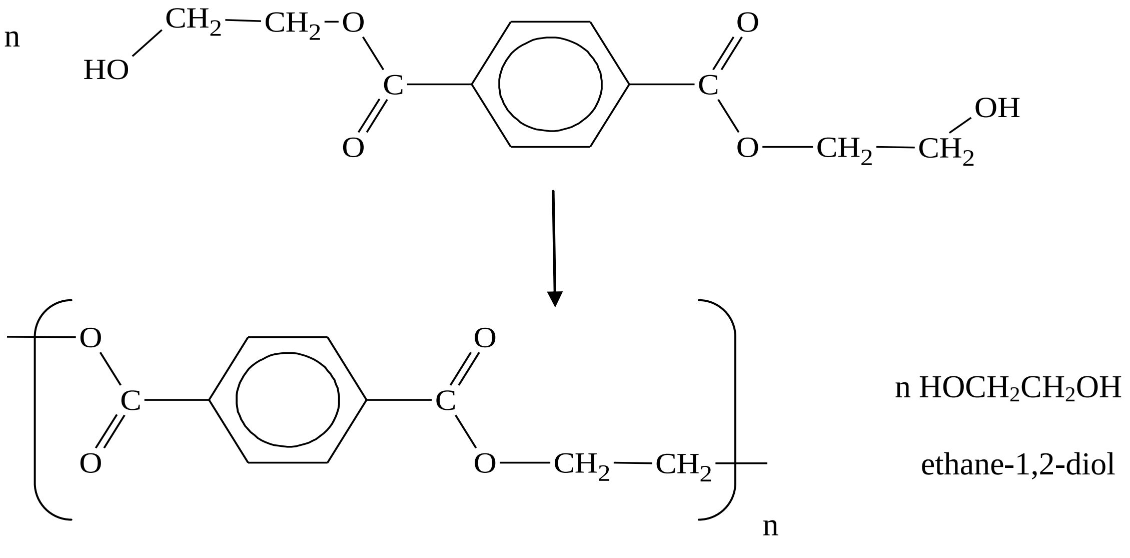
The starting materials are the dimethyl ester of 1,4-benzenedicarboxylic acid (terephthalic acid) and ethan-1,2-diol (ethylene glycol).

They are heated to 210 °C when transesterification occurs.



At this temperature the methanol boils off from the intermediate compound.

On raising the temperature to 270 °C polymerisation takes place

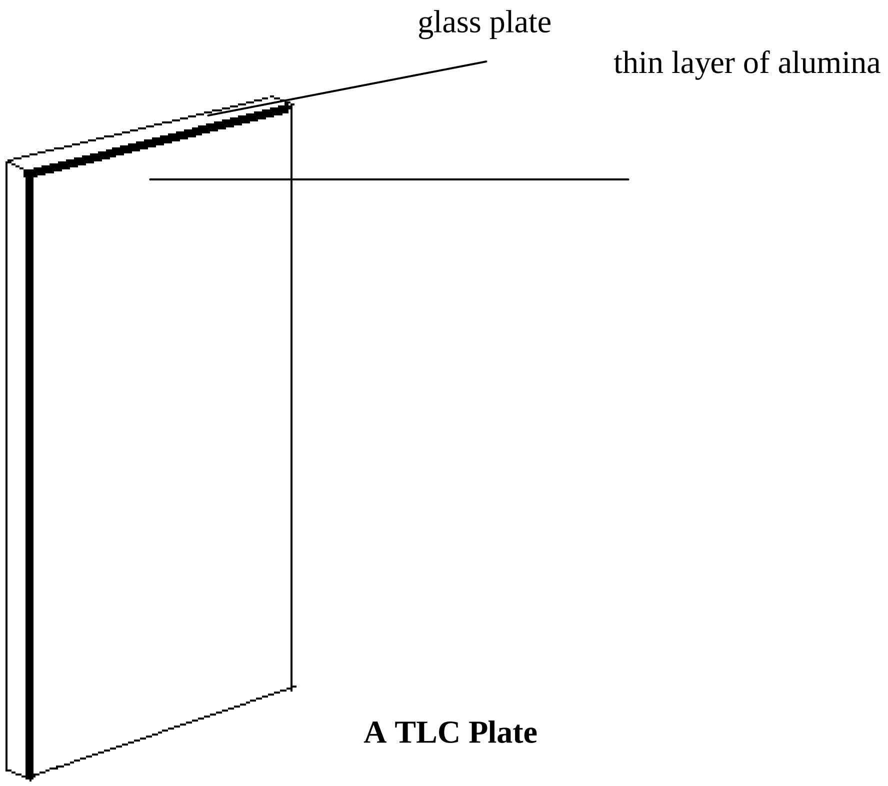


Terylene

(l) Chromatography

Thin layer chromatography (TLC)

In chromatography, components of mixtures are separated by the different ways they distribute themselves between a stationary phase and a moving or mobile phase. In TLC the stationary phase is a uniform thin layer of silica gel or alumina spread over the surface of a thin glass plate or plastic sheet.



A TLC Plate

The plate is spotted with a small sample of the mixture. The plate is then suspended in a tall vessel with the spot just above the surface of the solvent. The vessel is often covered so that the plate is surrounded by solvent vapour. As the solvent front rises up the plate, the components separate and the plate may be removed and developed as necessary. Identification can be made from R_F values.

The **retardation factor** or R_f value is defined as:

$$\frac{\text{Distance moved by component}}{\text{Distance moved by solvent front}}$$

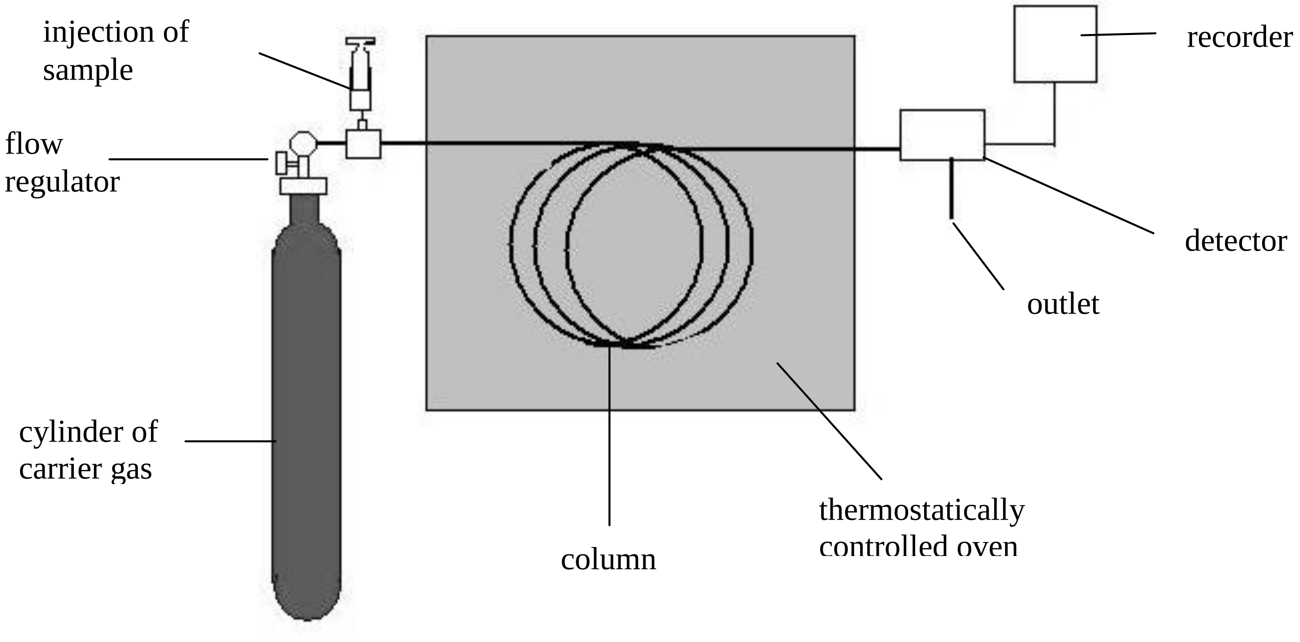
It is easy to measure R_f values if the components are coloured but if they are not visible the plate may have to be developed with a reagent that makes the components visible. In some cases the components may be seen under ultraviolet light.

Gas Liquid Chromatography

This is a highly sensitive method for separating organic mixtures and may be used quantitatively and is also used in conjunction with mass spectrometry.

A schematic instrument is shown below.

The mobile phase is an inert carrier as such as nitrogen, argon, helium etc.
The stationary phase is an inert non-volatile oil supported upon solid particles within a long coiled tube (or column). The column is contained within a thermostatically controlled oven.
As each component of the injected mixture emerges from the column, it is detected and recorded.
The components distribute themselves between the carrier gas and the oil in the column so some move more quickly than others do, through the instrument.



The technique is very accurate and is used for determining drugs in body fluids such as alcohol in blood.

In analysis, the components of a mixture may be identified by the time taken for the component to reach the detector. (The retention time). By integrating the area under a peak in the recording of the detector, the amount of a component present may be estimated.

High Performance Liquid Chromatography

The basic principle is to force the mixture to be analysed a column of the stationary phase (small particles in a small diameter tube), by pumping a liquid, the mobile phase, through the tube. By pumping the liquid under pressure the retention times are reduced and better separations are achieved. By careful selection of the chemical nature and the particle size of stationary phase, the mobile phase, the diameter of the tube, the temperature and the pressure, very good separations of complex mixtures can be achieved.

Components may be identified by their retention times and, just like GLC, the areas under peaks found by integration.

Applications of HPLC

- Isolation and purification of compounds.
- Chemical separations
- Identification of compounds
- Determination of concentration of a compound. Usually this involves constructing a calibration curve from known concentrations.

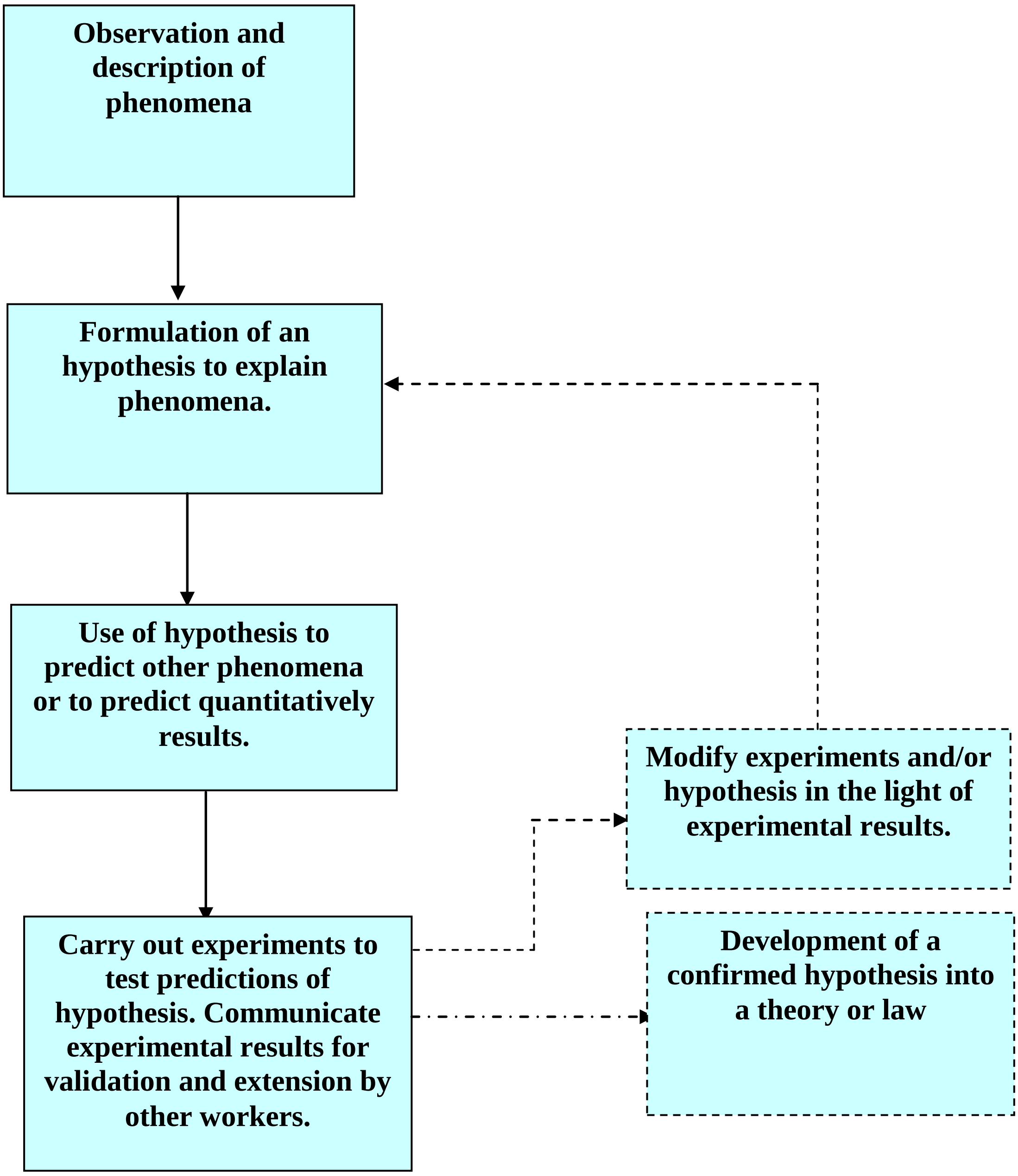
Topic 14 The process of how science work

Candidates should be able to:

(a) *understand and use the methods scientists employ in determining the accuracy, reliability and validity of their own and others' work;*

(b) *appreciate the methods scientists employ in developing their own and others' work to produce new materials and applications, for example in natural product synthesis, using computational chemistry and in aspects of nanotechnology.*

(a) The scientific method may be summarised as follows.



The specification asks candidates to consider each of the following.

- Accuracy

All physical measurements have an accuracy. This may be illustrated by the following given measurements of distance, 1 cm, 1.0 cm and 1.00 cm.

Of the three, 1.00 cm is the most accurate and implies a distance of 1.00 ± 0.01 cm.

Errors are additive and any quantity which has been found using a number of different measurements cannot be more accurate than the least accurate of all the measurements.

- Reliability

Scientists must vouch for the reliability of their work.
All procedures undertaken must be recorded in detail so that work can be repeated.
Multiple operational runs must be undertaken to eliminate spurious errors.
When many factors are being studied it is usual to change only one variable at a time.

- Validity

In order for scientific work to be valid it must be complete in every detail so that any other workers in the field can refer to the original work and be able to reproduce it.

(b) Candidates are expected to appreciate the methods scientists employ in developing their own and others’ work to produce new materials. The production of new materials is usually a commercial decision and the decision to produce is an economic one.

Before any development of a new material is undertaken various points must be considered, including the following

- The siting of the plant.
- Market research as to the viability of selling the product.
- Research and development on the process. This may include using the work of the company’s staff and of other scientists.
- The building of a pilot plant.
- Thorough costing of the process and predictions of selling price and the time taken for the company to make a profit on the operation.
- Mass and energy balances for the process.
- Safety and environmental considerations.
- Copyright and patent legislation.
- Scale of operation.
- Should the process be a continuous process or a batch process?

The specification requires candidates to be aware of the part scientists play in natural product synthesis.

Natural product synthesis may be thought to have begun in 1828 with the work of Frederich Wöhler who formed urea from ammonium cyanate

$$NH_4CNO \rightarrow CO(NH_2)_2$$

In modern laboratories, steps in the synthesis of a natural product are planned using computer programmes which suggest possible synthetic routes. It has been found that the use of computers can save much time being wasted down blind alleys. In addition, nanotechnology may be used in synthetics steps such as catalytic hydrogenation.

4-Aminophenol has been formed by the catalytic hydrogenation of 4-nitrophenol using nano nickel particles.