Indira Gandhi National Open University
School of Sciences

BCHCT-133
CHEMICAL ENERGETICS, EQUILIBRIA AND FUNCTIONAL ORGANIC CHEMISTRY-I

Block

4

OXYGEN CONTAINING ORGANIC COMPOUNDS

OXYGEN CONTAINING ORGANIC COMPOUNDS

The important classes of organic compounds with functional groups containing oxygen are alcohols, phenols, ethers, aliphatic aldehydes and ketones, aromatic aldehydes and ketones, carboxylic acids and their derivatives. In this Block, we shall study the chemistry of five classes of compounds, *viz*., (i) alcohols (ii) phenols (iii) ethers (iv) aliphatic aldehydes and ketones, and (v) aromatic aldehydes and ketones . Another important class of oxygen containing organic compounds is carboxylic acids and their derivatives. The chemistry of these compounds will be taken up in third semester course.

This Block has five Units. Units 15 and 16 are on alcohols and phenols, respectively. An alcohol has a −OH group bonded to an aliphatic carbon atom. In a phenol, a –OH group is bonded to an aromatic carbon atom. In these Units, we shall discuss laboratory and industrial preparations of alcohols and phenols. We shall also explain the behavior of alcohols and phenols as weak acids and illustrate their chemical properties.

Unit 17 deals with the chemistry of ethers. In this unit, first we shall discuss different types of ethers and their preparations. After that, we shall explain their physical and chemical properties.

The chemistry of aliphatic and aromatic aldehydes and ketones is discussed in Unit 18 and Unit 19, respectively In these units we will study the preparation and properties of these compounds in detail.

Expected Learning Outcomes

After studying this block, you should be able to:

- classify and draw structures of simple alcohols, phenols, ethers, aliphatic and aromatic aldehydes and ketones;
- outline the methods of preparation of the above classes of compounds;
- describe the physical properties, chemical reactions and laboratory detection of compounds belonging to the above classes;
- explain the mechanism of nucleophilic substitution and elimination reactions of alcohols, and
- describe the mechanism of nucleophilic addition to carbonyl group of aldehydes and ketones.

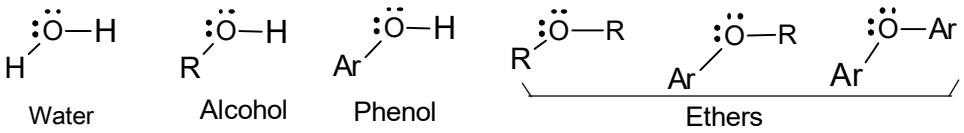
UNIT 15

ALCOHOLS

Structure

15.1 INTRODUCTION

In the previous Unit, we described the aryl halides. In this Unit and in subsequent Units, we will discuss oxygen-containing organic compounds. Alcohols and phenols can be regarded as mono-alkyl and mono-aryl substitution products of water, respectively. Similarly, ethers can also be considered as derivative of water in which both the hydrogen atoms of the water molecule have been replaced by alkyl or aryl groups or by both. We shall study the chemistry of phenols and ethers in Unit 16 Unit 17, respectively.



In this unit, we shall take up chemistry of alcohols in detail. Alcohols may also be defined as hydroxy (−OH) derivatives of hydrocarbons. Monohyric alcohols have general formula $C_nH_{2n+1}OH$. Alcohols provide us with a great number of useful products, which include germicides, antifreeze agents, pharmaceuticals,

explosives, solvents and plastics. Alcohols also play central role in synthetic organic chemistry. They can be converted into many other types of compounds, including alkenes, alkyl halides, ethers, aldehydes, ketones, and carboxylic acids. These compounds can also be converted back to alcohols.

In this unit, first we will discuss the classification of alcohols, their structure and then give an outline of the different methods available for the preparation of alcohols. We will then review the physical properties of alcohols. Finally, we will consider the chemical properties of alcohols and diols.

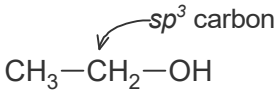
Expected Learning Outcomes

After studying this unit, you should be able to:

- ❖ classify alcohols;
- ❖ outline the preparation of alcohols;
- ❖ describe the commercial methods for manufacture of alcohols;
- ❖ define the physical properties of alcohols;
- ❖ explain acidic and basic nature of alcohols;
- ❖ describe the reactions of alcohols with active metals such as Li, Na, and K;
- ❖ explain the nucleophilic substitution reactions and acid-catalysed dehydration reactions of alcohols;
- ❖ describe various reagents used for oxidation of alcohols; and
- ❖ explain pinacol-pinacolone rearrangement .

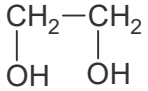
15.2 CLASSIFICATION OF ALCOHOLS

Hydrocarbons in which an sp^3 carbon carries a hydroxyl (−OH) group are called alcohols. Depending on the number of hydroxyl groups present in the molecule, alcohols are called monohydric (1 −OH group), dihydrics (2 −OH groups), trihydric (3 –OH groups) or polyhydric (more than 3 −OH groups).



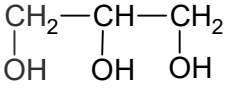
Ethanol
(ethyl alcohol)

Monhydric alcohol



1,2-Ethanediol or
ethane-1,2-diol
(ethylene glycol)

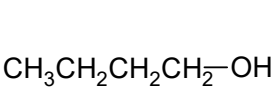
Dihydric alcohol



1,2,3-propanetriol or
propane-1,2,3-triol
(glycerol, glycerine)

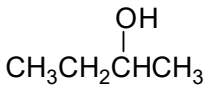
Trihydric alcohol

Monohydric alcohols, like the alkyl halides, may be subdivided into primary, secondary and tertiary alcohols. Primary alcohols contain a -–CH_2–OH group, secondary alcohols contain the R_2CH–OH group and tertiary alcohols contain the R_3C–OH group. For example, the molecular formula C_4H_9OH can represent the following four monohydric alcohols:



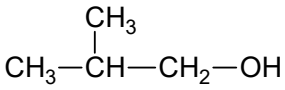
1-Butanol
(butyl alcohol)

Primary alcohol



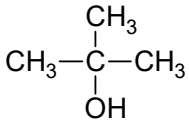
2-Butanol
(*sec*-butyl alcohol)

Secondary alcohol



2-Methyl-1-propanol
(isobutyl alcohol)

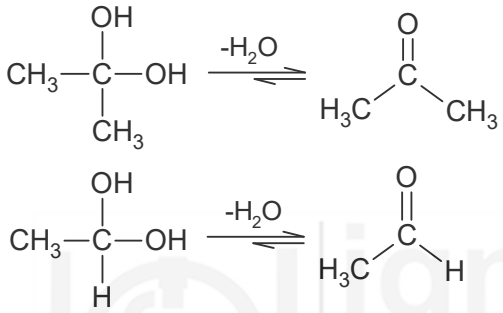
Primary alcohol



2-Methyl-2-propanol
(*tert*-butyl alcohol)

Tertiary alcohol

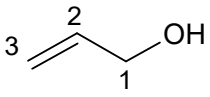
Unlike gem dihalides, gem diols are unstable as they undergo dehydration to the corresponding more stable aldehyde or ketone.



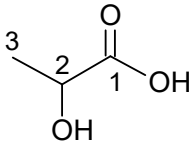
Just to recall, in IUPAC naming of alcohols, the longest chain of carbon containing the hydroxyl group is selected as the parent alkane and numbered from the end closer to hydroxyl group. Finally *-e* of the parent alkane is replaced with suffix *-ol*. For naming polyhydric alcohols, the *-e* of the alkane is retained and suffix *–diol* (for two hydroxyl groups) , triol (for three hydroxyl groups) and so on is added, depending on the number of hydroxyl groups present in a molecule. The common names for alcohols are derived by naming the alkyl group bonded to hydroxyl group and then adding the word alcohol. Common names of several low molecular weight alcohols are still widely used. Therefore, we have used both the common names and the IUPAC names. The common names are given in parentheses below the IUPAC names of the compounds.

In substituted alcohols, the number for the hydroxyl group is often placed between the infix and suffix. For example, IUPAC name of *tert*-butyl alcohol may be written as 2-methylpropan-2-ol or either 2-methyl-2-propanol, both names are acceptable.

Alcohols with double or triple bonds are named using the *-ol* suffix on the alkene or alkyne by replacing their *-e*. In such alcohols, numbering is done in such a way so as to give the hydroxyl group the lowest possible number. When the hydroxyl functional group is present together with a functional group of higher nomenclature priority such as aldehyde, ketone, carboxylic acid derivative or carboxylic acid group, then it must be cited and located by the prefix *hydroxy* and with an appropriate number. For further illustration, some examples are given below.



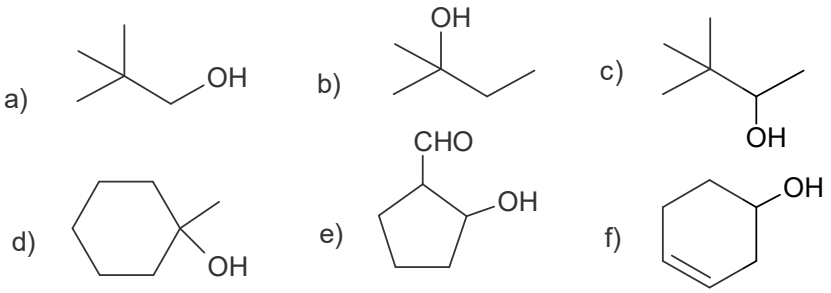
2-Propen-1-ol
(allyl alcohol)



2-Hydroxypropanoic acid
(lactic acid)

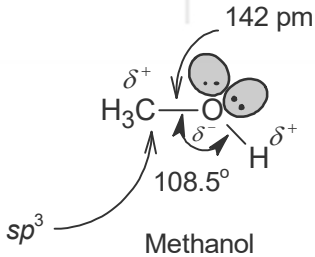
SAQ 1

Classify each alcohol as primary, secondary or tertiary. Also write IUPAC names of each alcohol.



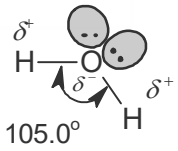
15.3 STRUCTURE OF ALCOHOLS

The Hydroxyl functional group (–OH) of an alcohol is bonded to a sp^3 hybridised carbon. The oxygen atom of an alcohol is also sp^3 hybridised. The two sp^3 hybridised orbitals of oxygen form two σ bonds, one with hydrogen atom and one with carbon atom. Each of the remaining two sp^3 hybridised orbitals of oxygen contain an unshared pair of electrons.



Methanol

μ = 1.7 D



Water

μ = 1.8 D

The geometry around oxygen atom of an alcohol molecule is essentially the same as that in water. The measured C−O−H bond angle in methanol is 108.5°, very close to the perfectly tetrahedral angle of 109.5°. Further, both the C−O and the O−H bonds are polar covalent bonds due to the high electronegativity of the oxygen atom. As shown above, in case of methanol molecule, carbon and hydrogen bear partial positive charges and oxygen bears a partial negative charge. The presence of these polar bonds makes alcohols to be polar molecules. The dipole moment (μ) of methanol is very similar to water. You will find, in alcohols their physical and chemical properties are due to these structural aspects i.e. presence of lone pairs of electrons on oxygen and polar bonds (C−O and O−H). We will take up physical and chemical properties after a brief discussion on the preparation of alcohols.

15.4 PREPARATION OF ALCOHOLS

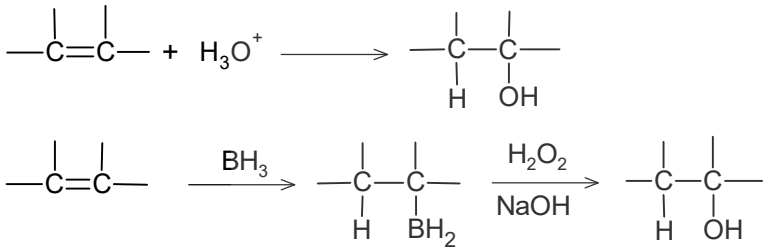
In this section, we will first consider the general methods for the laboratory preparation of alcohols and then take up the industrial preparation of a few important members of this class of compounds.

15.4.1 General Methods of the Preparations of Alcohols

Alcohols can be prepared from alkenes, alkyl halides, esters, ethers, aldehydes, ketones and from the Grignard reagents. The general reactions of these methods of preparation are summarised below in Table 15.1.

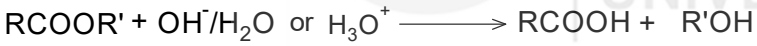
Table 15.1: Preparation of Alcohols

i) From alkenes

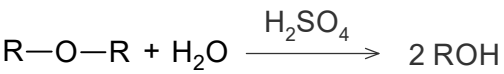


ii) From alkyl halides

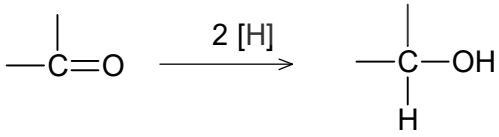
iii) From esters



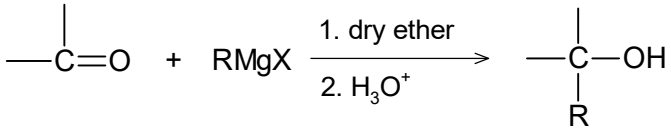
iv) From ethers



v) From aldehydes and Ketones

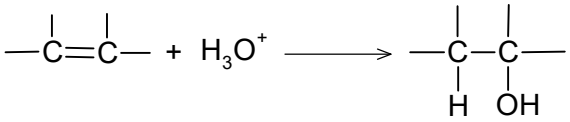


vi) From Grignard reagent

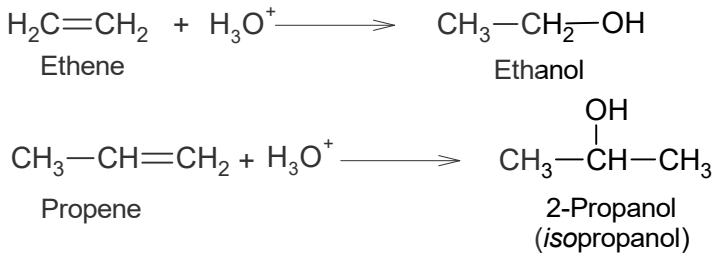


Let us study these methods of preparation in a brief manner.

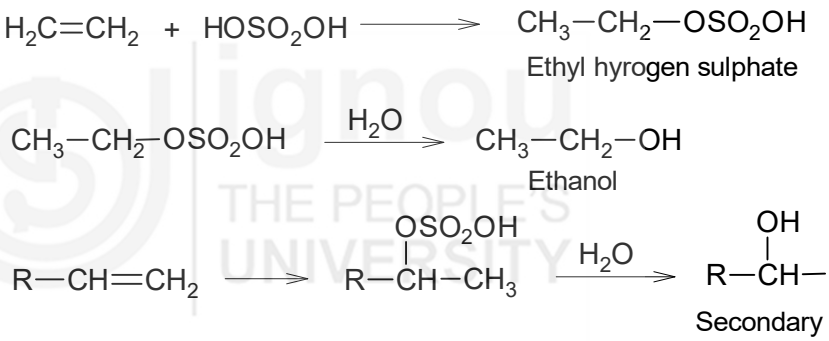
i) **From Alkenes:** We have already described the acid catalysed hydration of alkenes in Unit 17 of the first Semester chemistry course. In this reaction, the direction of addition is governed by the Markownikoff's rule. The general reaction is,



This method is employed for the preparation of several alcohols:

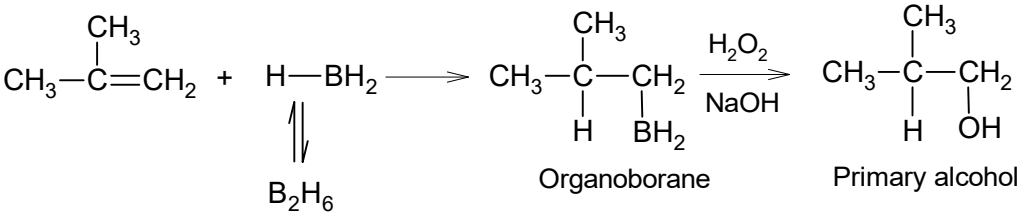


If sulphuric acid is used as the acid catalyst, then the reaction proceeds as follows:



These reactions are useful for laboratory synthesis as well as industrial preparation of alcohols.

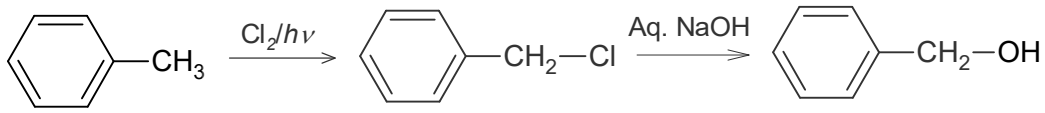
Hydroboration-oxidation method is also important because it leads to overall, effective anti-Markownikoff addition of water. We have already described this method earlier in Unit 17 of the first Semester chemistry course. In this method diborane, B_2H_6, is allowed to react with an alkene in an inert solvent such as ether. Diborane is in ready equilibrium with the Lewis acid borane, BH_3, which adds to the alkene. Here, the electron seeking (acidic) part of reagent is boron, and addition of BH_3 proceeds according to MarkowniKoffs rule to give an intermediate organoborane compound. Oxidation of this intermediate with basic hydrogen peroxide converts it to an alcohol.



ii) **From Alkyl Halides:** Hydrolysis of alkyl halides with an aqueous solution of an alkali is a common and convenient method for the synthesis of alcohols, e.g.,

$$\underset{\text{Alkyl halide}}{R{-}X} + OH^-/H_2O \longrightarrow \underset{\text{Alcohol}}{ROH} + X^-$$

These reactions can proceed *via* S_N1 or S_N2 mechanism which we have described in Unit 13. A useful application of this method is in the synthesis of phenylmethanol (benzyl alcohol) from (chloromethyl)benzene (benzyl chloride) which is itself obtained from methylbenzene (toluene) as shown below:



Methylbenzene (Chloromethyl)benzene Phenylmethanol

iii) **From Esters:** Alcohols may be prepared by base or acid catalysed hydrolysis of esters.

$$\underset{\text{Ester}}{RCOOR'} + OH^-/H_2O \text{ or } H_3O^+ \longrightarrow \underset{\text{Caboxylic acid}}{RCOOH} + \underset{\text{Alcohol}}{R'OH}$$

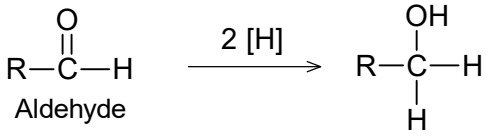
This method is used industrially as certain alcohols occur in nature as esters.

iv) **From Ethers:** Alcohols are also obtained by heating ethers with dilute sulphuric acid under pressure:

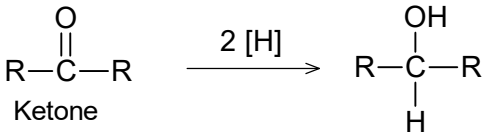
$$C_2H_5{-}O{-}C_2H_5 + H_2O \xrightarrow{\Delta} \underset{\text{Ethanol}}{2\ C_2H_5{-}OH}$$

This method is important industrially as the ethers are formed as by-products in the preparation of some alcohols. We will discuss this reaction further in detail in Unit 17.

v) **From Aldehydes and Ketones:** Alcohols are also obtained by the reduction of aldehydes and ketones with sodium and ethanol or H_2/Ni or by metal hydrides, such as lithium aluminium hydride. Aldehydes give primary alcohols while ketones secondary alcohols. We will discuss this reaction further in detail in Unit 18.

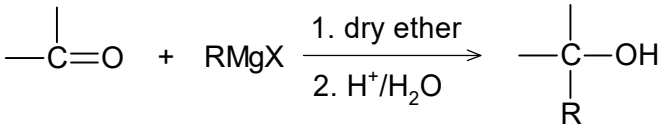


Aldehyde Primary alcohol



Ketone Secomdary alcohol

vi) **From Grignard Reagents:** Primary, secondary and tertiary alcohols are also prepared by the reaction of suitable carbonyl compound with the Grignard reagent. You have already studied this method in Unit 13.



SAQ 2

Write chemical equations, showing all necessary reagents, for the preparation of i) 2-butanol and ii) 1-butanol by each of the following methods:

a) from an alkene

b) from an alkyl halide

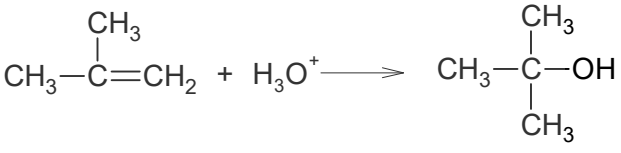
c) by the Grignard reagent

d) by the reduction of ketone/aldehyde.

15.4.2 Commercial Preparations of Alcohols

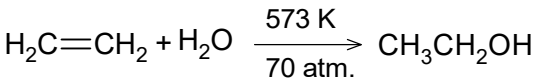
Alcohols are of great commercial importance. In this Sub-sec. you will learn how large quantities of these compounds are prepared from different abundant natural sources.

i) **By the catalytic hydration of alkenes using dilute acid solution:** We have already come across the conversion of alkenes to alcohols in connection with the general methods for small scale preparation of alcohols. The method has been extended to commercial preparations of some alcohols, such as ethanol and 2-propanol. The reactions for the preparation of ethanol and 2-propanol have been already shown. Similarly, hydration of 2-methylpropene (isobutene) in aqueous acidic medium gives *tert*-butanol.



2-Methylpropene — 2-Methyl-2-propanol (*tert*-butanol)

In a recent modification ethene is hydrated directly by passing a mixture of the alkene and steam over a solid acid catalyst (phosphoric acid or silica at 573 K at a pressure of about 70 atmospheres:



Ethene — Ethanol

ii) **By heating a mixture of carbon monoxide and hydrogen under pressure in the presence of a catalyst:** This method is used for the preparation of methanol.

$$CO + 2H_2 \xrightarrow[533\ K,\ 150\ atm]{Cu\ Catalyst} \underset{Methanol}{CH_3OH}$$

iii) **By the oxidation of natural gas:** A mixture of methanol, ethanol, propanols and butanols is obtained.

Catalytic oxidation of methane gives methanol:

$$CH_4 + 1/2\ O_2 \xrightarrow[473\ K]{Cu} \underset{Methanol}{CH_3OH}$$

iv) **Fermentation of starch:** This method has been the source of ethanol, the constituent of alcoholic beverages responsible for their intoxicating action, since times immemorial. Common sources of starch are wheat, barley, potato, etc. These are mashed with hot water and heated with malt (germinated barley) which contains the enzyme 'diastase'. Enzymatic hydrolysis of starch at 323 K gives the sugar maltose:

$$(C_6H_{10}O_5)_n + n/2\ H_2O \xrightarrow{Diastase} n/2\ C_{12}H_{22}O_{11}$$

Enzymes are a particularly important group of proteins. They are the catalysts which enable living organism to bring about necessary reaction.

The product is cooled to 303 K and fermented with yeast, which contains various enzymes. One of these, 'maltase', converts maltose to glucose and the other 'zymase' decomposes glucose to ethanol:

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

$$C_6H_{12}O_6 \xrightarrow{Zymase} \underset{Ethanol}{CH_3CH_2OH} + 2\ CO_2$$

Fermentation of molasses (a by-product of sugar industry) also gives ethanol.

$$\underset{Cane\ sugar}{C_{12}H_{22}O_{11}} + H_2O \xrightarrow{Inverase} 2\ C_6H_{12}O_6$$

$$C_6H_{12}O_6 \xrightarrow{Zymase} \underset{Ethanol}{CH_3CH_2OH} + 2\ CO_2$$

Ethanol may also be prepared from glucose directly. Grape juice, a rich source of glucose, ferments to produce wine with a maximum alcoholic content of approximately 12% by volume. The alcoholic content of liquors is usually designated in terms of proof spirit, 100 proof indicating an alcoholic content of about 50% by volume. The term "proof spirit" supposedly has its origin in an early and rather crude analytical procedure for determining the alcoholic content of whisky. Whisky of high alcoholic content, when poured onto the gun powder would ignite and burn with a flame sufficiently hot to ignite the powder also. This was 'proof' of spirit content. If the gunpowder failed to ignite, the presence of too much water was indicated, as the powder would have **become** too wet to burn.

Absolute ethanol: Regardless of the methods of manufacture, all aqueous solutions of ethanol on fractional distillation yield a 'constant boiling mixture' of 95 percent ethanol and 5 per cent water which is known as rectified spirit. A constant boiling mixture of two or more liquids, called an azeotrope, cannot be separated by fractional distillation. In order to obtain absolute or 100% pure ethanol, water has to be removed by methods other than fractionation. In the laboratory, rectified spirit is refluxed over quick lime for about 6 hours, and then allowed to stand overnight. On distillation, this gives 99.5 % or lime distilled alcohol. The remaining water is removed by reaction with magnesium metal, by which water is converted into insoluble $Mg(OH)_2$.

In industry, calculated amount of benzene is added to the rectified spirit. Distillation of the mixture yields three fractions:

At 338 K, a constant boiling mixture of ethanol, benzene and water (a 'ternaryazeotrope').

At 341 K, a constant boiling mixture of ethanol and benzene (a 'binary azeotrope').

At 351 K, pure ethanol or absolute alcohol.

SAQ 3

How can the following conversion be carried out on the commercial scale?

a) Ethanol from ethene

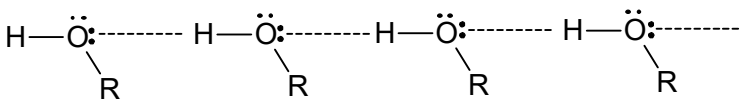
b) Methanol from carbon monoxide

c) Ethanol from cane sugar.

15.5 PHYSICAL PROPERTIES

The physical properties of alcohols can be understood if we consider the fact that alcohols are similar in structure to water. As mentioned earlier, the oxygen in an alcohol molecule is in the sp^3 hybridised state and has two unshared pairs of valence electrons. Similar to H−O bonds in water molecules, the C−O and O−H bonds of hydroxyl group of alcohols are polar bonds.

As might be expected, molecules of alcohol like water are strongly hydrogen bonded. The formation of hydrogen bonds leads to the association of a large number of alcohol molecules. These molecular associations have to be broken up before boiling occurs. Hence, alcohols have the higher boiling points when we compared to other molecules of the same size.



Hyrogen bonding in alcohol molecules

Table 15.2 compares the boiling points of some alcohols and chloro compounds with the same carbon skeletons.

Table 15.2: Comparison of the boiling points of some alcohols and chloroalkanes

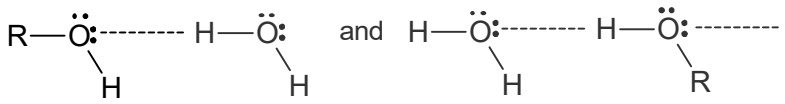
Alcohol	Bp/K	Chloroalkane	Bp/K
CH_3-OH	337	CH_3-Cl	249
CH_3CH_2-OH	351	CH_3CH_2-Cl	286
$CH_3CH_2CH_2-OH$	370	$CH_3CH_2CH_2-Cl$	319

Further, in a group of isomeric alcohols, the primary alcohol has the highest boiling point and the tertiary, the lowest, with the secondary alcohols having an intermediate value. In the straight chain compounds, the van der Waals attractive forces are relatively large due to the large surface area. In the branched chain structures, the molecule tends to become spherical and hence with the decrease in surface area, the attractive forces are also reduced. The physical properties of some alcohols are summarised in Table 15.3.

Table 15.3: Physical properties of some alcohols

IUPAC Name	Common name	Formula	Bp/K	Density/ kg dm^{-3}	Solubility in water
Methanol	Methyl alcohol	CH_3O-H	337	0.79	infinite
Ethanol	Ethyl alcohol	CH_3CH_2-OH	351	0.79	infinite
1-Propanol	Propyl alcohol	$CH_3CH_2CH_2-OH$	370	0.80	infinite
2-Propanol	Isopropyl alcohol	$(CH_3)_2CH-OH$	355	0.79	infinite
1-Butanol	Butyl alcohol	$CH_3CH_2CH_2-OH$	380	0.81	8.3 g/100 cm^3

The water solubility of lower alcohols can also be explained by their ability to form hydrogen bonds with water molecules.

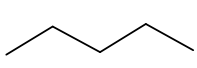


Hyrogen bonding with water molecules

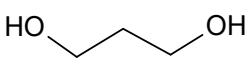
The solubility of alcohols in water decreases as the length of the hydrocarbon chain of the alcohol molecule increases. As discussed in earlier units, the hydrocarbon character of the molecule, i.e., hydrophobic character, increases in higher alcohols.

SAQ 4

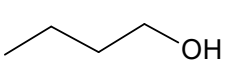
Arrange following compounds in order of their increasing boiling points:



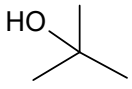
Pentane



1,3-Propandiol



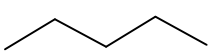
1-Butanol



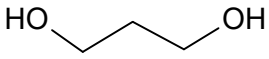
2-Methyl-2-propanol

SAQ 5

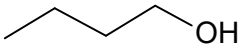
Arrange following compounds in order of their increasing solubility in water:



Pentane



1,3-Propandiol



1-Butanol

15.6 CHEMICAL PROPERTIES

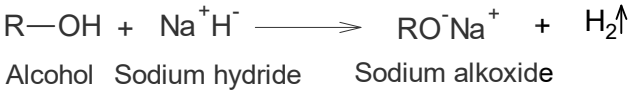
Recall the structure of an alcohol molecule. As mentioned earlier, alcohols have two polar covalent bonds, the C−O bond and the O−H bond. Due to high electronegativity of oxygen both the bonds are polarised so that oxygen is electron rich (nucleophilic) and both carbon and hydrogen are electron deficient (electrophilic). The nucleophilicity of oxygen is further enhanced by the presence of two lone electrons pairs on oxygen.You will find that all these structural characteristics will be very useful in predicting the reaction path and mechanism of reactions of alcohols.

The chemical reactions of alcohols involve breaking of either the O−H bond or the C−O bond. In this section, we shall first take up the reactions of O−H bond and C−O bond. Then, we shall look at the oxidation reactions of alcohols. It is observed that many reactions of alcohols are initiated by either accepting a proton or donatinga proton. Thus before going in details of these types of reactions of alcohols, let us review acidic and basic properties of alcohols.

15.6.1 Acidic and Basic Nature of Alcohols

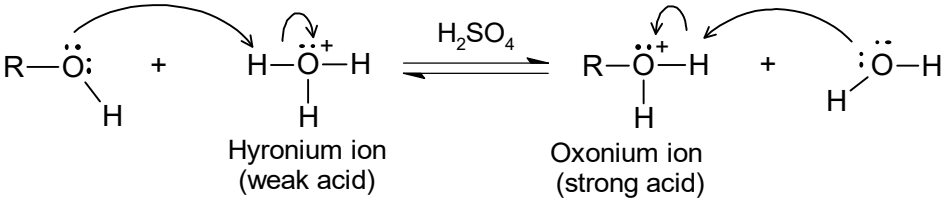
Molecules that act both as acids and as bases are called amphoteric *(ampho,* Greek, both). Examples are water, alcohol, etc.

Alcohols can function as both weak acids (proton donors) and weak bases (proton accepters) similar to water. Polar nature of O−H bond is mainly responsible for the acidic behavior of alcohols. Alcohols are much stronger acids than alkanes (by roughly 10^{30} times), and nearly that much stronger than ethers. An alcohol can lose a proton to a strong base yielding an alkoxide ion, RO^-. In the reaction given below, alcohol behaves as an acid.

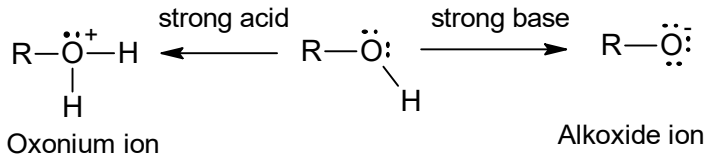


Alkoxides are strong bases, generally stronger than hydroxides. To prepare an alkoxide from an alcohol, we need a base stronger than the alkoxide itself, such as, alkali metal hydrides, NaH, KH, etc.

The oxygen atom of the alcohol molecule has two lone pairs of electrons. These lone pair electrons make alcohols act as a base. For example, in acidic solutions, alcohols are protonated to form oxonium ion. In the reaction given below, alcohol behaves as a base.



In dilute aqueous solutions, alcohol has approximately the same pK_a values as water. For example, the pK_a of methanol in water is 15.5, while that of pure water is 15.74. Therefore, methanol is as acidic as water. Now we can conclude that alcohols are both weak acids and weak base depending on the reaction conditions.



Alcohols are both acidic and basic

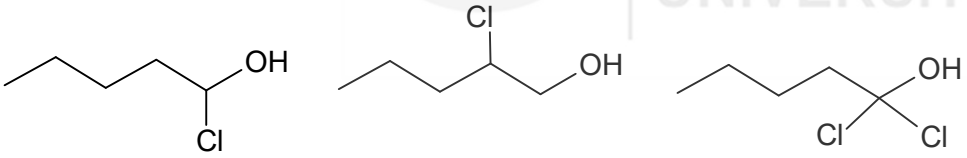
As mentioned above, acidic nature of alcohol is due to the polar nature of the O−H bond. The electron releasing/donating groups such as alkyl group if attached to α–carbon, increase electron density on oxygen tending to decrease the polarity of O−H bond. This decreases the acid strength of substituted alcohol. Reverse is true with electron attracting/withdrawing group. Electron withdrawing group at α–carbon, further increases the polarity of O−H bond. The effect of substituents decreases with the distance from the carbon to which O−H group is attached.

We can now write the order of decreasing acid strength.

$H_2O > CH_3OH >$ primary > *sec* > *tert*-alcohols

SAQ 6

Arrange following alcohols in order of increasing acidity.



15.6.2 Reactions of the O–H Bond

In the previous sub-section, we have seen that with strong base alcohols furnish alkoxides which are valuable both as strong bases and as nucleophiles. Strong acids can protonate alcohols into oxonim ions.This protonation process converts −OH (a poor leaving group) into $-OH_2^+$ (a good leaving group) and enabling subsequent nucleophilic substitution or elimination reactions to take place in alcohols similar to alkyl halides. Now, we will take up reactions of alcohols in detail.

i) Reaction with Active Metals:

Strongly electropositive metals like K, Na, Mg, Al and Zn liberate hydrogen from alcohols and form alkoxides, e.g.,

$$2C_2H_5OH + 2Na \longrightarrow 2C_2H_5O^-Na^+ + H_2\uparrow$$

Ethanol Sodium ethoxide

The alkoxides of the alkali metals are strong bases (nucleophiles) that enter into S_N2 substitution of halogen from alkyl halides. This reaction, referred to as the Williamson ether synthesis, is best used to prepare ethers.

$$CH_3O^-Na^+ + C_2H_5{-}I \xrightarrow{S_N2}$$

Sodium iodoethane methoxide

$CH_3{-}OC_2H_5 + NaI$

Ethyl methyl ether

In the above reaction, the oxygen-hydrogen bond of the alcohol is broken and the alcohol, thus behaves as an acid. We have mentioned in the previous subsection that alcohols are, however, weaker acids than water. Therefore, the conjugate base of alcohols, the alkoxide ion, is a stronger base than the hydroxide ion, the conjugate base of water. The order of reactivity for different types of alcohols in this reaction is **CH_3OH > primary > *sec.* > *tert***. This order is the same as given earlier for the acidity of alcohols.

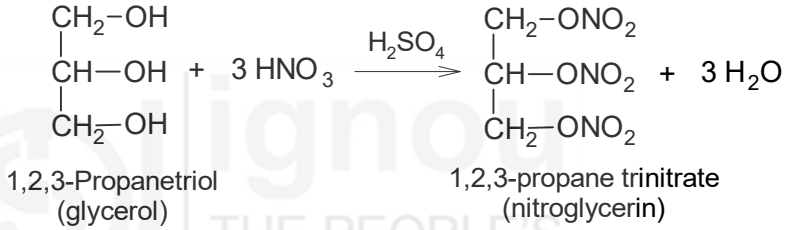
ii) Esterification:

Another interesting reaction of alcohols is with acids to form esters and water. In this reaction, the oxygen-hydrogen bond in the alcohol is broken.

$$RCOOH + R'OH \rightleftharpoons RCOOR' + H_2O$$

This reaction is known as esterification. These types of reactions will be discussed again in greater detail in the third semester DSC course.

Any inorganic acid can be used in place of carboxylic acid to produce inorganic ester. Inorganic esters are valuable commercial products. For instance, nitroglycerin is readily prepared by the esterification of nitric acid with glycerol.



1,2,3-Propanetriol (glycerol)

1,2,3-propane trinitrate (nitroglycerin)

Nitroglycerin is an explosive used to make dynamite. Similarly, sodium laurylsulphate, a synthetic detergent, can be obtained by esterification of lauryl alcohol,

1-Dodecanol (lauryl alcohol)

1-Dodecanyl hydrohen sulphate (lauryl hydrogen sulphate)

Sodium-1-Dodecanyl hydrohen sulphate (sodium lauryl hydrogen sulphate)

Synthetic detergent

Another important ester is cellulose trinitrate (gun cotton). It is a product obtained when cellulose (a polysaccharide) is almost completely nitrated under conditionscarefully controlled to prevent degradation of the cellulose molecule.

$$[C_6H_7O_2(OH)_3]_n \xrightarrow{3n\ HNO_3/H_2SO_4} (C_6H_7O_2(ONO_2)_3]_n$$

Cellulose — Gun cotton

Gun cotton contains about 12-13% of nitrogen, is explosive and is used in the manufacture of smokeless powder.

Esterification of cellulose with acetic anhydride gives cellulose acetate; it is an ester but is not explosive. Cellulose acetate is used to produce thin fibers. From such fiber, the acetate fabrics are woven. Photographic film is also produced from cellulose acetate.

iii) Reaction with Grignard Regents:

Alcohols react with Grignard reagents to form alkanes.

$$R{-}OH + R'MgX \xrightarrow{\text{Ether}} R'H + Mg(OR)X$$

$$CH_3{-}OH + C_2H_5MgI \xrightarrow{\text{Ether}} C_2H_6 + Mg(OCH_3)I$$

Methanol — Methyl magnesium iodide — Ethane

15.6.3 Reactions of the C−O bond

We have seen above that the breaking of O−H bond in alcohols is readily achieved with strong bases. We have also mentioned that −OH group (a very poor leaving group) can be changed into a $-OH_2^+$ (a better leaving group) by strong acids. Subsequently, C−O may be broken; thereby leading to substitution or elimination reactions. Details of these reactions are as follows.

i) Substitution Reactions of Alcohols: The reactions of alcohols with HX, PX_3, $SOCl_2$, PCl_5 to prepare alkyl halides have already been briefly discussed in Unit 13.

$$R{-}OH + HX \longrightarrow R{-}X + HX$$

Alcohol — Hydrogen halide — Alkyl halide

$$3R{-}OH + PX_3 \longrightarrow R{-}X + H_3PO_4$$

Phosphorus trihalide — Alkyl halide

$$R{-}OH + SOCl_2 \longrightarrow R{-}Cl + SO_2 + HCl$$

Thionyl chloride — Alkyl chloride

$$R{-}OH + PCl_5 \longrightarrow R{-}Cl + POCl_3 + HCl$$

Phosphorous pentachloride — Alkyl chloride

Let us first look more closely at substitution reaction of alcohol with hydrogen halides (HX). Alcohols can undergo substitution reactions with HX under acidic conditions or in the presence of Lewis acid like anhydrous zinc chloride ($ZnCl_2$). The general reaction can be represented as,

$$R{-}OH + HX \underset{\text{or } ZnCl_2}{\overset{H^+}{\rightleftharpoons}} R{-}X + HX$$

Alcohol — Alkyl halide

Example

$$CH_3CH_2CH_2CH_2{-}OH + HBr \xrightarrow[\text{Heat}]{ZnCl_2} CH_3CH_2CH_2CH_2{-}Br + H_2O$$

1-Butanol — 1-Bromobutane

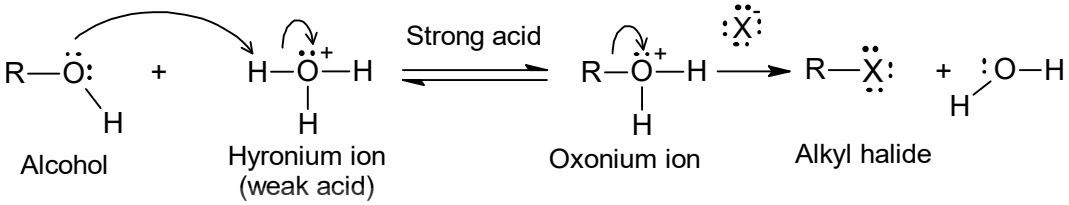
$$(CH_3)_3{-}OH + HCl \xrightarrow{ZnCl_2} (CH_3)_3{-}Cl + H_2O$$

2-Methyl-2-propanol — 2-Methyl-2-chloropropane

If we compare substitution reactions of alcohols and alkyl halides, we can notice that unlike alkyl halides, alcohols do not undergo substitution under neutral or alkaline condition. The reaction requires acidic conditions

A tertiary R_3C–OH most easily gives a carbocation and tends to react by the $S_N1$mechanism. It is very difficult for a primary RCH_2–OH to form a carbocation, but the primary structure is open to backside attack, so an S_N2 reaction is possible. A secondary alcohol R_2CH–OH may react by either $S_N1$or S_N2 mechanism.

(protonation of −OH group)) or catalysts like $ZnCl_2$. In Unit 13, we have seen that Cl^-, Br^- and I^- are good leaving-groups and weak bases. But, as you know, OH^- is a strong base and thus, a very poor leaving group. In acidic solution, alcohols get protonated to $-OH_2^+$, which is a good leaving group because it is lost as water, a weak base. A weak nucleophile, such as a halide ion can displace the water molecule to yield an alkyl halide.



The function of zinc chloride is similar to that of proton. Anhydrous zinc chloride is a powerful Lewis-acid with empty orbitals that can accept electrons from the oxygen atom of alcohol. The formation of a complex of $ZnCl_2$, with the alcohol oxygen weakens the C−O bond and thus, enhances the leaving ability of the hydroxyl group.

In substitution reactions of alcohols, the reactivity of the hydrogen halides is as follows:

HF < HCl < HBr < HI

Thus, the higher the acid strength and nucleophilicity of the halide ion, the higher will be the reactivity towards ROH.

The order of reactivity of alcohols towards hydrogen halides is as follows:

Methyl < primary < *sec* < *tert*-alcohols

Increasing reactivity of ROH towards HX

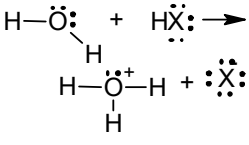
This order of reactivity forms the basis for the Lucas test which is used to differentiate primary, secondary and tertiary alcohols. The Lucas reagent is made up of concentrated HCl and $ZnCl_2$. Tertiary alcohols react immediately upon shaking with the Lucas reagent to produce an immiscible upper layer of alkyl chloride. Secondary alcohols react in 2-3 minutes, and primary alcohols do not react unless the mixture is heated.

Mechanism

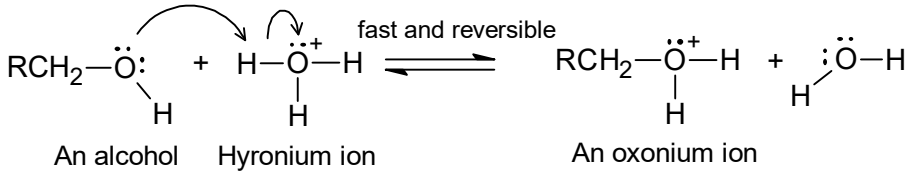
Like alkyl halides, primary alcohols react by the S_N2 mechanism, tertiary alcohols by S_N1 mechanism, and secondary alcohol by either an S_N1 or S_N2 mechanism.

The mechanism for the reaction of primary alcohols is as follows:

Step 1

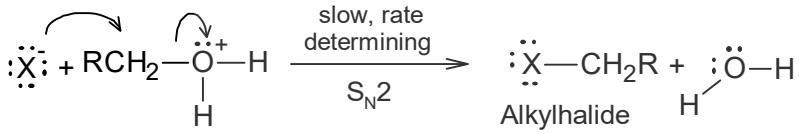


Addition of proton: When an aqueous solution of acid like HX is used, it forms a hydronium ion. Hydronium ion, actually acts as an acid and transfers proton to –OH group of an alcohol. The −OH group of the alcohol gives oxonium ion on accepting proton from hydronium ion. This process converts −OH, a poor leaving group, into $-OH_2^+$ which is a good leaving group.



Step 2

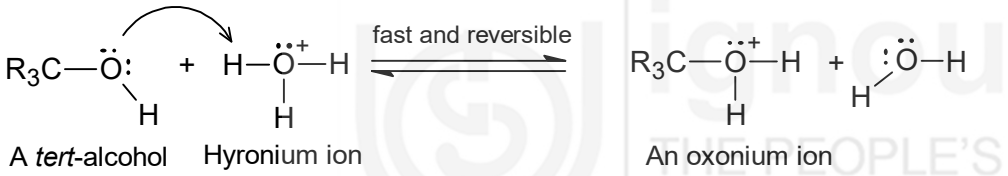
Nucleophile (halide ion) forms new bond with electrophilic carbon centre and simultaneously bond is broken with the leaving group to give stable molecule (an alkyl halide).



The mechanism for the reaction of tertiary alcohols is as follows:

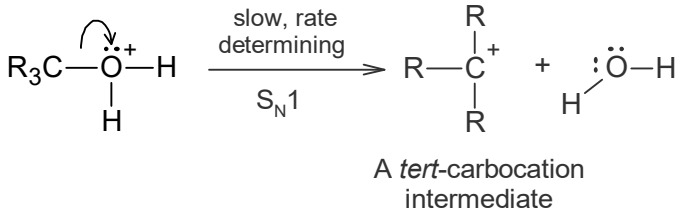
Step 1

Similar to the first step of the mechanism of the primary alcohol, proton is transferred to convert −OH of a *tert*-alcohol, a poor leaving group, into $-OH_2^+$, a good leaving group.



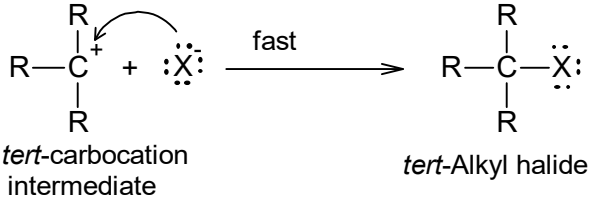
Step 2

With the loss of water, C−O bond of the alcohol is broken to give a stable carbocation intermediate.



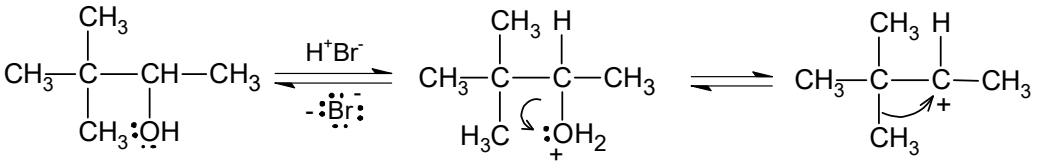
Step 3

A new bond is formed between electrophilic carbocation and nucleophilic halide ion to form an alkyl halide molecule.



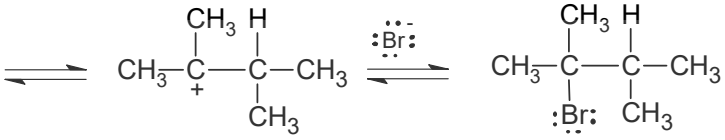
The key feature of nucleophilic substitution reactions with hydrogen halides is conversion of −OH group into a good leaving group by the protonation. Such substitution reactions have some limitations. Primary alcohols do not react

with HCl or HF as both chloride and fluoride ions are poor nucleophile in comparison to bromide and iodide ions. Secondary and tertiary alcohols, similar to secondary and tertiary alkyl halides, also tend to undergo rearrangements during the S_N1 reaction.



3-Dimethyl-2-butanol

Secondary carbocation (less stable)



Tertiary carbocation (more stable)

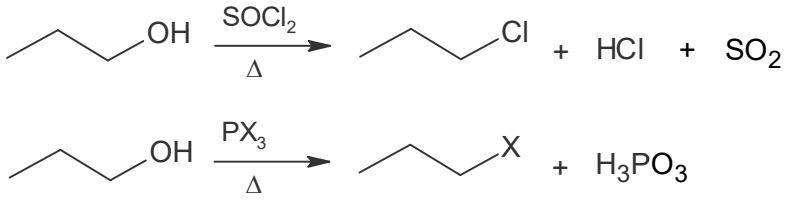
2-Bromo-2,3-dimethylbutane

There is also a possibility of protonation of neucleophile in strong acidic conditions unless our nucleophile is a weak acid as our halide ions. Because of all such difficulties, several alternative methods for the preparation of alkyl halides from alcohols have been developed.

Phosphorus and sulphur halides also convert the −OH group into a good leaving group and provide a nucleophile, a halide ion, to replace the leaving group.

Most widely used reagents for the conversion of primary and secondary alcohols to alkyl halides are thionyl chlonde ($SOCl_2$) and phosphorus trihalide (PX_3). These reagents undergo reaction under milder reaction conditions with alcohols to form intermediate inorganic esters. The resulting inorganic ester groups are good leaving groups that can be displaced by halide ions.

The reaction with thionyl for conversion of alcohols to alkyl chloride is preferred as by products (SO_2 and HCl) are gases and are removed from reaction mixture on heating.



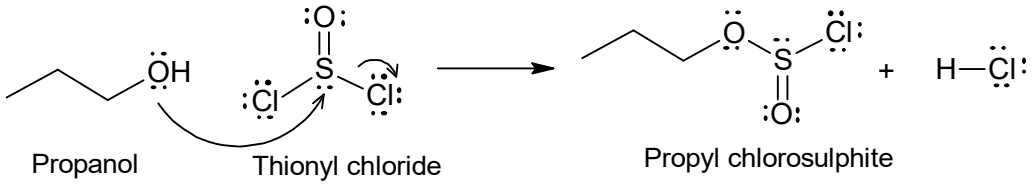
Both these reactions produce good yield of alkyl halides. The mechanisms of these reactions may be written as:

Mechanism of Reaction with Thionyl Chloride:

The mechanism of the transformation of the alcohols into corresponding alkyl halides depends on the nature of alcohols. Primary alcohols undergo an S_N2 reaction and tertiary alcohols follow an S_N1 pathway. Secondary alcohols follow both S_N1 and S_N2 pathways.

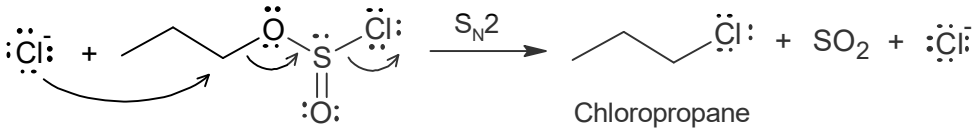
Step 1

Alcohol reacts with thinoyl chloride to form alkyl chlorosulphite, this converts −OH, a poor leaving group, into a chlorosulphite that now has a good leaving group.

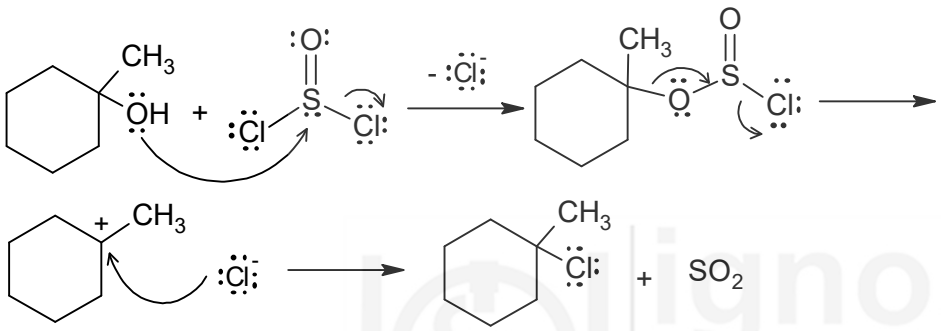


Step 2

In this step nucleophile, i.e. chloride ion displaces leaving group to form the alkyl halide.



Mechanism with *tert*-alcohols



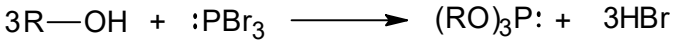
An S_N2 pathway is favoured in secondary alcohols when a base such as pyridine is added to the reaction mixture.

Mechanism of Reaction with Phosphorus Trihalides:

Several phosphorus halides such as PCl_3, PBr_3 and PCl_5 are commonly used to convert alcohols to alkyl halides. Amongst them, PBr_3 is the best reagent for this purpose. Reaction of phosphorus tribromide with primary and secondary alcohols follows S_N2 pathway. With tertiary alcohols, phosphorus bromide works poorly as in this case back side attack of halide ion on intermediate product (trialkylphosphite) is hindered (S_N2 condition) and also its ionisation is slow (S_N1 condition).

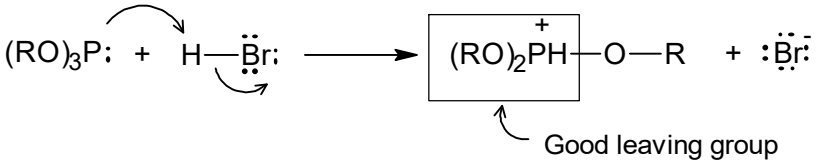
Step 1

In the first step of the reaction with PBr_3, an alcohol forms trialkylphosphite.



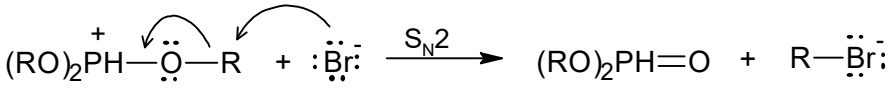
Step 2

By extracting a proton from hydrogen bromide, trialkylphosphite forms a good leaving group and generates a nucleophile, bromide ion for next step.



Step 3

This step leads to substitution with formation of very stable phosphorus-oxygen double bond. This provides the driving force for this step.



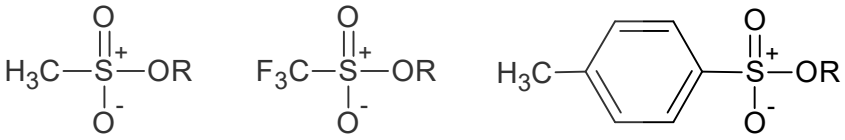
As we have seen that primary, secondary and tertiary alcohols react with different reagents by different pathways. In Table 15.4, we have summarised the best reagent used for the substitution reactions of alcohols leading to alkyl halides.

Table 15.4: **Summary of best reagent used for substitution reactions of alcohols leading to akyl halides**

Alcohol	Chloride	Bromide	Iodide
Primary	$SOCl_2$	PBr_3	P/I_2*
Secondary	$SOCl_2$	PBr_3	P/I_2*
Tertiary	HCl	HBr	HI

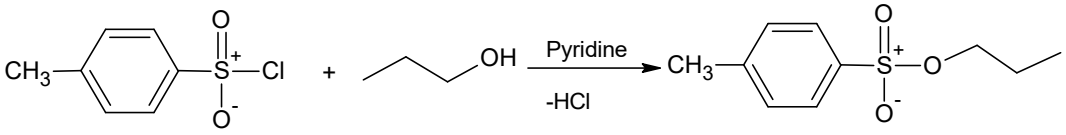
* Phosphorus triiodide is not a stable compound; therefore, it is generated in the reaction mixture by the reaction of phosphorus with iodine.

Nucleophiles other than halides also bring about substitution reactions with alcohols. But the –OH group of an alcohol has to be converted into a good leaving group. This is commonly done by converting alcohols into alkyl sulphonate esters. They have very good leaving group, a sulphonate ion. Common sulphonate esters are methanesulphonate (also called mesylate), abbreviated −OMs; trifluromethanesulphonate (also called triflate), abbreviated −OTf; and *p*-toluenesulphonate (also called tosylate), abbreviated −OTs.



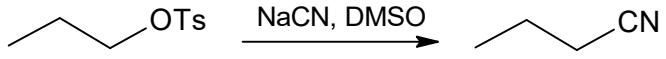
Methanesulphonate | Trifluoromethane-sulphonate | *p*-Toluenesulphonate

Sulphonates can be prepared by treating an alcohol with alkyl/aryl sulphonyl chloride [for example *p*-toluene sulphonyl chloride ($CH_3C_6H_4SO_2Cl$ or TsCl)] and base which is usually pyridine, triethylamine, or NaOH.



p-Toluenesulphonyl chloride | Propanol | Propyl-*p*-toluenesulphonate (propyl tosylate)

Tosylate (−OTs) being a very good leaving group, can readily be displaced by nucleophile.



Propyl tosylate

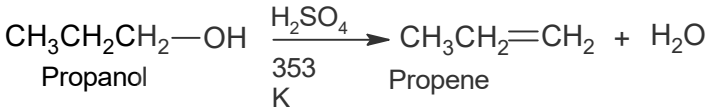
Butanenitrile
(*n*-propyl cynide)

A verity of useful products can be synthesised from alcohols using these two step process.

ii) **Dehydration of Alcohols to Alkenes:** Another reaction of alcohols is the dehydration. This involves cleavage of C−O bond along with loss of a proton from the *β* position. It may be affected by heating alcohols to 673- 1073 K or heating to a lower temperature in the presence of a catalyst such as alumina or a mineral acid, e.g., sulphuric acid. The product of dehydration of an alcohol is an alkene or a mixture of alkenes. The order of the ease of dehydration of alcohols is:

tert > *sec* > primary

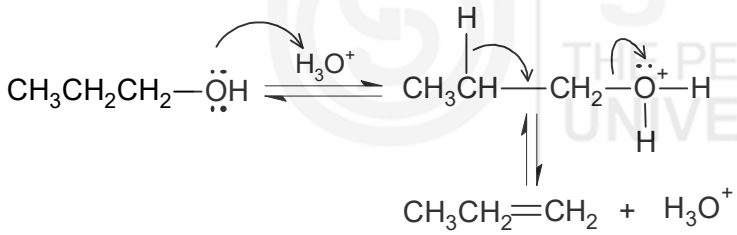
Dehydration of primary alcohols gives only one product, e.g.,



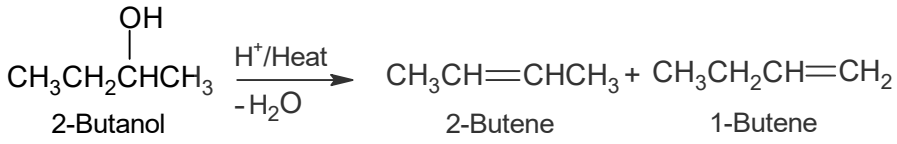
Propanol Propene

Primary alcohols undergo dehydration reaction by E2 path similar to the dehydrohalogenation mechanism discussed in Unit 13.

For the above reaction the E2 mechanism can be written as,



In the case of secondary or tertiary alcohols, a mixture of two alkenes is formed, e.g.,

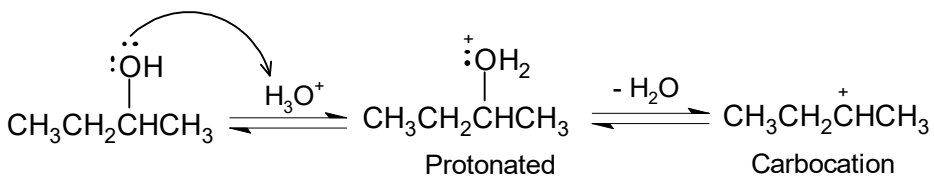


2-Butanol 2-Butene 1-Butene

Like the dehydrohalogenation reaction of alkyl halides, the major product in the above reaction is 2-butene, the more substituted alkene (according to Saytzeff rule which was given earlier in Unit 13).

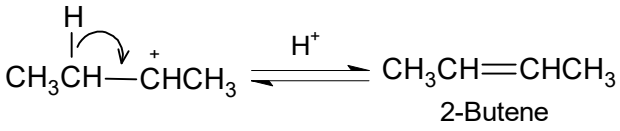
In secondary and tertiary alcohols, dehydration follows the E1 pathway. A detailed discussion of the E1 mechanism has already been given in Unit 13. Now let us write the mechanism for dehydration of 2-butanol.

Step 1



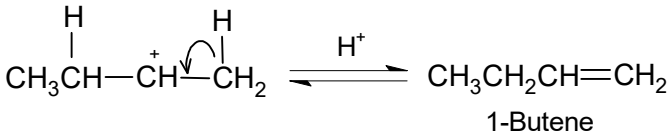
Protonated Carbocation

Step 2



(more favourable)

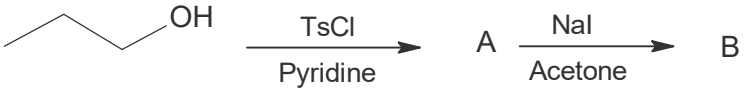
or



(less favourable)

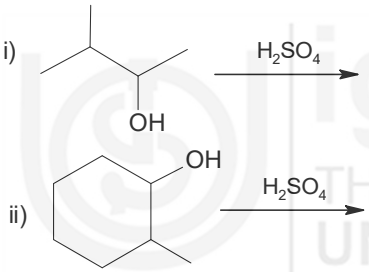
SAQ 7

Complete the following reaction and write its mechanism:



SAQ 8

Draw the structure for the alkenes formed in the reactions given below and also predict the major product in each case.



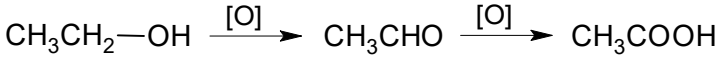
The combination of chromic acid and sulphuric acid is called Jones reagent. This reagent is suitable for the oxidation of secondary alcohols to ketone and primary alcohols to carboxylic acid.

The chromium trioxide complex with pyridine is available in two forms. One is called Collin's reagent: It is prepared by the addition of chromium trioxide to pyridine. The other is Corey's reagent, also called pyridinium chromate complex (PCC), It is made from CrO_3, HCl and pyridine. Both these reagents are suitable for the selective oxidation of primary alcohols to aldehydes.

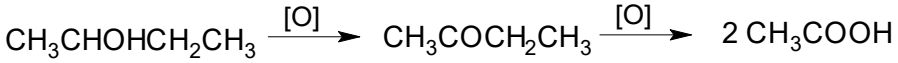
15.7 OXIDATION OF ALCOHOLS

Alcohols undergo oxidation and the nature of the product depends on whether the alcohol is primary, secondary or tertiary. The common oxidising agents used are acidic dichromate, acidic or alkaline potassium permanganate or hot concentrated nitric acid or chromic acid (H_2CrO_4) or the chromium trioxide (CrO_3) complex with pyridine.

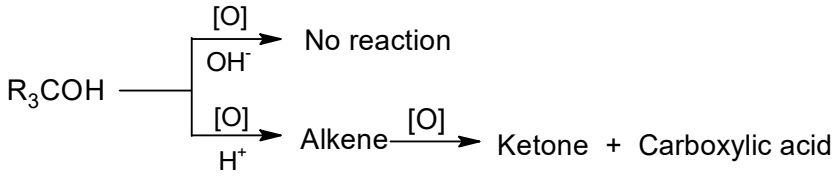
A primary alcohol on oxidation gives an aldehyde, which on further oxidation gives a carboxylic acid. The oxidation products have the same number of carbon atoms as the alcohol, e.g.,



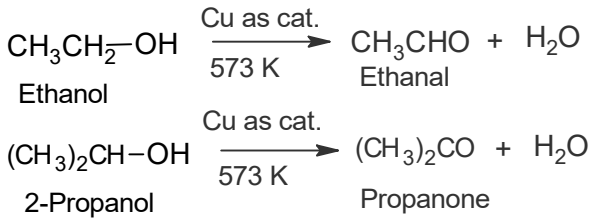
A secondary alcohol on oxidation gives a ketone with the same number of carbon atoms as the alcohol. Ketones are not further easily oxidised. However, drastic oxidations give a mixture of carboxylic acids containing a fewer carbon atoms than the alcohol:



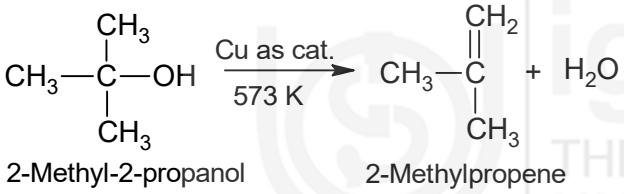
Tertiary alcohols are not easily oxidised in neutral or alkaline conditions. Acidic oxidising agents convert a tertiary alcohol to the alkene and then it is oxidised to a mixture of ketones and carboxylic acids, each having a lesser number of carbon atoms than the alcohol. Oxidation of alkene was discussed in Unit 17 of first semester chemistry course.



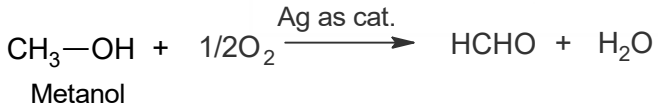
Oxidation of alcohols can also be brought about by catalytic dehydrogenation. In this process, vapours of the alcohol is heated over copper, for example,



As mentioned above, tertiary alcohols are resistant to oxidation. When vapours of tertiary alcohols are passed over copper heated at 573 K, they undergo dehydration to give alkenes, for example,



Silver catalyst is also employed. For example,



Dehydrogenation is more often used for industrial preparation of aldehydes and ketones.

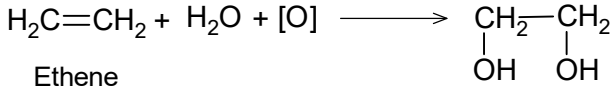
SAQ 9

Write the product of treating each of the following alcohols with i) PCC, ii) chromic acid.

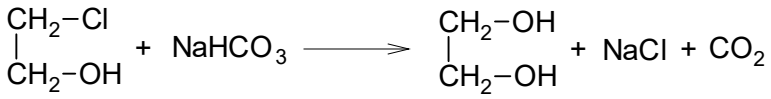
a) 1-Butanol; b) 2-Butanol; c) Cyclopantanol

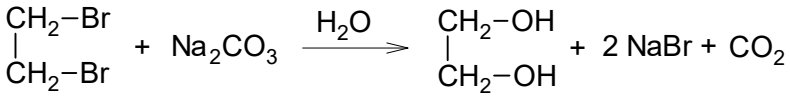
15.8 DIOLS

The dihydric alcohols are known as glycols or diols (in IUPAC nomenclature). 1,2-Ethanediol (ethylene glycol or simply glycol) can be prepared by the hydroxylation oxidation of ethene with cold dilute alkaline potassium permanganate:

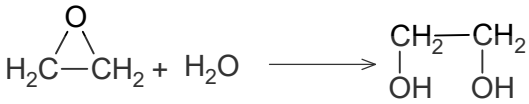


Hydrolysis of ethene chlorohydrin or 1,2-dihalide with mild alkali, such as aq. $NaHCO_3$ or Na_2CO_3 also gives 1,2-ethenediol.





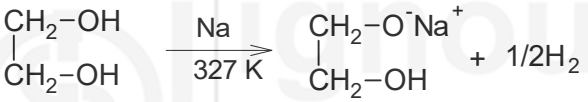
1,2-Ethanediol is manufactured by the hydration of oxirane (ethylene oxide).

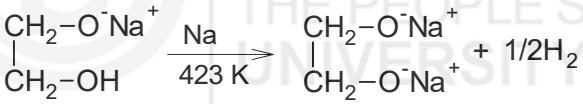


This is carried out in acid solution at about 333 K or with water at 473 K under pressure.

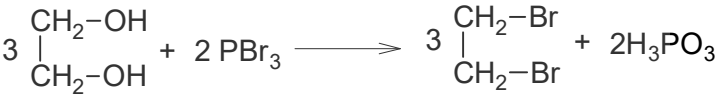
1,2-Ethanediol is taken as a typical example of diols. It shows the chemical reactions of monohydric alcohols except that more vigorous conditions are sometimes needed for reaction of the second of the two hydroxyl groups. For example:

i) It reacts with sodium to form a monoalkoxide and at higher temperature forms the dialkoxide:

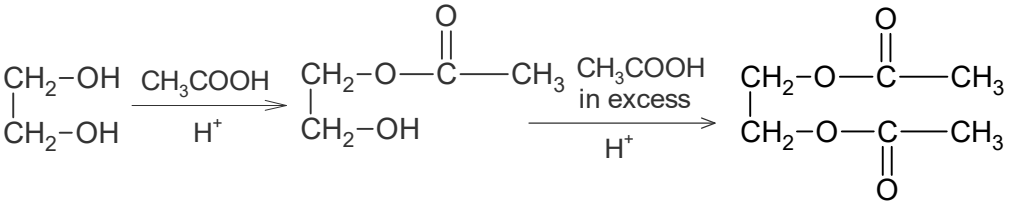




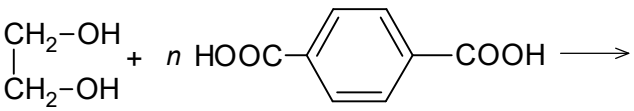
iii) It reacts with phosphorus halide to yield dihalide:



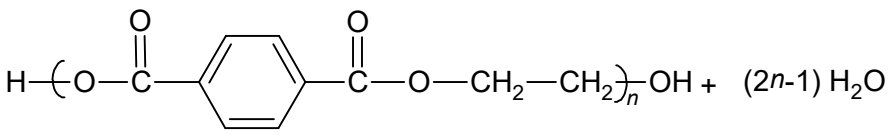
iv) It reacts with carboxylic acids to form esters:



When esterified with a dibasic acid, it forms polymers, for example,



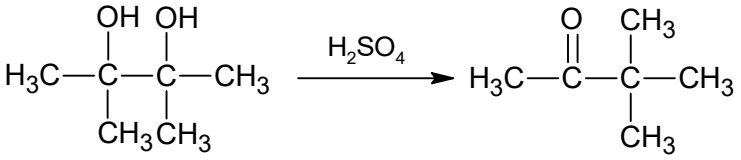
Benzene-1,4-dicarboxylic acid



Terylene

v) Acid-catalysed Dehydration of Glycols:

The products of acid-catalysed dehydration of diols are quite different from those of acid catalysed dehydration of alcohols. For example, reaction of 2,3-dimethyl-2,3-butanediol (commonly called pinacol) with concentrated sulphuric acid gives 3,3-dimethyl-2-butanone (commonly called pinacolone).



2,3-dimethyl-2,3-butanediol (pinacol) — 3,3-Dimethyl-2-btanone (pinacolone)

You can notice two important features of this reaction:

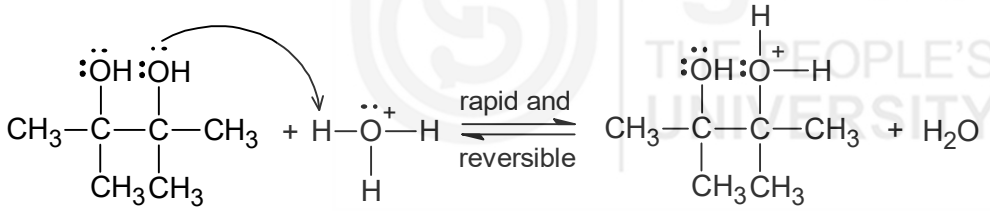
i) dehydration product is a ketone

ii) migration of methyl group from one carbon to adjacent carbon

The acid catalysed conversion of pinacol to pinacolone is an example of a rearrangement reaction and called as **Pinacol-pinacolone or simply pinacol rearrangement**. The mechanism of the reaction can be given as shown:

Step 1

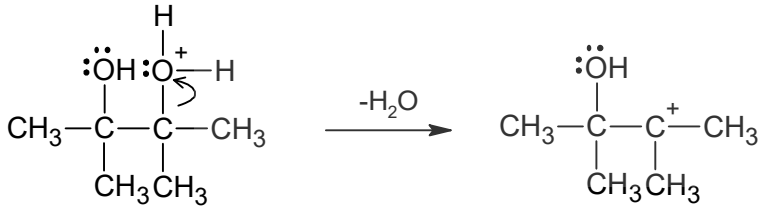
Protonation of hydroxyl group.



2,3-dimethyl-2,3-butanediol (pinacol)

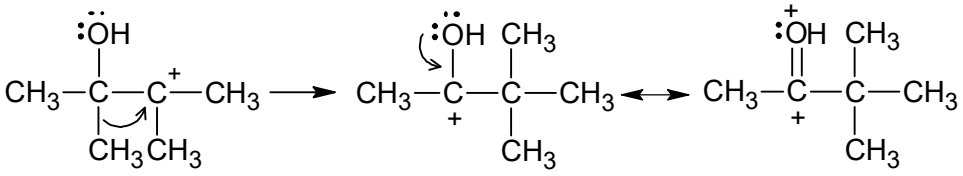
Step 2

Loss of H_2O from oxonium ion to form *tert*-carboction intermediate.



Step 3

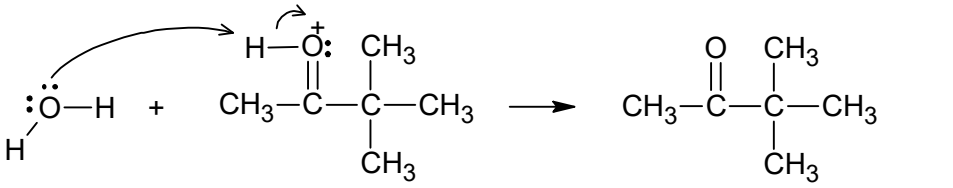
Migration of methyl group from one carbon to adjacent carbon to form more stable carbocation.



Carbocation intrmediate stabilised by charge delocalisation

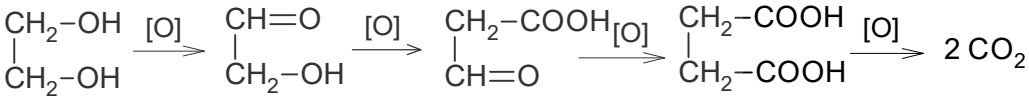
Step 4

Transfer of proton to solvent

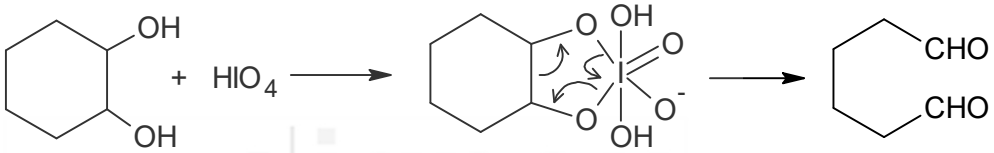


3,3-Dimethyl-2-butanone
(pinacolone)

vi) On oxidation with nitric acid, both the primary alcoholic groups are oxidised, first to aldehyde and then to carboxyl groups. Ethanedioic acid is finally oxidised to carbon dioxide and water,



Oxidising agents such as periodic acid, $HIO_4.2H_2O$ are used for the cleavage of diols, into aldehydes or ketones.

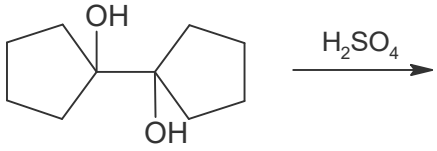


The oxidative cleavage of diols with periodic acid is very useful in the constitutional analysis of sugars.

1-2 Ethanediol is widely used as a solvent, antifreeze agent and in the manufacture of terylene.

SAQ 10

Complete the following reaction:



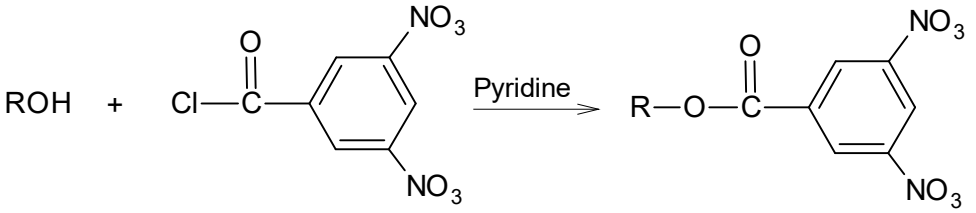
SAQ 11

What products are formed when 2,3-butanediol is treated with HIO_4?

15.9 LAB DETECTION

The reaction with sodium metal to evolve hydrogen gas is of some use for the detection of alcohols. The presence of traces of moisture, however, affects the characterisation. The presence of a hydroxyl group in a molecule is often indicated by the formation of an ester upon treatment with an acid chloride or an anhydride. Compounds like alcohols, phenols, primary and secondary amines (those containing an active hydrogen atom) on treatment with benzoyl chloride in the presence of dilute aqueous sodium hydroxide give benzoyl

derivatives (Schotten-Baumann reaction). Sometimes, 4-nitrobenzoyl or 3,5-dinitrobenzoyl chlorides are used to prepare derivatives of alcohols and phenols and thus, for the characterisation of these compounds.



3,5-dinitrobenzoyl chloride 3,5-dinitrobenzoate

As mentioned earlier, alcohols of different classes can be differentiated on the basis of their reaction rates with $HCl/ZnCl_2$. If we take alcohol in a test tube and add mixture of $HCl/ZnCl_2$ the following results are obtained:

primary alcohols $\xrightarrow{HCl/ZnCl_2}$ No reaction at room temperature.

secondary alcohol $\xrightarrow{HCl/ZnCl_2}$ Reaction mixture gets cloudy in 5-10 minutes.

Tertiary, alkenyl, benzyl alcohols $\longrightarrow$ Reaction mixture gets cloudy immediately.

15.10 SUMMARY

In this unit, we have described the chemistry of alcohols. We are summarising below what we have studied:

- Alcohols are obtained by the hydrolysis of alkyl halides and reduction of aldehydes and ketones. They are prepared on a large scale by hydration of alkenes, catalytic treatment of water gas, catalytic oxidation of natural gas and fermentation of starch or sugars.
- Alcohols are very weak acids. The molecules tend to associate themselves by forming hydrogen bonds. They react with carboxylic acids to form esters.
- Alcohols can undergo S_N1 and S_N2 reaction with hydrogen halides to form alkyl halides. They can also be converted to alkyl halides by the reaction with phosphorous halides and sulphur halides.
- Nucleophiles other than halides also bring about substitution reactions with alcohols. But before that the −OH group of an alcohol has to be converted into a good leaving group. This is commonly done by converting alcohols into alkyl sulphonate esters.
- Dehydration of alcohols leads to alkenes. Oxidation or dehydrogenation of alcohols gives mainly carbonyl compounds.
- Diols undergo pinacol-pinacolone rearrangement reaction under acidic condition.

- Diols can be oxidised by periodic acid to two carbonyl species due to cleavage of the C−C bond between the −OH groups.

15.11 TERMINAL QUESTIONS

1. Show a structural formula for each name and tell whether it is a primary, secondary or a tertiary alcohol.

   a) 3-pentanol

   b) 2,2-dimethyl-1-propanol

   c) 2-methyl-1-butanol

   d) 3-methyl-2-pentanol

   e) 1-methylcyclopentanol

2. Which compound from each pair has a higher boiling point and is more soluble in water.

   a) 1-chloropropane or propanol

   b) 1-butanol or 2-methyl-2-propanol

   c) 2-butanol or 2-propanol

3. Which is the stronger base, ethanol or 2-methyl-2-propanol? Explain.

4. Write the mechanism for the reaction of

   a) ethyl alcohol with HBr

   b) 3,3-dimethyl-2-butanol with HBr.

5. Complete the following reactions:

   a) $(CH_3)_3COH + HCl \longrightarrow$

   b) $C_2H_5OH \xrightarrow[H_2O]{Na}$

6. Show all the alkenes that could possibly be formed by dehydration of each alcohol given below. Which alkene would be produced in largest amount ?

   a) 2-methyl-2-butanol

   b) 2-pentanol

   c) 2-methylcyclohexanol

   d) 1,2-dimethylcycloxexanol

7. What product, if any, would be obtained by passing each of these alcohols over copper metal at 573 K?

   a) 1-propanol

   b) 2-butanol

c) 2-propanol

d) 2-methyl-2-propanol

8. Give a simple chemical test that would distinguish primary alcohol from a secondary alcohol and secondary alcohol from a tertiary alcohol.

15.12 ANSWERS

Self Assessment Questions

1. a) 2,2-Dimethyl-1-propanol or 2,2-Dimethylpropanol, primary

b) 2-Methyl-2-butanol, tertiary

c) 3,3-Dimethyl-2-butanol, secondary

d) 1-Methylcyclohexanol, tertiary

e) 2-hydroxycyclopentane-1-carbaldehyde, secondary

f) 3-Cyclohexene-1-ol or Cyclohex-3-en-1-ol, secondary

2. i) Preparation of 2-Butanol

a) $CH_3CH_2CH{=}CH_2 \xrightarrow{H^+/H_2O} CH_3CH_2\underset{\displaystyle OH}{\underset{|}{C}}HCH_3$

b) $CH_3CH_2\underset{\displaystyle Cl}{\underset{|}{C}}HCH_3 \xrightarrow{OH^-/H_2O} CH_3CH_2\underset{\displaystyle OH}{\underset{|}{C}}HCH_3$

c) $CH_3CH_2\overset{\displaystyle O}{\overset{\|}{C}}H \xrightarrow[ii\ H_3O^+]{i)\ CH_3MgX} CH_3CH_2\underset{\displaystyle OH}{\underset{|}{C}}HCH_3$

d) $CH_3CH_2\overset{\displaystyle O}{\overset{\|}{C}}CH_3 \xrightarrow[ii)\ H_2O]{i)\ LiAlH_4,\ ether} CH_3CH_2\underset{\displaystyle OH}{\underset{|}{C}}HCH_3$

ii) Preparation of 1-Butanol

a) $CH_3CH_2CH_2{=}CH_2 \xrightarrow[ii)\ H_2O_2/NaOH]{i)\ BH_3} CH_3CH_2CH_2CH_2{-}OH$

b) $CH_3CH_2CH_2CH_2{-}Cl \xrightarrow{OH^-/H_2O} CH_3CH_2CH_2CH_2{-}OH$

c) $H_2C\overset{\displaystyle O}{\diagup\diagdown}CH_2 \xrightarrow[ii)\ H_3O^+/H_2O]{i)\ C_2H_5MgBr/ether} CH_3CH_2CH_2CH_2{-}OH$

or

$H{-}\overset{\displaystyle O}{\overset{\|}{C}}{-}H \xrightarrow[ii)\ H_3O^+/H_2O]{i)\ C_3H_7MgBr/ether} CH_3CH_2CH_2CH_2{-}OH$

d) $CH_3CH_2CH_2CH_2CHO \xrightarrow[ii)\ H_2O]{i)\ LiAlH_4/ether} CH_3CH_2CH_2CH_2-OH$

3. a) $H_2C{=}CH_2 + H_2O \xrightarrow[70\ atom]{573\ K} CH_3CH_2OH$

b) $CO + 2H_2 \xrightarrow[533\ K,\ 150\ atom]{Cu\ Catalyst} CH_3OH$

c) $\underset{Cane\ Sugar}{C_{12}H_{22}O_{11}} + H_2O \xrightarrow{Invertase} C_6H_{12}O_6 + C_6H_{12}O_6$

$C_6H_{12}O_6 \xrightarrow{Zymase} 2C_2H_5OH + 2CO_2$

4. Order of increasing boiling point

Pentane < 2-Methyl-2-propanol < 1-Butanol < 1,3-Propanediol

Explanation: Boiling point mainly depends on two factors:

(i) The strength of inter molecular hydrogen bonding

(ii) van der Waals' forces

In case of pentane, there is no possibility of hydrogen bonding, therefore, this has the lowest boiling point.1,3-propanediol has two −OH groups therefore, this alcohol has more sites within its molecule for intermolecular hydrogen bonding than 1-butanol. Now, compare 1-butanol and 2-methyl-2-propanol. Being larger surface area of 1-butanol, this alcohol besides intermolecular hydrogen bonding association has more effective van der Waals forces than 2-methyl-2-propanediol. Thus, 1-butanol has higher boiling point than 2-methyl-2-propanol.

5. Order of increasing solubility in water

Pentane < 1-Butanol < 1,3-Propandiol

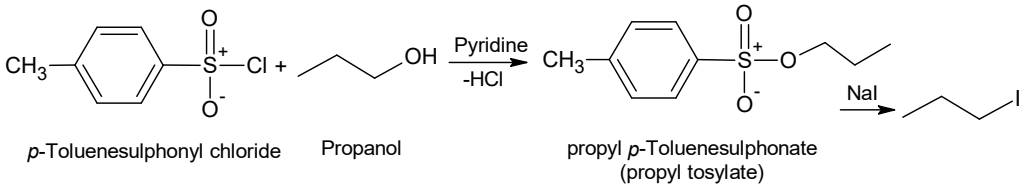
Explanation: Pentane, is a nonpolar molecule, has the lowest solubility in water. Due to the process of polar −OH group in 1-butanol and 1,3-propanediol, they interact with water molecule by hydrogen bonding. 1,3-propanediol is more soluble in water than 1-butanol as it has more sites within its molecule for hydrogen bonding.

6. Chlorine atom being an electron withdrawing group stabilises the negative charge in the alkoxide oxygen by electron attraction (Inductive effect). Further, such inductive effect is increases with the number of electronegative groups on α-carbon of alcohol but decreases with distance from the oxygen. Thus, on the basis of these facts, the order of acidity will be

$CH_3CH_2CH_2CH_2CCl_2(OH) > CH_3CH_2CH_2CH_2CHCl(OH) >$

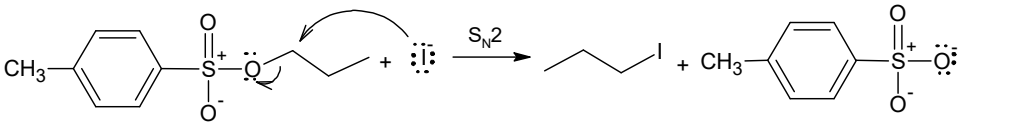
$CH_3CH_2CH_2CH(Cl)CH_2OH$

7.



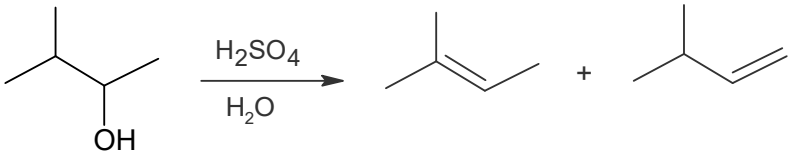
p-Toluenesulphonyl chloride Propanol propyl *p*-Toluenesulphonate (propyl tosylate)

Mechanism



p-Toluene sulphonate ion (very weak base and being a stable ion acts as very good leaving group)

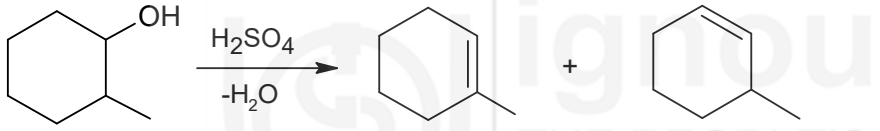
8. i)



3-Methyl-2-butanol 2-Methyl-2-butene (Major product) 3-Methyl-1-butene

2-Methyl-2-butene has three alkyl groups (methyl groups) on the double bond and 3-methyl-1-butene has only one substituent; thus, former will be the major product as per the Saytzaff rule i.e. formation of more substituted alkene is favoured.

ii)

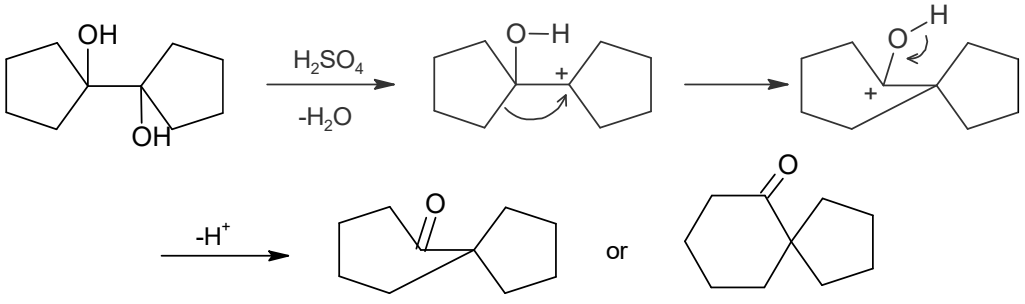


2-Methylvycloheanol 1-Methylcyclohexene Major product 3-Methylcyclohexene

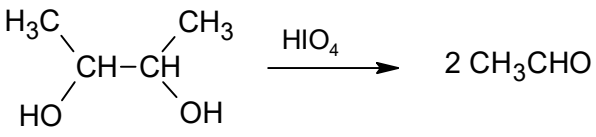
1-Methylcyclohexene has three alkyl substituents on the double bond and 1-Methylcyclohexene has two, therefore,1-Methylcyclohexene will be the major product.

9. 1-Butanol, a primary alcohol, is oxidised to butanal with PCC and to butanoic acid with chromic acid. On the other hand 2-butanone is a secondary alcohol oxidised to butanone by both PCC and chromic acid. Cyclopentanol is also secondary alcohol; it is oxidised to cyclopentanone by both oxidising agents.

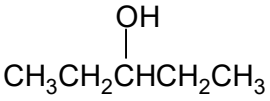
10.



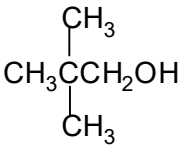
11. The bond between the carbons bearing –OH group is cleaved and each −OH is converted to a carbonyl group.



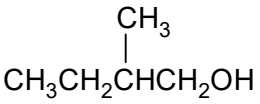
Terminal Questions

1. a) 

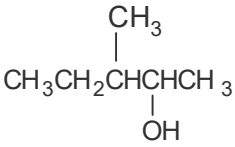
(secondary)

b) 

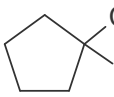
(Primary)

c) 

(Primary)

d) 

(secondary)

e) 

(tertiary)

2. Boiling point a) propanol b) 1-butanol c) 2-butanol

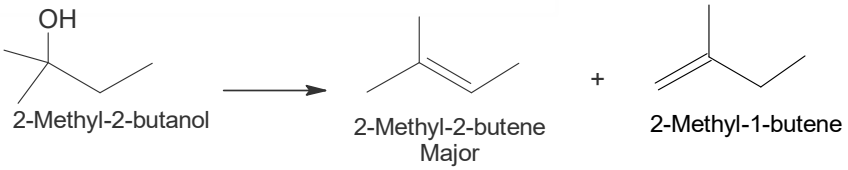
   Solubility in water a) propanol b) 1-butanol c) 2-butanol

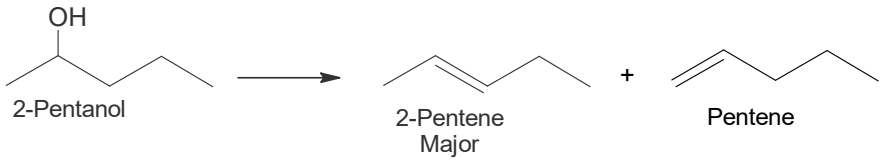
3. 2-Methyl-2-propanpl is less acidic and more basic as it has two electron releasing methyl groups at α-carbon.

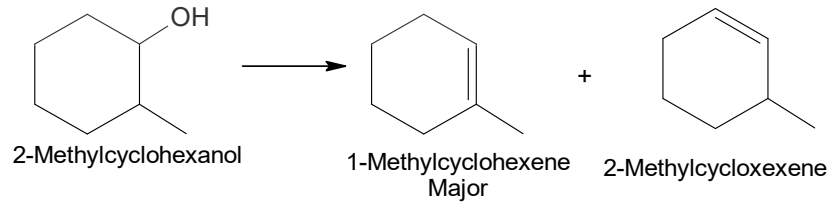
4. See Subsec. 15.6.2.

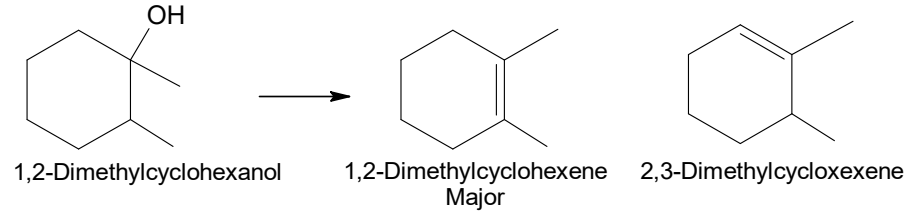
5. a) $(CH_3)_3COH + HCl \longrightarrow (CH_3)_3CCl + H_2O$

   b) $C_2H_5OH \xrightarrow{Na} C_2H_5ONa + 1/2\ H_2$

6. a) 

   b) 

   c) 

   d) 

7. a) 1-propanal, b) 2-butanone

   c) Propanone, d) 2-methylbutene

8. Lucas reagent ($HCl/ZnCl_2$) is used to differentiate primary, secondary and tertiary alcohols. Tertiary alcohols react immediately upon shaking with Lucas reagent in a test tube. Secondary alcohols react in 2-3 minutes and primary alcohols do not react with reagent unless the mixture is heated.

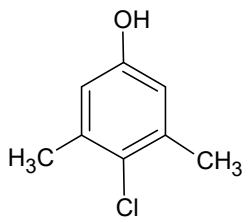
UNIT 16

PHENOLS

Structure

16.1 INTRODUCTION

In the previous Unit, we have discussed the chemistry of alcohols. In this Unit, we will discuss another class of compounds have hydroxyl group called phenols. The phenols are grouped as a separate class of compounds because their chemical properties are quite different from alcohols.



4-Chloro-3,5-dimethylphenol (Dettol)

Phenols are aromatic compounds in which hydroxyl group(s) is attached to the benzene nucleus. Their general formula is Ar−OH, where Ar is phenyl, substituted phenyl, or some other aryl group. These compounds have several applications and are indispensable in our daily life. Phenolic functional groups are often encountered in a variety of household disinfectants, pharmaceuticals, agrochemicals and polymer materials. Phenol-formaldehyde resins, the polymers derived from phenols, for example, are the most widely used industrial polymers.

In this Unit, we will discuss general preparations and the chemical properties of phenols. Phenols are important both as substrates and as reagent. Phenols can be derivatised either at the hydroxyl group or the aromatic ring.

Expected Learning Outcomes

After studying this unit, you should be able to:

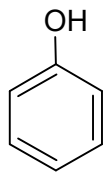
- classify phenols;

- ❖ explain physical properties of phenols;
- ❖ outline the preparation of phenols; and
- ❖ describe the reactions of phenols.

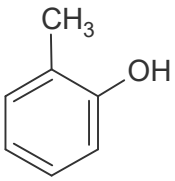
16.2 STRUCTURE AND REACTIVITY

Phenols are aromatic compounds in which hydroxyl groups are attached to the benzene ring; so they have the hydroxyl group on an aryl sp^2 hybridised carbon. Before going to detail of their structure and reactivity, let us recall some important aspects of their classification and nomenclature. Phenols are classified as mono-, di- or tri- hydric on the basis of the number of −OH groups present in the ring. Some examples of phenols are given below.

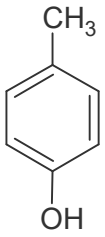
Monohydric Phenols



Benzenol
(phenol)



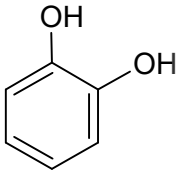
2-Methylbenzenol
(*o*-cresol)



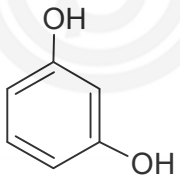
4-Methylbenzenol
(*p*-cresol)

Although benzenol is the systemic name of C_6H_5OH, the IUPAC rules permit 'phenol' to be instead.

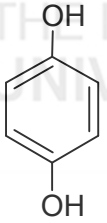
Dihydric Phenols



1,2-Benzenediol
(catechol)

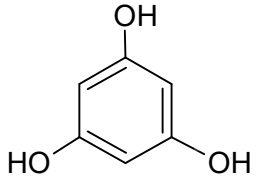


1,3-Benzenediol
(resorcinol)

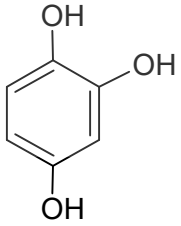


1,4-Benzenediol
(quinol or hydroquinone)

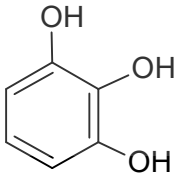
Trihydric Phenols



1,3,5-Benzenetriol
(phloroglucinol)



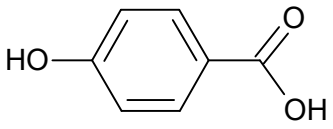
1,2,4-Benzenetriol
(hydroxyquinol)



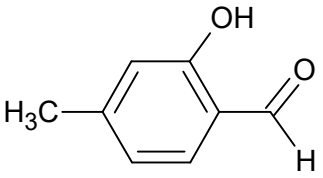
1,2,3-Benzenetriol
(pyrogallol)

The common names of important phenols are still widely used; therefore, in this text we use both common names and IUPAC names. In the IUPAC system, substituted phenols are named as derivatives of bezenols. Numbering of the ring begins at the hydroxyl-substituted carbon and proceeds in the direction that gives the lower number to next substituted carbon. Substituents are cited in alphabetical order. The prefixes ortho (*o*), meta (*m*) and para (*p*) are also

used to indicate the relative positions of substituents. The dihydroxy and trihydroxy derivatives of benzene are named as benzenediol and benzenetriol, respectively with the relative positions of hydroxyl groups in ring. If one of substituent is carboxyl or acyl group, then hydroxyl(s) group is treated as a substituent. For example:



4-Hydroxybenzoic acid
(*p*-hydroxybenzoic acid)



2-hydroxy-4-methylbenzaldehyde
(4-methylsalicyldehyde)

You might expect phenols to be very similar to alcohols as they also have the hydroxyl group. But when we go in details of the structure of a phenol, we find the bonded aromatic ring interacts with the −OH group and in many aspects reactions of phenols are quite different from those of alcohols. Let us study in details of the structure of a phenol.

The carbon-oxygen bond lengths of phenol and alcohol are 136 and 142 pm, respectively.

The hydroxyl functional group (−OH) in a phenol is bonded to a sp^2 hybridised aromatic carbon atom. The oxygen atom of hydroxyl group, similar to an alcohol is sp^3 hybridised. The two sp^3 hybridised orbitals of oxygen form σ bonds to carbon atom of aromatic ring and hydrogen atom and the remaining two sp^3 hybridised orbitals each contain a lone pair of electrons. Similar to aryl halides, interaction between the delocalised electrons in the benzene ring and the lone pairs on the oxygen atom is also possible in phenols (see Fig. 16.1). This interaction causes partial double bond character in C−O bond. Thus, because of these two factors i.e. the increased *s* character of the sp^2 hybridised carbon and resonance delocalisation of electron pair of oxygen with aromatic ring, the C−O bond in phenol will be shorter and stronger than of an alcohol. This can be confirmed by measurement of bond lengths. The carbon-oxygen bond lengths of phenol and alcohol are 136 and 142 pm, respectively.

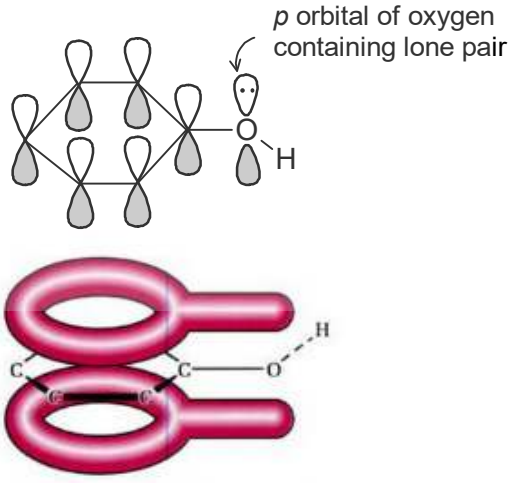
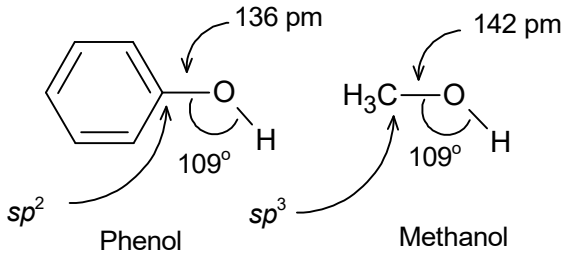


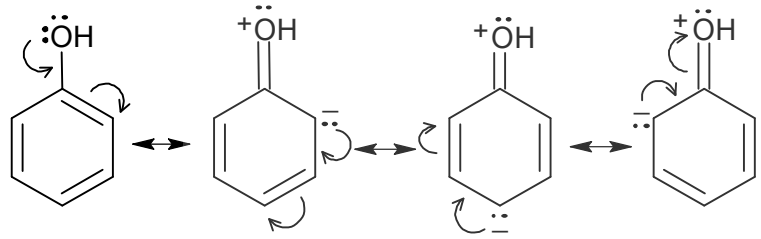
Fig. 16.1: Interaction of the lone pair of oxygen with the aromatic ring system

The geometry around oxygen atom of phenol is essentially the same as that in alcohols. The C−O−C angle has the tetrahedral angle of 109°. Further, both the C−O and the O−H bonds are polar in nature due to the high electronegativity of the oxygen atom. All these structural aspects of phenols

have an important effect on both the properties of the ring and of the −OH group.



The delocalisation of lone pair electrons of oxygen onto benzene ring can be shown by following resonating contributing structures:



The resonance effect shown by these contributing structures along with other structural features discussed above can explain many of the unique properties of phenols. Examples are as follows:

- Elecrophilic aromatic substitution in phenols is much faster than benzene. This is because of the strong delocalisation effect of lone pair electrons of oxygen. In phenols, the hydroxyl group activates the ring, and therefore, it is ortho-para directing during electrophilic substitution reactions. The ortho-para directing nature of hydroxyl group can be understood by the resonating structures shown above for phenol, these structures clearly indicate that benzene ring is relatively electron rich at the positions ortho and para to hydroxyl group.

- Phenols generally do not undergo nucleophilic substitution reactions. The resonance effect also reduces the partial positive charge on the carbon bonded to the oxygen by spreading it over the whole delocalised benzene ring system and thus, making this carbon less susceptible to attack by nucleophile than the corresponding carbon in alcohols. Because of this factor and partial double bond between carbon and oxygen, phenols generally do not undergo nucleophilic substitution reactions (see Fig. 16.2).

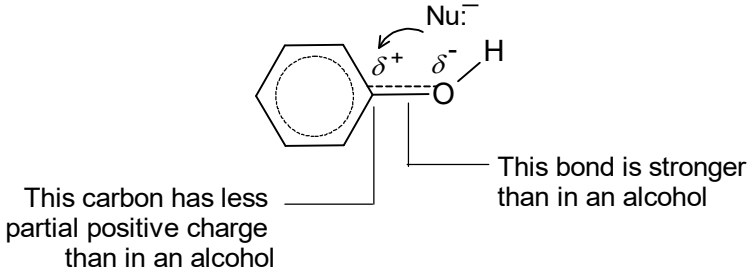


Fig. 16.2: Phenols are less susceptible to attack by nucleophiles than alcohols.

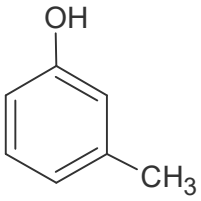
- Phenols are more acidic than alcohols. Benzene ring also contributes

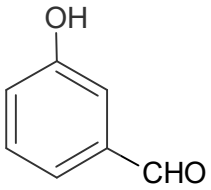
towards bond polarisation of O−H bond and stabilisation of phenoxide ion formed after ionization of phenol. These factors result in more acidic hydroxyl proton and more basic hydroxyl oxygen in phenols in compared to alcohols.

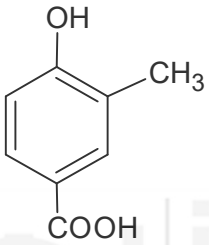
We will further go in details of these properties in successive sections, but before that try following SAQs.

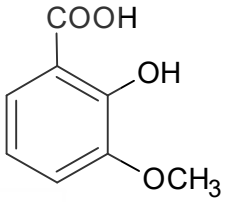
SAQ 1

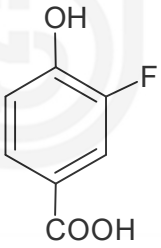
Write IUPAC names of the following:

i) 

ii) 

iii) 

iv) 

v) 

SAQ 2

Explain, why the C−O bond in phenols is shorter and stronger than the C−O bond in alcohols?

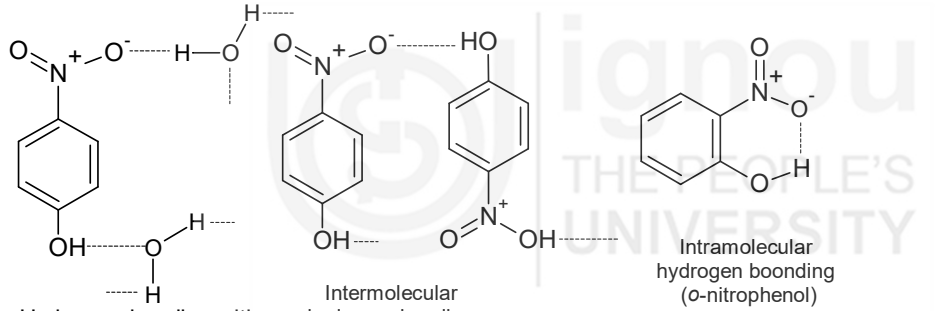
16.3 PHYSICAL PROPERTIES

Like alcohols, the physical properties of phenols are also strongly influenced by the hydroxyl group. Due to the polar nature of the O−H bond (both atoms have different values of electronegativity); phenols form hydrogen bonds with other phenol molecules and H-bonding systems like water. Thus, phenols also have high boiling points and moderate solubility in water compared to analogous aromatic hydrocarbons. On exposure to air and light they turn pink due to auto-oxidation. The physical properties of some phenols are summarised in Table 16.1.

Table 16.1: Physical properties of some phenols

Name	MP, K	BP, K	Solubility g/100 g H_2O
Phenol	314	455	9.3
Catechol	377	–	45.0
Resorcinol	383	–	123.0
Hydroquinone	446	–	8.0
o-Nitrophenol (volatile in steam)	318	–	0.2
p-Nitrophenol (nonvolatile in steam)	387	–	1.7

In Table 16.1, we notice that *ortho* and *para* isomers of nitrophenol differ considerably in their physical constants. How are we to account for these differences? Let us see how these isomers undergo hydrogen bonding:



From the above, we can expect that the *p*-isomer should have a higher melting point and solubility in water due to the **intermolecular hydrogen bonding** and its association with water molecules. On the other hand, *o*-nitrophenol has **intramolecular hydrogen bonding** or hydrogen bonding within a single molecule. It does not associate with other molecules or with water and, therefore, has lower melting point and lower solubility.

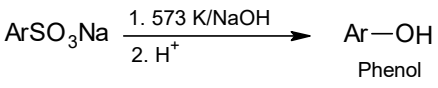
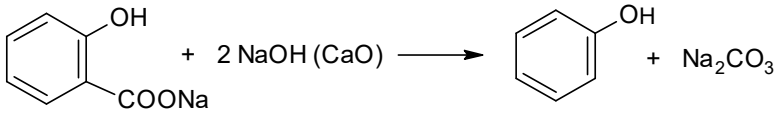
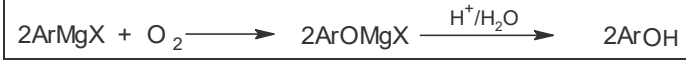
SAQ 3

The melting points of 2-flurophenol and 4-flurophenol are 289.1 K and 321.6 K, respectively. How will you account for these differences?

16.4 PREPARATION OF PHENOLS

Phenols can be prepared from arylsulphonic acid, phenolic acids, diazonium salts and from Grignard reagents. The general reactions of these methods of preparation are summarised in Table 16.2.

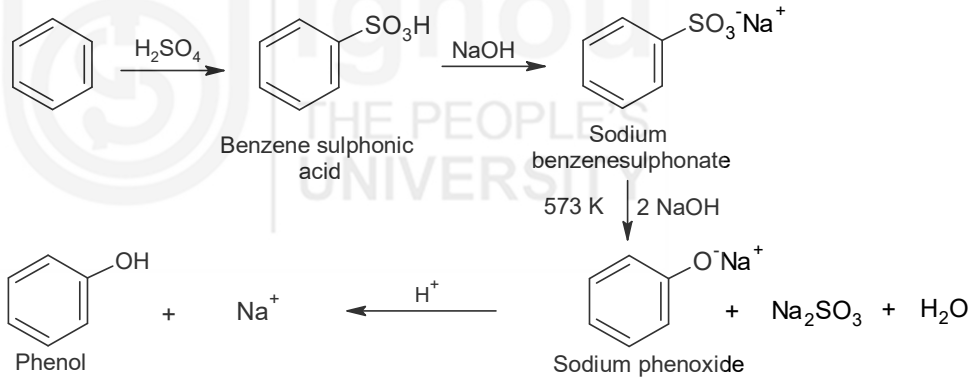
Table 16.2: Preparation of Phenols

Fusion of arylsulphonates with sodium hydroxide 
Heating phenolic acid with soda-lime 
Boiling diazonium salt with water 
Action of oxygen on Grignard reagent followed by hydrolysis 

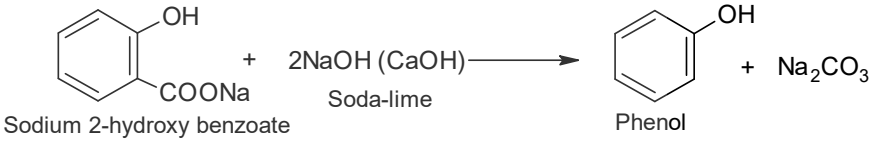
Let us study these reactions one by one.

i) Fusion of arylsulphonate with sodium hydroxide:

Phenol may be prepared by the fusion of sodium benzenesulphonate obtained through sulphonation of benzene (Unit 11), with sodium hydroxide. The sodium phenoxide produced in the reaction is converted into the free phenol by treatment with acid.

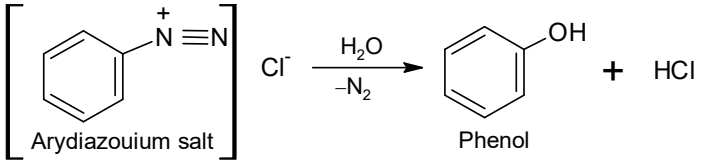


ii) Decarboxylation of phenolic acids with soda-lime:



iii) Boiling diazonium salt with water:

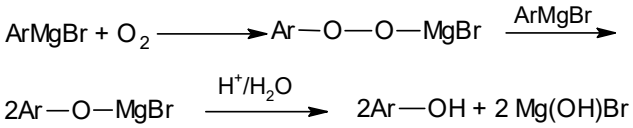
Aromatic amines react with nitrous acid to give diazonium salts which, unlike their aliphatic analogues, are stable at low temperature and can be isolated. The aqueous solution of the salt decomposes to phenol on boiling with water with evolution of N_2.



iv) Action of oxygen on Grignard reagent followed by hydrolysis:

Just as Grignard reagent adds to CO_2, aryl Grignard reagents add to molecular oxygen.

The intermediate reacts with another molecule of the Grignard reagent and hydrolysis of the product gives phenol.



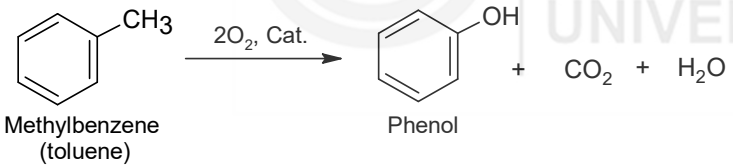
Commercial Preparation

Phenols are of great commercial importance. In this section you will learn how large quantities of these compounds are prepared from different abundant natural sources.

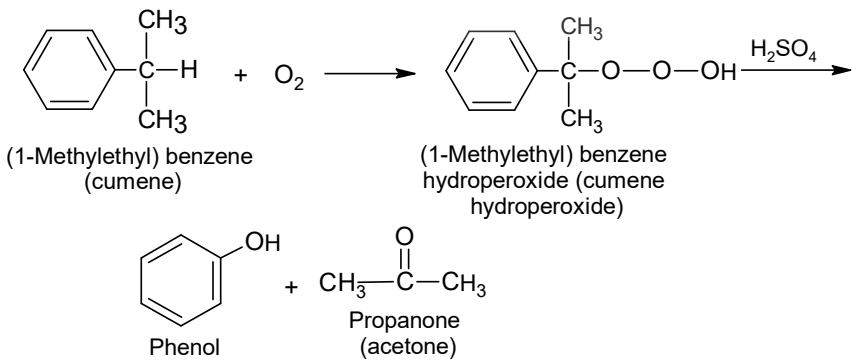
From natural sources: On a commercial scale, phenols are obtained from coal tar. Coal tar is fractionated and the middle oil is cooled when naphthalene crystallises out. The liquid is treated with aqueous sodium hydroxide which dissolves phenols. Carbon dioxide is passed into the liquid and the aqueous layer is separated. Fractionation of remaining oil gives phenol (20%), cresols (43%), xylenols (26%) and the residue is pitch.

From other aromatic hydrocabons:

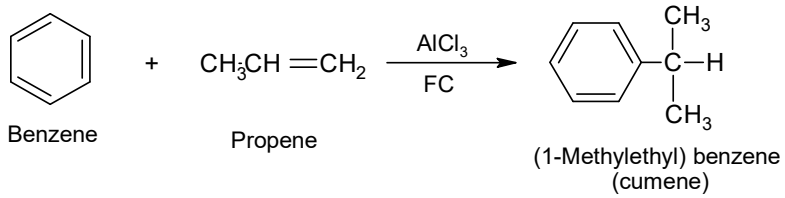
a) Phenol can be obtained by the catalytic oxidation of methylbenzene toluene) by air in presence of manganous and cupric salts.



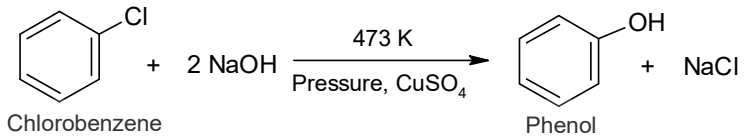
b) **The cumene process:** (1-Methylethyl) benzene (cumene or isopropylbenzene) is a constituent of crude oil and refined fuels. Oxidation of cumene to hydroperoxide followed by decomposition by acid gives phenol and an important by-product propanone (acetone):



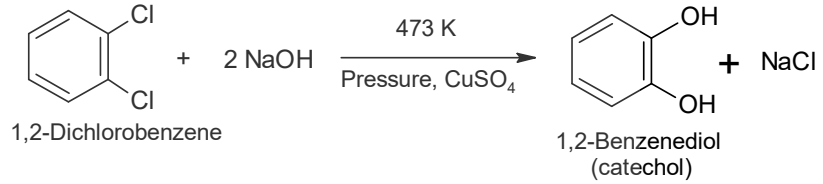
Synthetic cumene is made almost exclusively from benzene and propene via a Friedel-Crafts reaction.



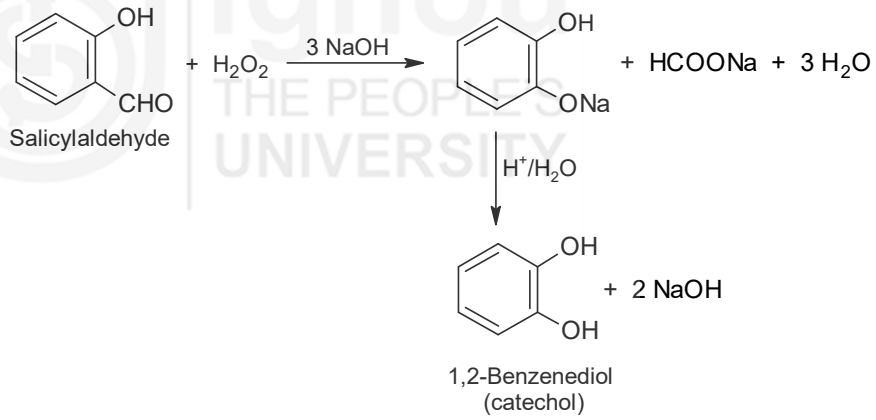
c) **The Dow process:** Chlorobenzene and sodium hydroxide react at high temperature and under pressure in the presence of a catalyst (copper salts) to give phenols.



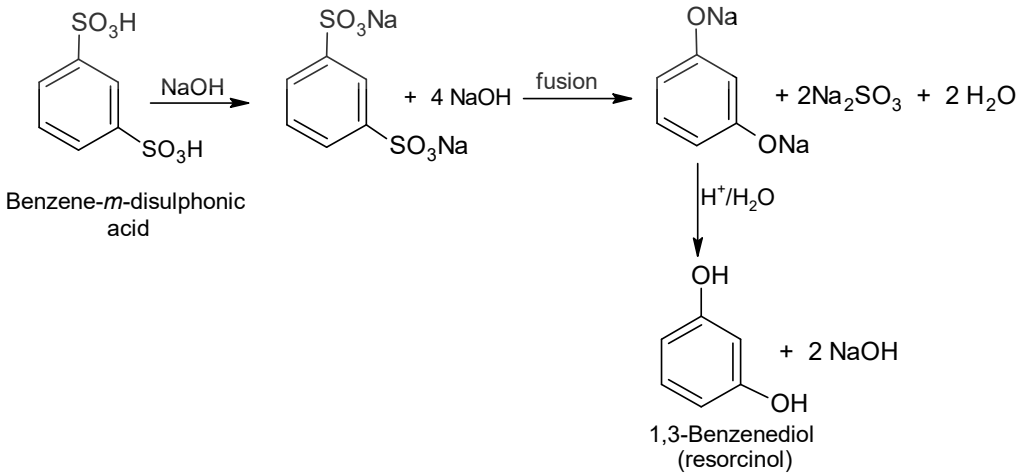
When this process is applied to 1,2-dichlorobenzenes (catechol) is obtained.



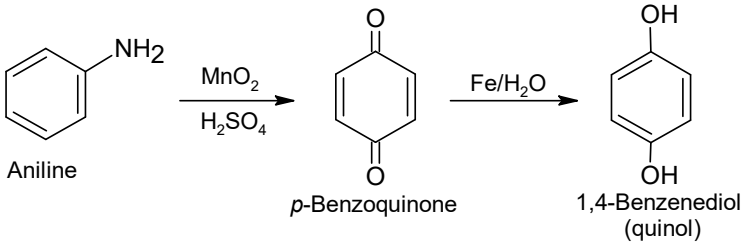
d) 1,2-Benzenediol (catechol) can be conveniently prepared by the action of alkaline hydrogen peroxide on salicyladehyde. The reaction is an example of Baeyer-Villiger rearrangement.



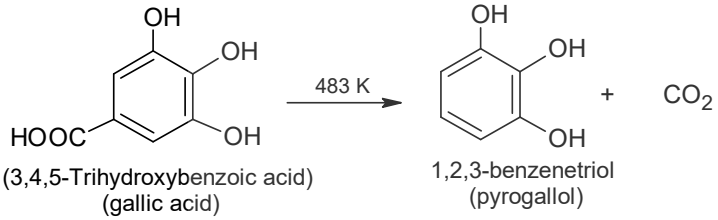
e) 1,3-Benzenediol (resorcinol) is prepared industrially by the alkaline fusion of benzene *m*-disulphonic acid:



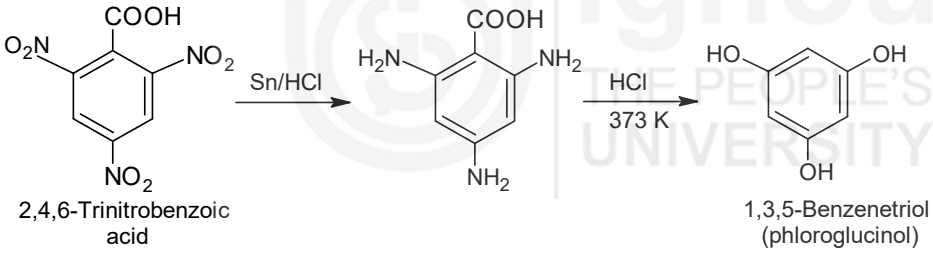
f) 1,4-Benzenediol (quinol) is made commercially by the oxidation of aniline with manganese dioxide and sulphuric acid. The product *p*-benzoquinone is reduced to quinol with iron and hot water.



g) 1,2, 3-Benzenetriol (pyrogallol) is prepared by heating gallic acid (3,4,5-trihydroxybenzoic acid) in a stream of carbon dioxide or by heating an aqueous solution of gallic acid at 483 K under pressure:

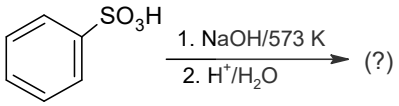


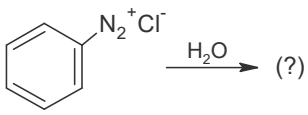
h) 1,3,5-Benzenetriol (phloroglucinol) is obtained by the fusion of many plant resins with alkali. It is also prepared by the reduction of 2,4,6−trinitrobenzoic acid to the amino derivative followed by reaction with hot hydrochloric acid.

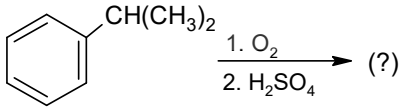


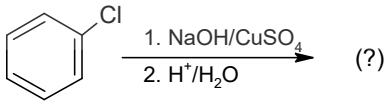
SAQ 4

Complete the following reactions:

a) 

b) 

c) 

d) 

SAQ 5

How the following conversion can be carried out?

a) Benzene to phenol

b) Phenylamine (Aniline) to phenol

c) Phenylmagnesium bromide to phenol

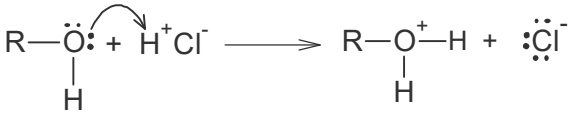
d) Chlorobenzene to phenol

16.5 CHEMICAL PROPERTIES

As stated earlier, phenols have very different chemical properties compared to alcohols. One of the most important differences is that phenols are significantly more acidic than alcohols. Therefore, it is worth comparing the acidity of alcohols and phenols and the effect of substituents on it before further going in details of various types of chemical reactions of phenols.

16.5.1 Acidity and Basicity of Alcohols and Phenols

Alcohols are neutral towards litmus. But in their reactions they behave both as an acid and as a base depending upon the reaction conditions. For example, in acidic solution, alcohols are protonated and thus the acid-base equilibrium with alcohol acting as a base is established. It is the same type of reaction that occurs between water and an acid. A protonated alcohol molecule is called an oxonium ion.

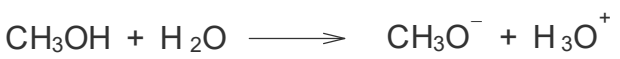


Oxonium ion

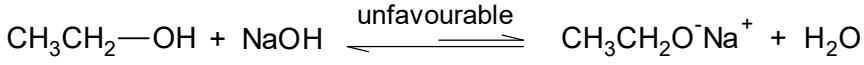
An alcohol can also lose a proton to a strong base yielding an alkoxide ion, RO^-. In this reaction, the alcohol behaves as an acid.

Alkoxides are strong bases, generally stronger than hydroxides. To prepare an alkoxide from an alcohol, we need a base stronger than the alkoxide itself, such as, alkali metal hydrides, NaH, KH, etc.

In dilute aqueous solutions, alcohol has approximately same pK_a values as water. For example, the pK_a of methanol in water is 15.5, while that of pure water is 15.74. Therefore it is as acidic as water.

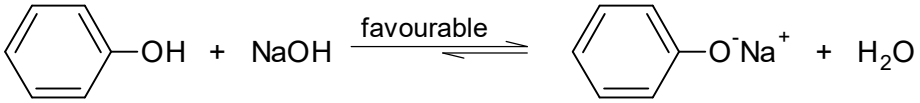


On the other hand, phenols are distinctly acidic in character. Phenol, with a pK_a of 10.00 is a stronger acid than an alcohol or water. Unlike alkoxide ion of alcohols, the phenoxide ion (ArO^-) is a weaker base than OH^-. Therefore, a phenoxide can be prepared by treatment of the phenol with aqueous sodium hydroxide.



Ethanol
pK_a = 15.9

Sodium ethoxide



Phenol
pK_a = 10

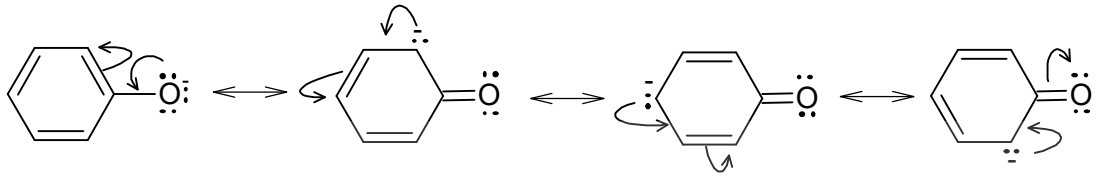
Sodium phenoxide

We can explain the acidic character of phenol if we recall the fact that the

degree of ionisation of a weak acid is determined by the relative stabilities of the unionized compound and the anion:

$$HA \longrightarrow H^+ + A^-$$ (if A^- is stabilised relative to HA, acidity is increased)

The reason for the greater acidity of phenol compared to that of alcohol is that the ionised product is resonance stabilised, with the negative charge delocalised by the aromatic ring.

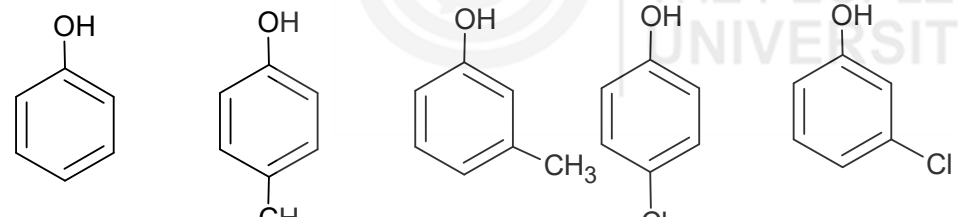


The negative charge in an alkoxide ion (RO^-) cannot be delocalised. Therefore, alkoxide ion is of higher energy relative to the alcohol, and as a result, alcohols are not as strong acid as phenols. Further, the alkyl group in the alkoxide ion has a destabilising effect because of positive inductive (+*I*) effect (electron releasing effect) of the alkyl group. Therefore, addition of alkyl groups to the α–carbon decreases the acidity of alcohols. We can now write the order of decreasing acid strength.

+ *I* effect of alkyl group further increase the intensity of negative charge on oxygen of alkoxide ion; thus destabilises the alkoxide ion.

H_2O > primary > *sec* > *tert*-alcohols

In phenols, substituents located ortho or para to the −OH group, can dramatically influence the acidity of the phenol due to a combination of inductive and resonance effects. The electron withdrawing groups enhance the acidity while the electron donating substituents decrease the acidity.



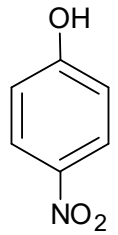
Phenol
pK_a 9.95

p-Cresol
pK_a 10.17

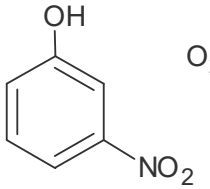
m-Cresol
pK_a 10.01

p-Chlorophenol
pK_a 9.18

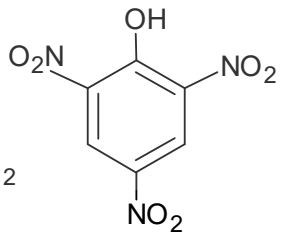
m-Chloropheol
pK_a 8.85



m-Nitropheol
pK_a 7.15



m-Nitropheol
pK_a 8.28

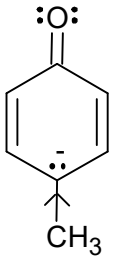


2,4,6-Niropheol
pK_a 0.38

H_3PO_4

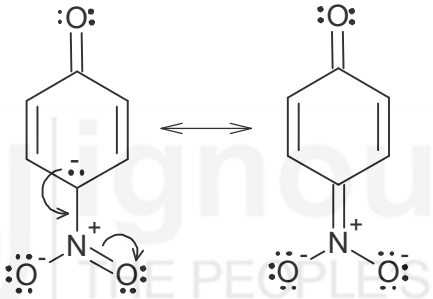
Phosphoric acid
pK_a 2.1

The acid-weakening effect of alkyl substituents can be understood in the following way. The +I effect of alkyl substituents are due to the higher electronegativity of sp^2 hybridised carbon of aromatic ring than sp^3-hybridised atom of an alkyl group. Thus, alkyl substituents are electron releasing towards the aromatic ring. Because of electron releasing effect of alkyl substituent, it will destabilise phenoxide ion contributing structures and in effect reduce the acidity of alkyl substituted phenol.



The +*I* inductive effect of methyl group destabilises this contributing structure

Halogens have –*I* effect as they are more electronegative than carbon, they withdraw electron density from the aromatic ring and thus stabilise the halophenoxide ion compared to phenoxide ion. As fluorine is most electronegative among halogens, the fluorophenol will be the most acidic. This effect will be less for chlorophenol and still less for bromophenol. In the case of nitophenol both the inductive and resonance effects are observed. Therefore, these phenols are highly acidic. 2,4,6-trinitophenol (picric acid) is a stronger acid than phosphoric acid. In the case of nitophenols, if nito group is ortho or para to hydroxyl group, it further contributes in negative charge delocalisation as shown by following contributing structure on the right.



Delocalization of negative charge onto oxygen further increase the resonance stabilization of phenoxide ion

Furthermore phenols, like alcohols, can be protonated by strong acids to give the corresponding oxonium ions. Also, similar to alcohols, the hydroxy group of phenols has amphoteric character. However, the basicity of phenols is even less than that of the alcohols, because the lone electron pairs on the oxygen are delocalised into benzene ring.

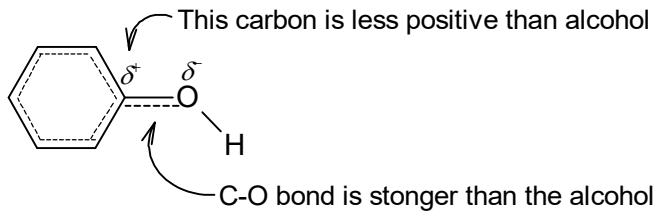
SAQ 6

4-Hydroxybenzaldehyde (*p*-hydroxybenzaldehyde) is more acidic ($pK_a = -7.3$) than phenol ($pK_a = 9.89$). Explain.

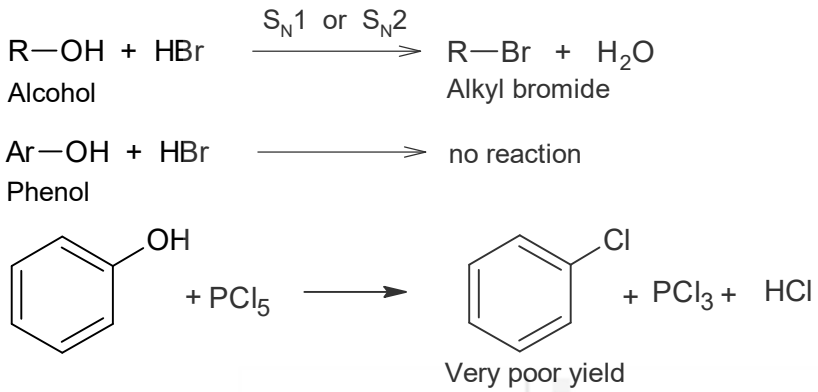
16.5.2 Reactions of Phenols

In phenols, as mentioned earlier, the hydroxyl group is attached to an sp^2 hybridised carbon of aromatic ring and the carbon oxygen bond of phenols has considerable double bond character as evident from the resonance structures shown for the delocalisation of lone pair of oxygen. Due to these factors, the bond is shorter and stronger than a carbon oxygen single bond. As hydroxyl group bonded to an aromatic ring is held tightly, therefore breaking up of the C – O bond is very difficult. Consequently, the nucleophhilic substitution and

elimination reactions so typical of an alcohol are generally not observed for a phenol. Nucleophilic substitution on carbon atom of carbon oxygen bond is also discouraged by the delocalisation of the positive charge created by more electronegative oxygen over benzene ring.



For example, hydrogen halides do not react at all with phenol and even phosphorus pentachloride produces only a poor yield of chlorobenzene.



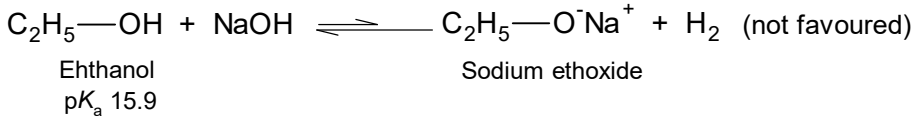
Somehow hydroxyl group can be removed by distillation of phenol with Zinc dust, but in this case again yield is very poor. Free radical mechanism is involved in this reaction.

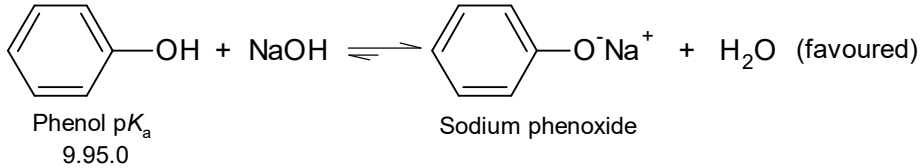
Phenols exhibit reactions mainly due to the phenolic hydroxy group and the aromatic ring.

With this background, now let us study the reactions of phenols.

16.5.3 Reactions due to Phenolic Hydroxyl Group

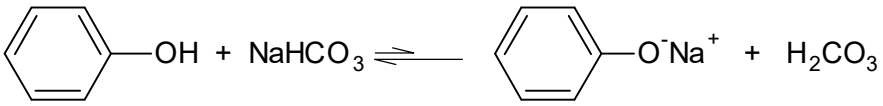
i) Formation of phenoxides: We have already mentioned that phenols are weak acids. They react with strong alkalis forming phenoxides and water. This reactivity is in direct contrast to that of alcohols. We have seen that alcohols form alkoxide only with strong bases like NaH and metals like Na, K, Mg, etc.





Phenol is about 1 million times more acidic than alcohols. However, phenol is not as strong an acid as carbonic acid or a carboxylic acid. This affords a method for distinguishing phenol from a carboxylic acid. Phenol does not react with an aqueous solution of sodium bicarbonate, whereas carboxylic acid reacts to liberate carbon dioxide. The separation of a mixture of phenol and a carboxylic acid is based on the same principle.

Carbonic acid is a stronger acid than phenol, therefore the equilibrium for the reaction of phenol and bicarbonate ions lies far to the left.

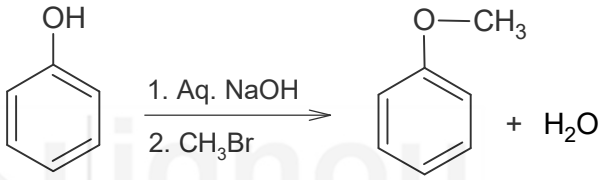


Ehthanol pK_a 9.95 (weaker acid) | Sodium bicarbonate | Sodium phenoxide | Carbonic acid pK_a 6.36 (stronger acid)

Therefore, phenol does not react with an aqueous solution of sodium bicarbonate, whereas carboxylic acid reacts to liberate carbon dioxide.

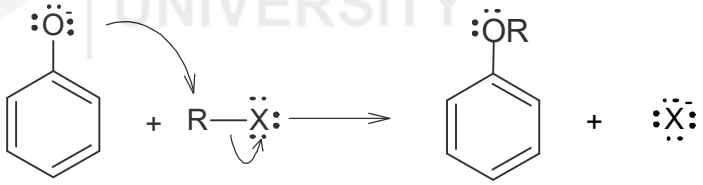
Again recall from earlier discussion that phenols are stronger acids than alcohols as the phenoxide ion is stabilised by resonance. No such stabilisation is possible in the case of alkoxide ions.

ii) **Alkylation:** Similar to alcohols, phenols undergo reaction with alkyl halide (Williamson ether synthesis) in presence of base.



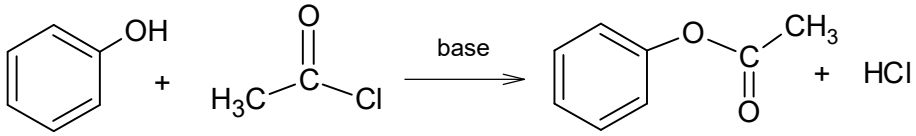
Methyl phenyl ether (anisole)

The reaction follows the S_N2 mechanism

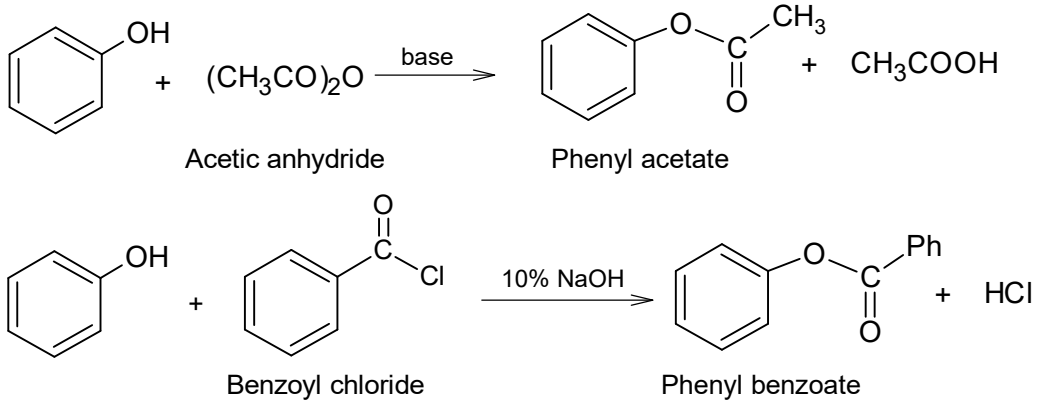


iii) **Esterification:** Unlike alcohols, phenol reacts slowly with carboxylic acids that we normally carry out its esterification with acyl halides (acid halides) or acid anhydrides instead.

Phenols react with acyl halides or anhydrides in presence of a base such as pyridine or NaOH to form esters. These reactions can be done under milder conditions than those used for alcohols due to the greater acidity of phenols as we have seen that phenols can be converted to phenoxide ions with sodium hydroxide rather than very strong bases or metallic sodium. It is important to note that phenoxide which formed in basic reaction conditions is a better nucleophile than phenol. Thus, the presence of base facilitates the ester formation.



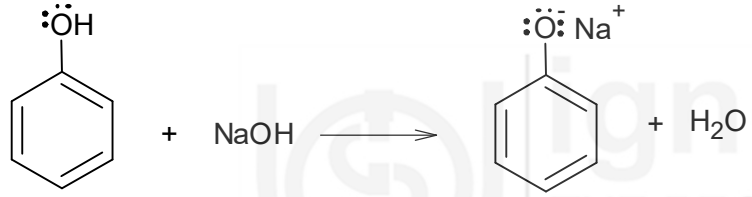
Acetyl chloride | Phenyl acetate



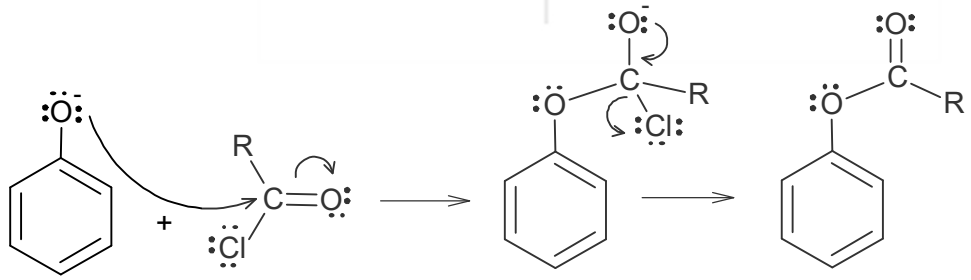
The reaction of phenols with benzoyl chloride in presence of 10 % NaOH is known as **Schotten-Baumann reaction**. Unlike alcohols, esterification of phenol does not occur with a carboxylic acid under acid catalyst as poor availability of lone pairs of phenolic group for nucleophilic attack on the carbon atom of carboxylic group.

Mechanism: Esterification of phenol is an example of nucleophilic acyl substitution reaction.

Step 1: Fornation of phenoxide ion



Step 2: Phenoxide ion (as nucleophile) attacks on carbonyl carbon of acyl chloride and replaces chloride ion (Addition elimination).



iv) Reaction with Iron(III) Chloride: Phenols produce coloured complexes when mixed with iron(III) chloride since phenols act as ligands in such reactions. These reactions are often used as a test for phenols.

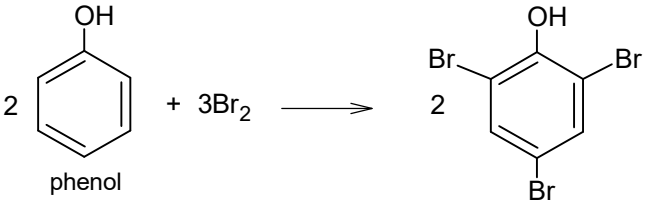
SAQ 7

Discuss the role of base in estrification reactions.

16.5.4 Reactions due to Aromatic Ring

As we mentioned earlier, the −OH group is a powerful activator in electrophilic aromatic substitution reactions and directs substitution to the ortho and para positions. Therefore, phenol is much more reactive towards electrophilic substitution reactions than benzene.

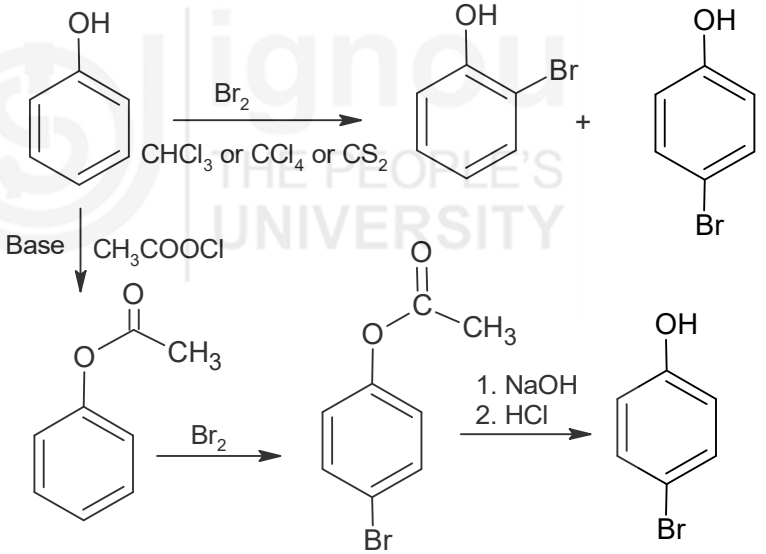
i) **Electrophilic aromatic substitution reaction:** Phenol undergoes electrophilic substitution quite readily. Sometimes phenolic group can be too powerful activating group and it is difficult to control the reaction to one substitution. For example, on shaking phenol with bromine water at room temperature, 2,4,6-tribromophenol is formed:



phenol

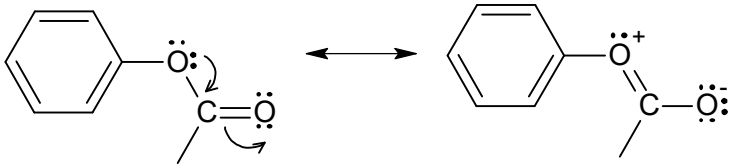
2,4,6-Tribromophenol

The activating power of phenolic group can be decreased by carrying out reaction in less polar or nonplar solvents such as $CHCl_3$, CCl_4 or CS_2 etc.. This is because, in more polar solvent such as water, phenol is available mainly in the form of phenoxide ion (PhO^-) which is more reactive than Phenol. On the other hand, in less polar solvent, phenol form dominates. Other way is by converting the phenol to ester that can be removed by hydrolysis once electrophilic substitution has been carried out. Since the ester is weak activating group and also bulky, it will discourage ortho attack and para product will be the major product.



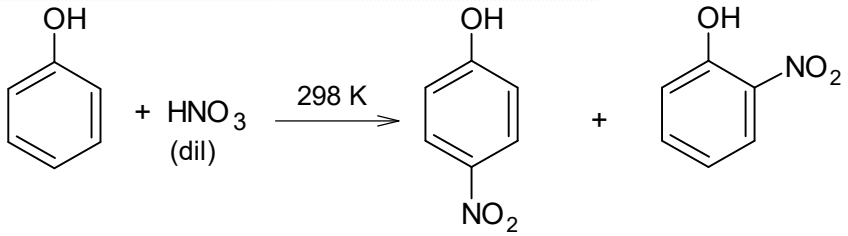
Major product

Following resonating structures explain less reactivity of phenyl acetate (acetoxybenzene):



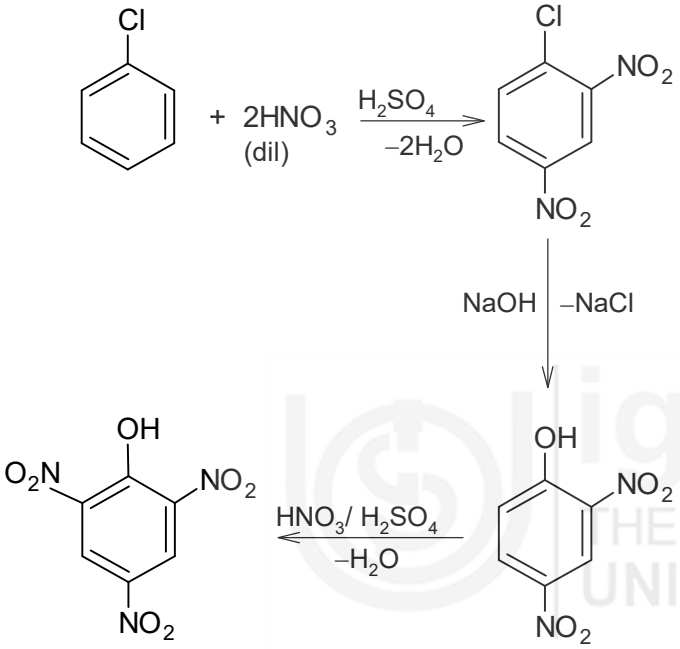
Due to these resonating structures, oxygen electrons are less available to ring

On treatment with dilute nitric acid, phenol gives *o*- and *p*-nitrophenols. Unlike nitration of benzene, there is no need of nitration mixture (conc. $HNO_3 + H_2SO_4$) because of high reactivity of phenol.



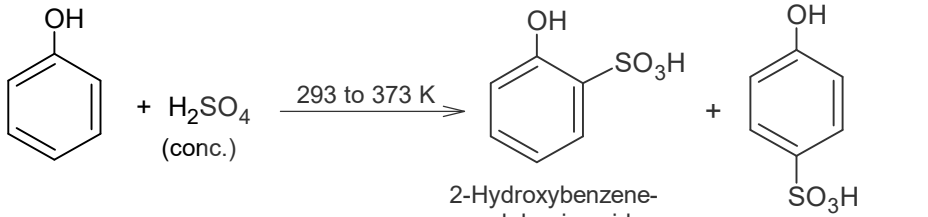
Phenol 4-Nitrophenol 2-Nitrophenol

Phenol, when nitrated directly with concentrated nitric acid, undergoes oxidation. For this reason, 2,4,6-trinitrophenol (picric acid) is obtained through a synthesis that begins with chlorobenzene. The first product is 2,4-dinitrochlorobenzene, which is then easily hydrolysed to, 2,4-dinitrophenol and the nitration continued to give picric acid in good yield.



2,4,6-Trinitrophenol
(picric acid)

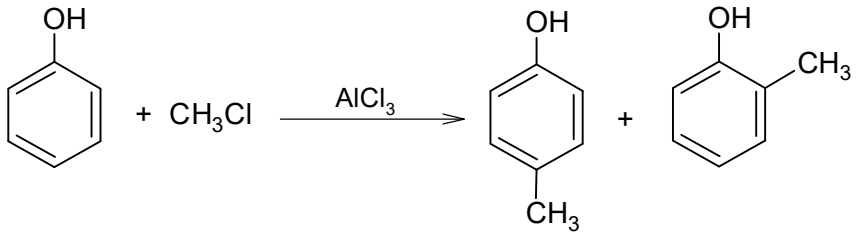
Phenol, when treated with sulphuric acid, yields both ortho and para products,

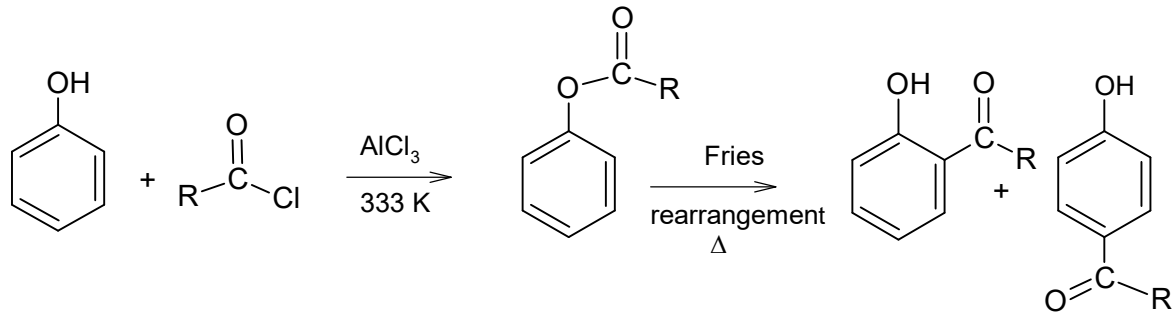


2-Hydroxybenzene-sulphonic acid

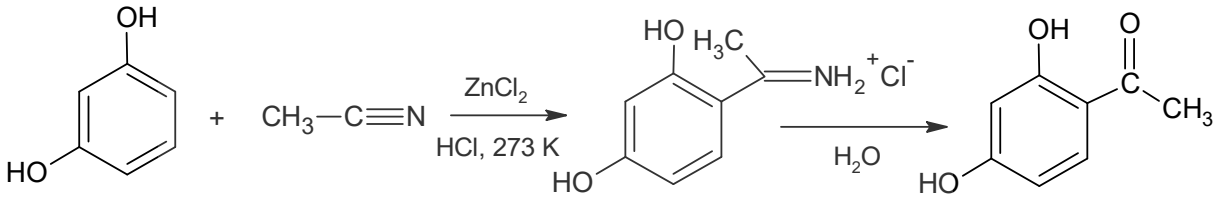
4-Hydroxybenzene-sulphonic acid

Phenol can easily undergo Friedel-Crafts alkylation or acylation. Acylation products in presence of $AlCl_3$ undergo Fries rearrangement.





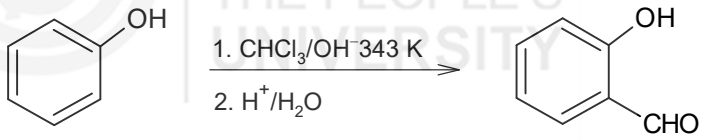
Similar to Friedel-Crafts acylation, acylation of phenol can also be carried out with organic nitriles in presence of hydrogen chloride gas and Lewis acid catalyst (e.g. $ZnCl_2$, $FeCl_3$, $AlCl_3$ etc.). This reaction is known as Hauben-Hoesch reaction. This reaction has been found to be very useful with polyhydroxy phenol. In this reaction, phenol gives imine as intermediate product which on hydrolysis gives aryl ketone.



Imine

1-(2,4-dihyroxyphenyl)ethanone

ii) Reimer-Tiemann reaction: Phenols undergo the Reimer-Tiemann reaction. In it an alkaline solution of phenol is heated with trichloromethane (chloroform) and the product is acidified to give 2-hydroxybenzalohyde (salicylaldehyde).

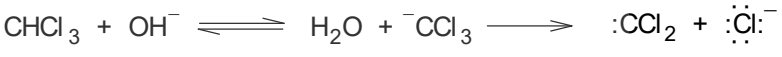


Phenol

2-Hydroxybenzaldehyde (salicylaldehyde)

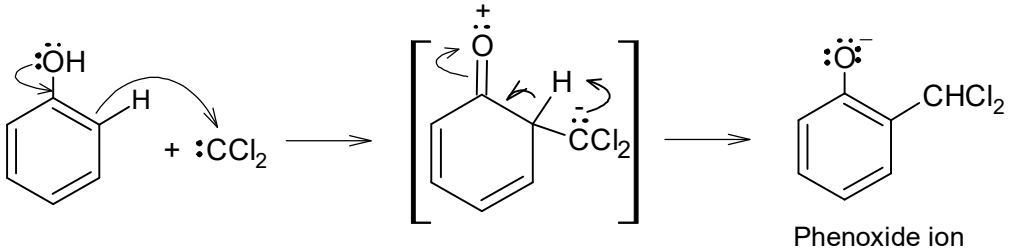
Mechanism: Reimer-Tiemann Reaction

Step 1: Formation of electrophilic dichloro carbene



Dichlorocarbene (electrophilic)

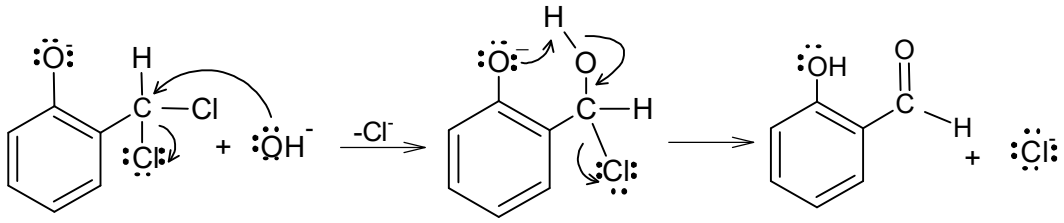
Step 2: Electrophilic addition of carbene to phenol.



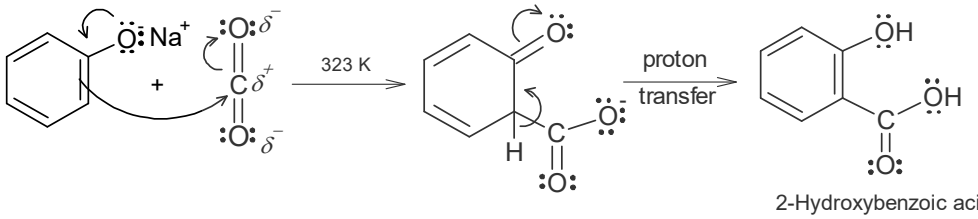
Phenoxide ion intermediate

Step 3: Phenoxide formed in Step 2 reacts with strong base to form

2-hydroxybenzaldehyde.



iii) Kolbe reaction: On heating sodium or potassium phenoxide with carbon dioxide and subsequent acidification, 2-hydroxybenzoic acid (salicyclic acid) is formed. This is known as **Kolbe reaction**. In this reaction, carbon of CO_2 acts as an electrophile in aromatic substitution.



2-Hydroxybenzoic acid
(salicylic acid)

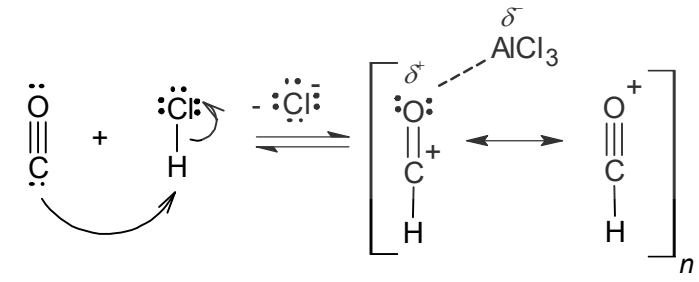
iv) Gattermann and Koch formylation: The introduction of a formyl group into electronic rich aromatic rings by using CO/HCl/Lewis acid catalyst ($AlCl_3$, $AlBr_3$, $FeCl_3$ etc.) is known as Gattermann-Koch formylation. Co-catalyst such as Cu_2Cl_2, $TiCl_4$ or $NiCl_2$ is needed to carry out reaction at normal atmospheric pressure; however, no catalyst is needed at high pressure (100-250 atm).

Gattermann introduced a modification where HCN is mixed with HCl in presence of $ZnCl_2$ to formylate phenols. This modification is called the Gattermann formylation or Gattermann synthesis. Formylation generally occurs *para* to hyrooxyl groups. Both these reactions belong to the category of electrophilic aromatic substitution.

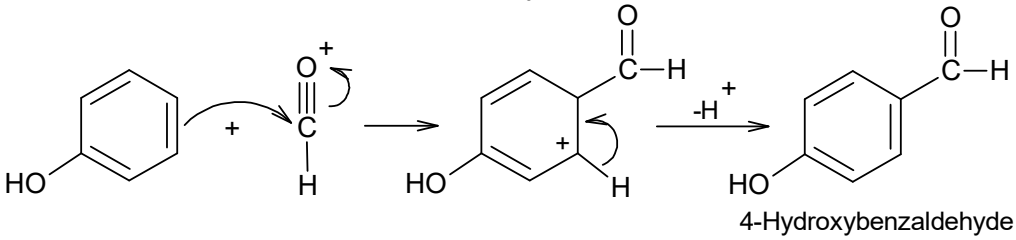
As HCN is very toxic compound so R Adams suggested modification for the Gattermann synthesis. He generated HCN during reaction (in situ) by the reaction of $Zn(CN)_2$ with HCl.

Mechanism: Gattermann-Koch Formylation

Step 1: Formation of formylation



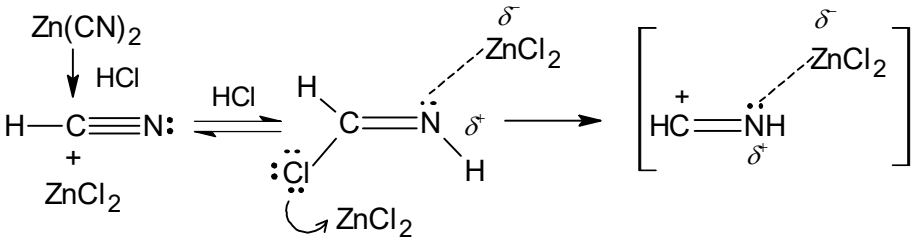
Step 2: Electrophilic substitution of formyl cation



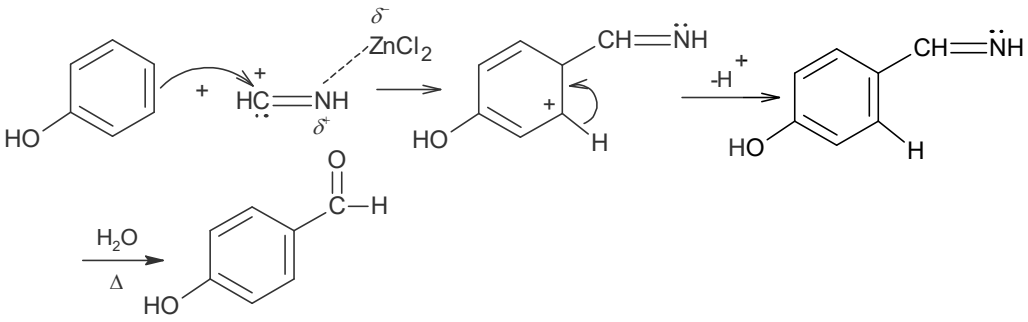
4-Hydroxybenzaldehyde

Gattermann Synthesis

Step 1: Formation of electrophilic [$^{+}$CH=NH]



Step 2: Electrophilic substitution of [NC^{+}=NH]

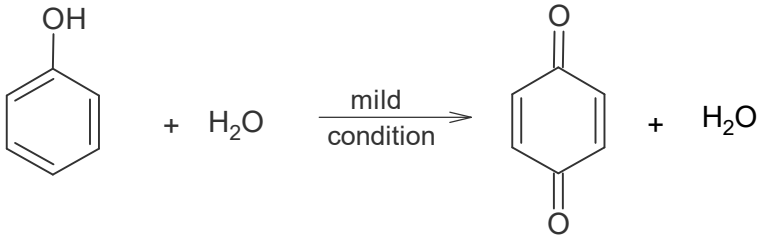


4-Hydroxybenzaldehyde

16.5.4 Oxidation of Phenols

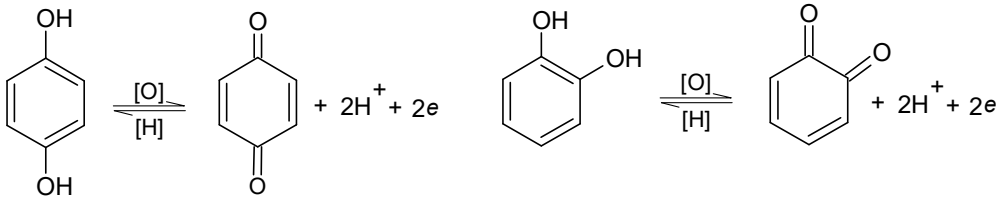
The ability of hydroquinone to reduce silver ions to silver metal is the chemical basis of photography. Hydroquinone is developer fluid which reduces the light activated silver ions at a faster rate than the nonexposed silver ions. In the fixing process unreacted silver halide is converted into a water soluble silver complex of sodium thiosulphate, and washed from film. The result is the familiar photographic negative.

Phenols are easily oxidised, but their products are often complex. The oxidation may occur with air alone **(autoxidation)** or with other oxidising agents. The reaction of phenols with oxygen in the air is exploited industrially by the use of phenol as antioxidants in gasoline, rubber and other products. Phenols react with oxygen more readily than most other organic compounds and protect them from oxidation.



1,4-Quinone
(1,4-benzoquinone)

Hydroquinone and catechol are easily oxidised to quinones by mild oxidising agents such as Ag^{+} of Fe^{3+}.

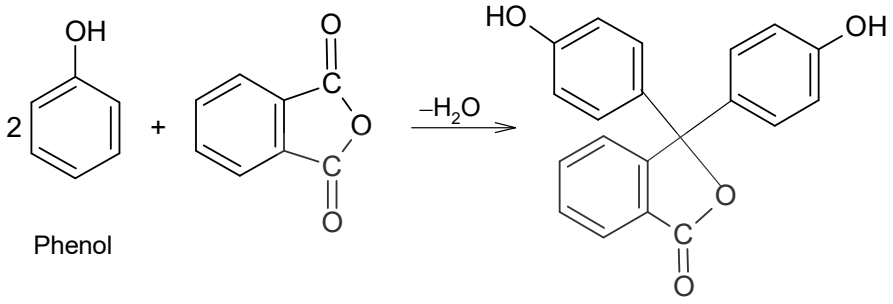


1,4-Benzenediol (hydroquinone) | 1,4-Quinone (1,4-benzoquinone) | 1,2-Benzenediol (catechol) | 1,2-Quinone

16.5.5 Condensation Reactions

Condensation of phenols with phthalic anhydride in the presence of a dehydrating agent gives a class of compounds known as **phthaleins**. These are dyes.

By heating a mixture of phenol and phthalic anhydride in the presence of concentrated sulphuric acid, phenolphthalein is formed:

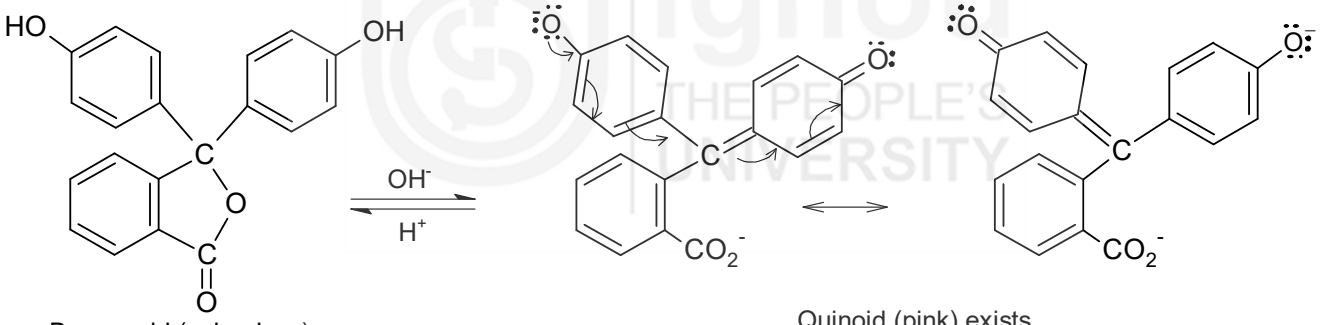


Phenol

Phenolphthalein (colourless)

Phenolphthalein is colourless in acidic medium. On addition of alkali, a pink coloration develops due to the quinoid form. Addition of excess alkali regenerates the benzenoid structure which is colourless. Phenolphthalein is commonly used in the laboratory as a pH indicator. At pH below 8.5, the molecule exists in colourless form and at pH~9 and above, in pink form.

Phenolphthalein as pH indicator

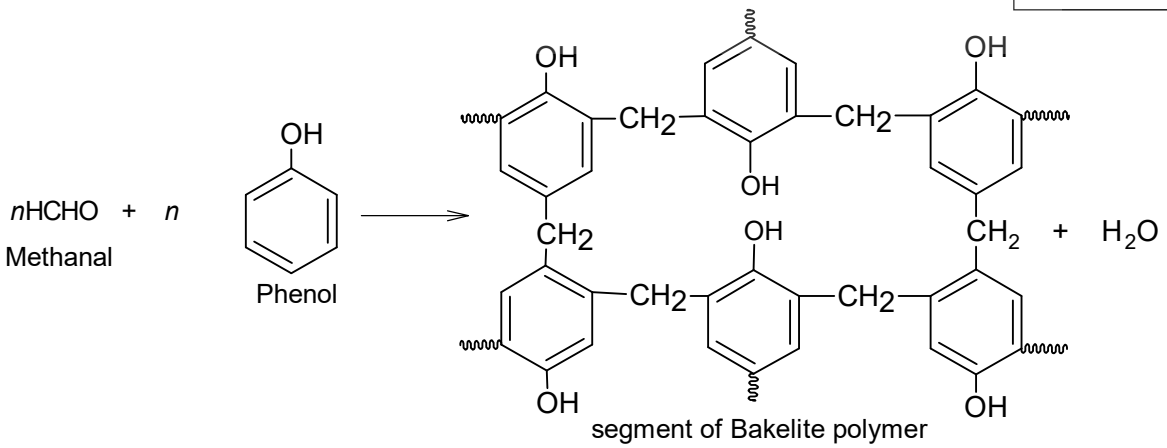


Benzenoid (colourless) exist below pH 8.5

Quinoid (pink) exists at pH~9 and above

The condensation of phenol with excess of methanal (formaldehyde) in the presence of dilute sodium hydroxide gives polymer which is known as Bakelite. These are phenol methanol (phenol-formaldehyde) resins which are three-dimensional polymer of the following possible structure:

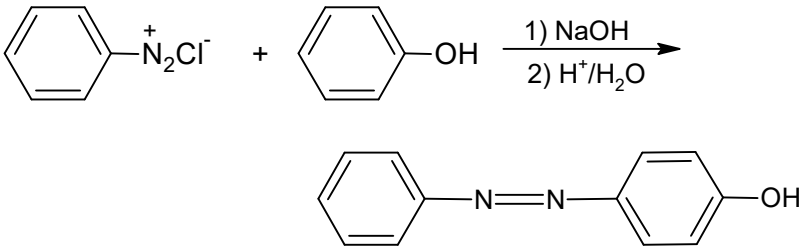
The electric resistance of Bakalite makes it especially useful for electric plugs, switches and tools.



segment of Bakelite polymer

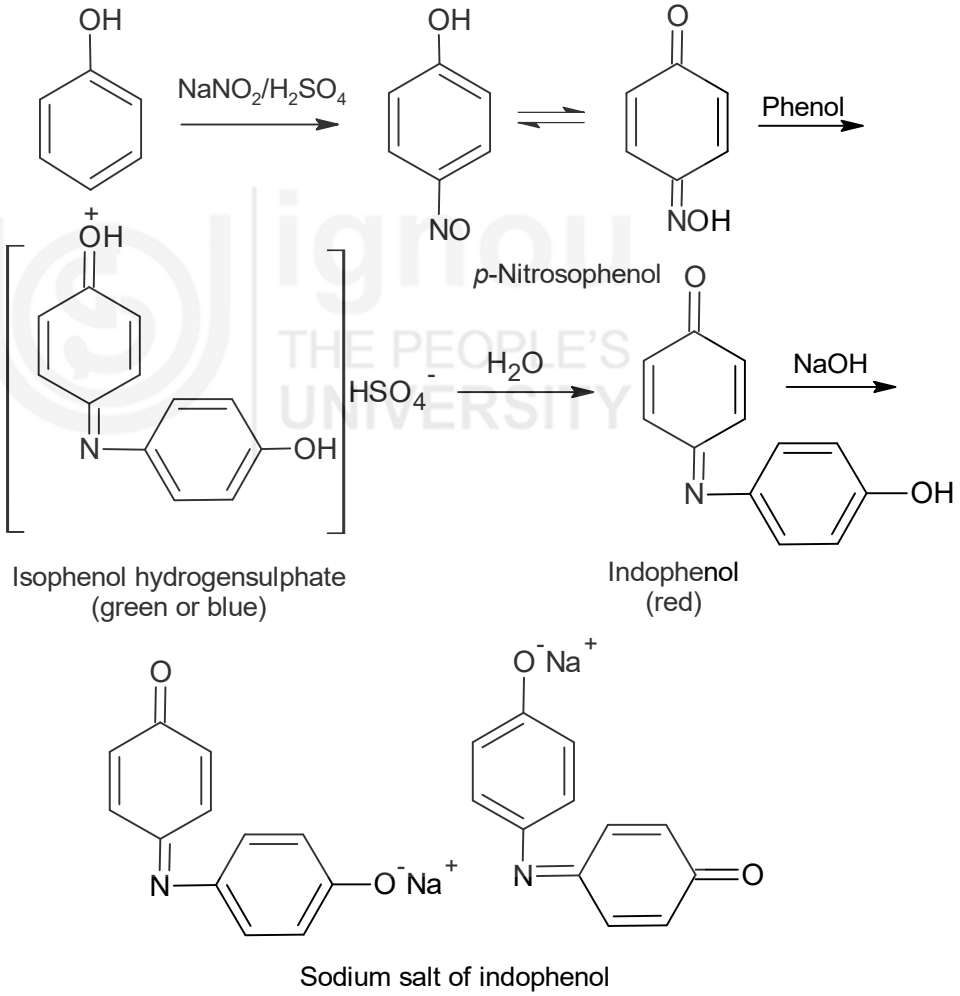
16.5.6 Coupling Reaction

Phenols couple with diazonium salts in alkaline conditions to form azo dyes. This reaction follows electrophilic substitution mechanism.



16.5.7 Libermann's Nitroso Reaction

Phenol reacts with sodium nitrite and concentrated sulphuric acid and forms a green or blue coloured complex. This blue colour of complex changes to red on dilution. The red colour of complex change to blue, if we change the acidic medium to alkaline.



Sodium salt of indophenol

SAQ 8

Treatment of phenol with trichloromethane (chloroform) and aqueous sodium hydroxide gives:

a) 2-chlorophenol
b) 2-hydroxybenzaldehyde
c) 3-hydroxybenzaldehyde
d) 3-chlorophenol

SAQ 9

How will you bring about following conversions?

a) Phenol to phenyl benzoate
b) Phenol to 4-hydroxybenzaldehyde
c) Phenol to 4-bromophenol
d) Chlorobenzene to picric acid

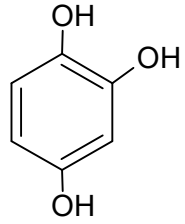
16.6 SUMMARY

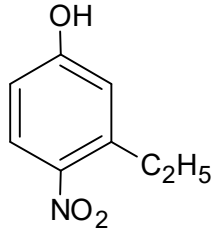
In this unit we have described the chemistry of phenols. We are summarising below what we have studied:

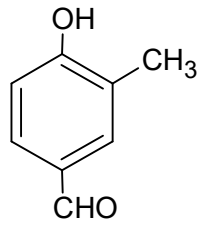
- Phenols are polar compounds and the –OH group of phenols participates in hydrogen bonding. Therefore, the boiling points and melting points of phenols are higher than aryl halides.
- Phenols are obtained by the decarboxylation of phenolic acid, action of water on diazonium salts and from Grignard reagent. They are prepared on a commercial scale by catalytic oxidation of methylbenzene (toluene) or decomposition of cumene pereoxide or from chlorobenzene by Dow process. Phenols are also obtained from coal tar.
- Phenols are stronger acids than alcohols. They are easily converted to phenoxide ions on treatment with aqueous sodium hydroxide.
- Electron releasing substituents attached to the ring, decrease acidity of phenols. Strongly electron withdrawing groups such as $–NO_2$ at ortho and para positions increase the acidity many fold.
- The –OH group pf phenol is powerful activator substituent and electrophilic aromatic substitution occurs readily in phenols.
- Phenol undergoes electrophilic substitution (nitration, halogenation, Friedel-Crafts reaction, sulphonation, etc.) quite readily giving a mixture ortho- and para-derivatives.
- On heating phenol with trichloromethane (chloroform) and potassium hydroxide, 2-hydroxy benzaldehyde is obtained. On passing carbon dioxide in a mixture of phenol and aq. sodium hydroxide, *o*-hydroxy benzoic acid is formed.
- On condensation with phthalic anhydride in the presence of a dehydrating agent, phenol gives phthalein dyes. With methanal, phenol gives a polymer, Bakelite.

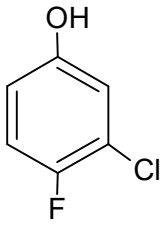
16.7 TERMINAL QUESTIONS

1. Name the following compounds:

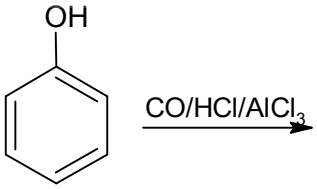
a) 

b) 

c) 

d) 

2. Write chemical reaction for each of the following reactions.
   a) Sodium salicylate + soda lime
   b) Benzene + propene + $AlCl_3$ + Heat
   c) 1,2-Dichlorobenzene + NaOH + $CuSO_4$ + Heat
   d) Phenyldiazonium salt + H_2O
3. Which compound in each of the following pairs is more acidic? Explain
   a) Cyclohexanol or phenol;
   b) 2,4-Dinitophenol or 3,5-dinitophenol;
   c) *p*-Nitrophenol or *m*-nitrophenol;
   d) 4-Hyroxybenzaldehyde or phenol.
4. Write the mechanism of the formation of salicylic acid from phenol.
5. How will you bring about following conversions?
   a) Phenol to anisol
   b) 1,4-Benzenediol to 1,4-quinone
   c) Phenol to monosubstituted bromophenol
   d) 1,3,5-benzenetriol to 1-(2,4,6-trihydroxyphenyl)ethanone
   e) Phenyl acetate to 1-(2-hyroxyphenyl)ethanone.
6. Identify compounds A to C in the synthetic sequence given below:
   i) Phenol + $CH_3COCl \xrightarrow{NaOH}$ A
   ii) A + $Br_2 \longrightarrow$ B
   iii) B + HCl $\xrightarrow{\Delta}$ C
7. Write all the steps involved in following reaction:



8. How will you test the presence of phenolic group?
9. Outline a reasonable preparation route of following:
   a) 2,4,6-Trinitophenol from chlorobenzene
   b) 4-Nitrophenyl phenyl ether from chlorobezene and phenol.

16.8 ANSWERS

Self Assessment Questions

1. i) 3-Methyl benzenol (*m*-cresol)

   ii) 3-Hyroxybenzaldehyde (m-hyroxybenzaldehyde)

   iii) 4-Hydroxy-3-methylbenzoic acid

   iv) 2-Hydroxy-3-methoxybenzoic acid

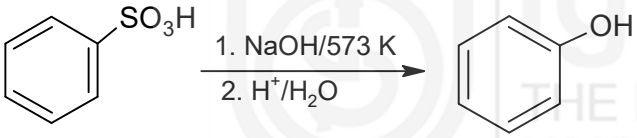
   v) 2-Fluoro-4-hyroxybenzoic acid

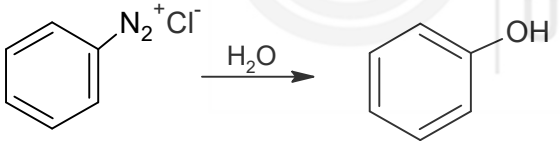
2. Two factors are mainly responsible for this, These are

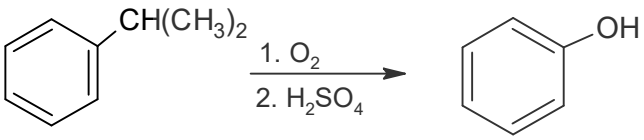
   i) C-O bond is formed by the overlapping of sp^2 orbital of carbon of benzene ring which has more *s* character and sp^3 of oxygen atom.

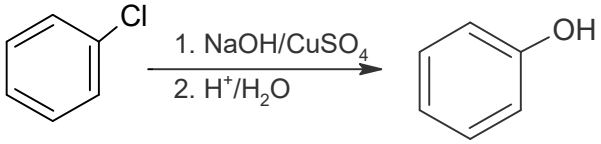
   ii) The lone pairs on the oxygen atom on phenol can overlap with the delocalised ring system of benzene.

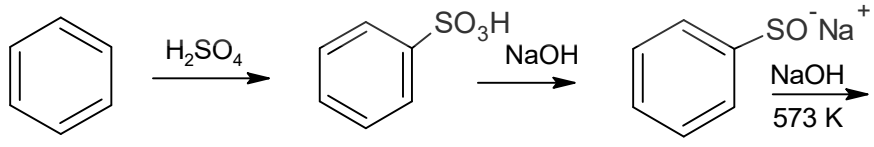
3. In case of *o*-flurophenol, fluorine atom is more electronegative than hydrogen atom of hydroxyl group attached to aromatic ring. This leads to intra-molecular hydrogen bonding within a single molecule. On the other hand, *p*-flurophenol has intermolecular hydrogen bonding. Therefore, *o*-flurophenol has lower melting point than *p*-flurophenol.

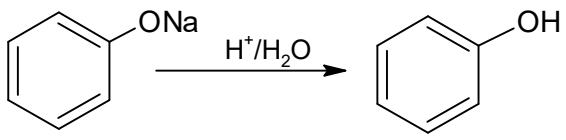
4. a) 

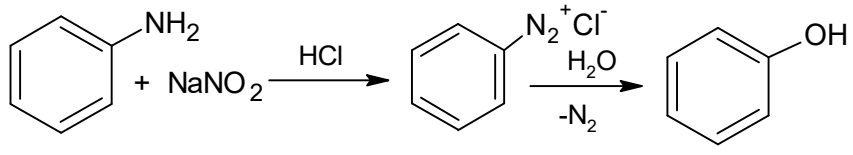
   b) 

   c) 

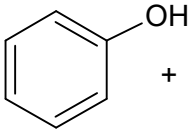
   d) 

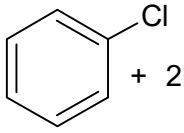
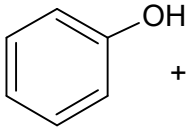
5. a) 

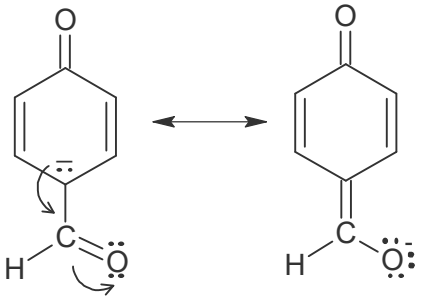
   b) 

c) $C_6H_5MgBr + O_2 \longrightarrow C_6H_5—O—O—MgBr \xrightarrow{C_6H_5MgBr}$

$2\,C_6H_5—O—MgBr \xrightarrow{H^+/H_2O}$  $+ \quad 2Mg(OH)Br$

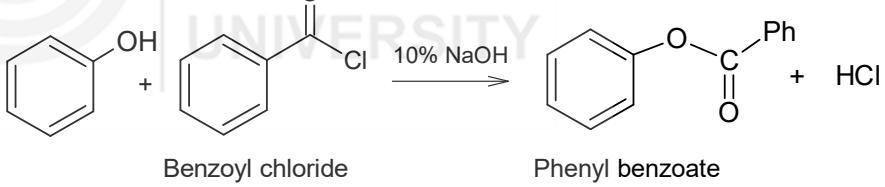
d)  $+ \; 2NaOH \xrightarrow[\text{Pressure, } CuSO_4]{473\ K}$  $+ \quad NaCl$

6. Similar to nitro group, aldehyde group contributes in delocalisation of negative charge of phenoxide ion.

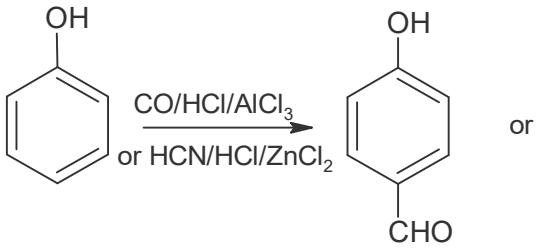


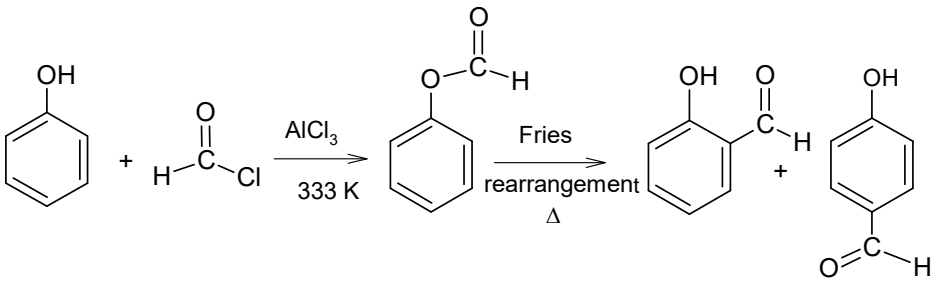
7. Base is used as a catalyst to increase nucleophilicity by converting the nucleophile to an anion nucleophile. In case of phenols, the phenoxide ion is better nucleophile than unionised phenol.

8. 2-Hyroxybenzaldehyde

9. a) 

Benzoyl chloride Phenyl benzoate

b) 



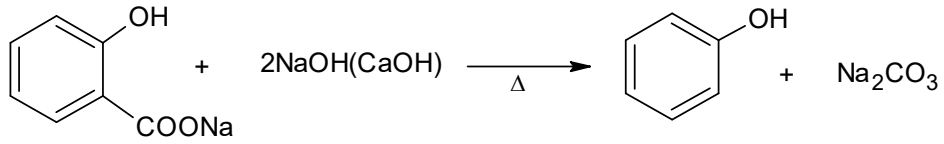
c) See sub-section 16.5.4.

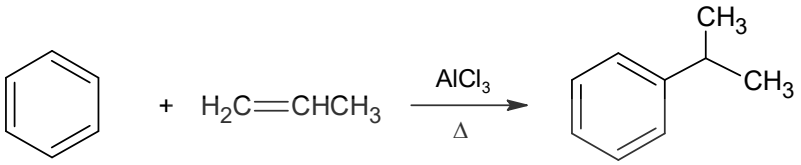
d) See sub-section 16.5.4.

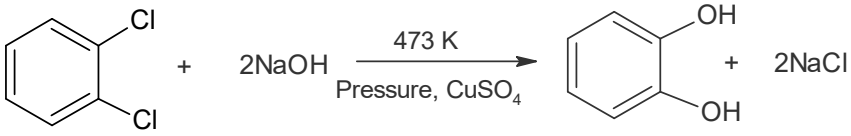
Terminal Questions

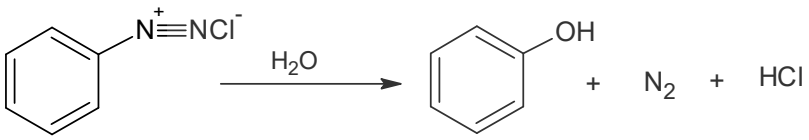
a a) 1,2,4-Benzenetriol; c) 2-Ethyl-4-nitophenol;

c) 3-Methyl-4-hyroxybenzaldehyde; d) 3-Chloro-4-fluorophenol.

2. a) 

b) 

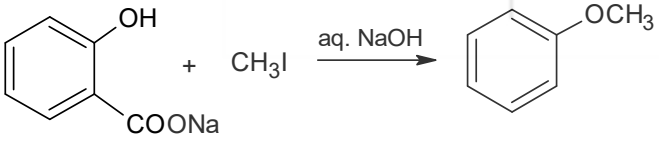
c) 

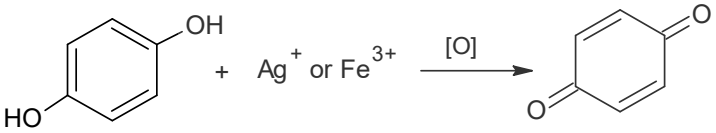
d) 

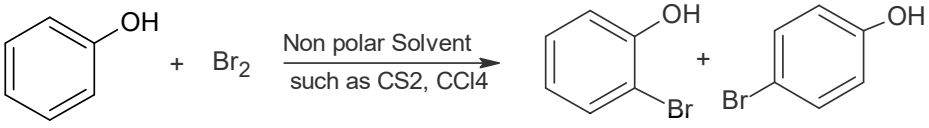
3. a) Phenol; b) 2,4-Dinitophenol; c) p-Nitrophenol; d) 4-Hydroxybenzaldehyde

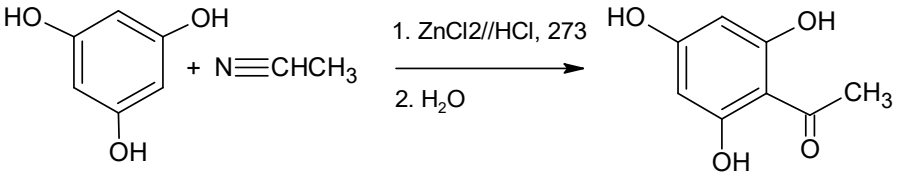
Explanation: Electron withdrawing group substituents increases the acidity of phenol, if such groups are at ortho and para to hydroxyl group this effect is more pronounced.

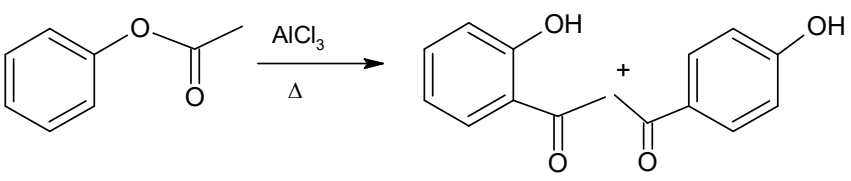
4. See page 169, Kolbe reaction.

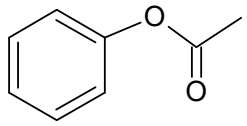
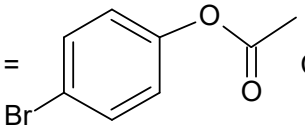
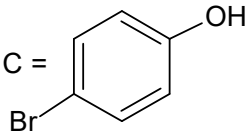
5. a) 

b) 

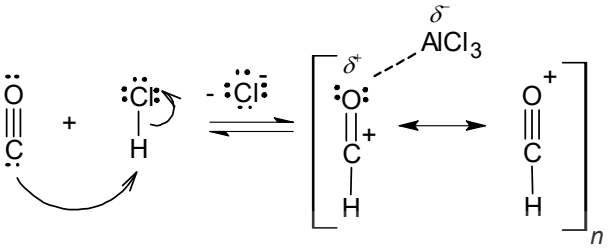
c) 

d) 

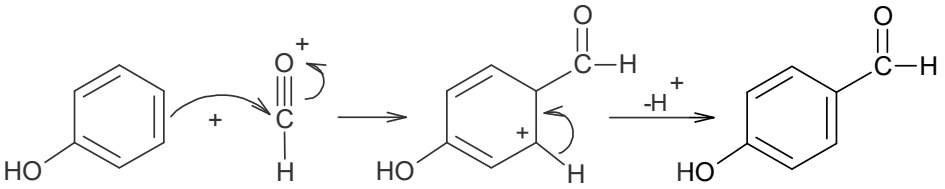
e) 

6. A =  B =  C = 

7. **Step 1:** Formation of formulation



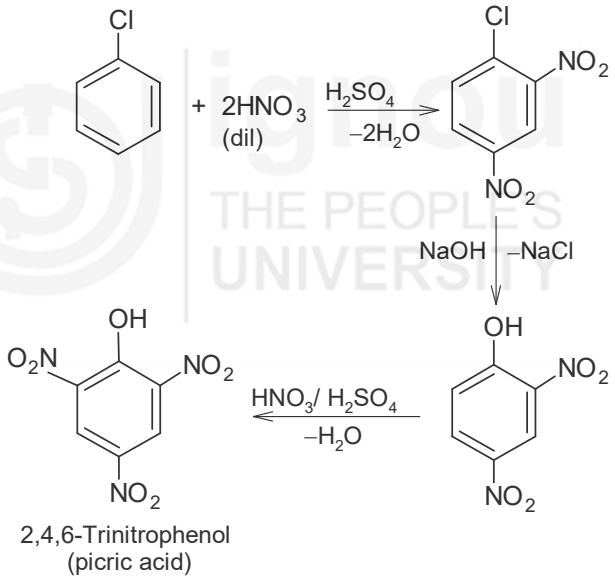
Step 2: Electrophilic substitution of formyl cation



4-Hydroxybenzaldehyde

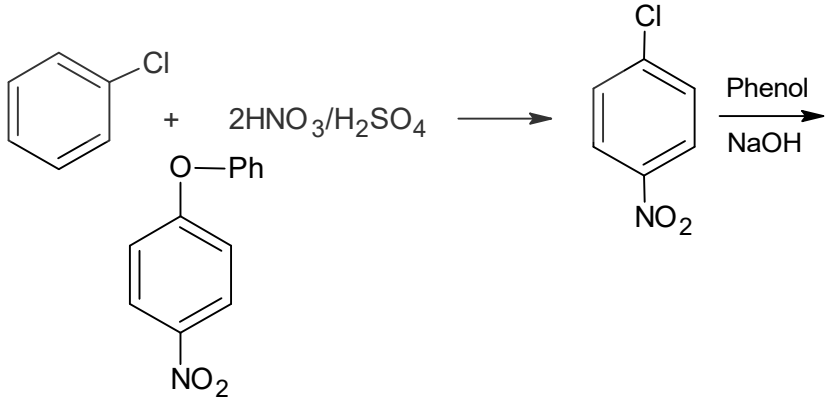
8. a) $FeCl_3$ solution test; b) Libermann's nitroso reaction

9. a)



2,4,6-Trinitrophenol
(picric acid)

b)



UNIT 17

ETHERS

Structure

17.1 INTRODUCTION

In the previous Unit 15, while discussing the chemistry of alcohols, it was pointed out that mono alkyl derivatives of water are called alcohols and dialkyl derivatives of water are called ethers. In this unit, we will study the chemistry of ethers in detail.

In this unit, we first discuss the structure and classification of ethers. Then, we will study the preparations, physical properties and chemical properties of both open chain ethers and a group of cyclic ethers, called epoxides. We shall also touch on a special group of macrocyclic (large ring) compounds, called crown ethers and cryptands.

The Nobel Prize for Chemistry in 1987 was given to Charles J. Pedersen, Donald J. Cramand Jean-Marie Lehn, for their efforts in discovering and determining uses of crown ethers and cryptands, thus launching the new growing field of Supramolecular Chemistry.

Expected Learning Outcomes

After studying this unit, you should be able to:

- list different types of ethers such as open chain ethers, epoxides, crown ethers and cryptands;
- outline the preparation of open chain ethers and epoxides;
- explain the physical properties of ethers;
- describe the chemical properties of open chain ethers and epoxides;

- describe the crown ethers and cryptands; and
- state the industrial uses of ethers and related compounds.

17.2 CLASSIFICATION

Like water and alcohols, ether molecule contains a sp^3hybridised oxygen atom, which is bonded to two carbon atoms. Fig. 17.1 shows the structure of dimethyl ether [CH_3OCH_3] also with its ball-stick model. In this molecule, two sp^3hybrid orbitals of oxygen form two σ bonds with the two carbon atoms. Similar to water molecule the other two sp^3 hybrid orbitals of oxygen each contain an unshared pair of electrons. The C−O−C bond angle in dimethyl ether is 110.3°, a value close to the tetrahedral angle of 109.5°.

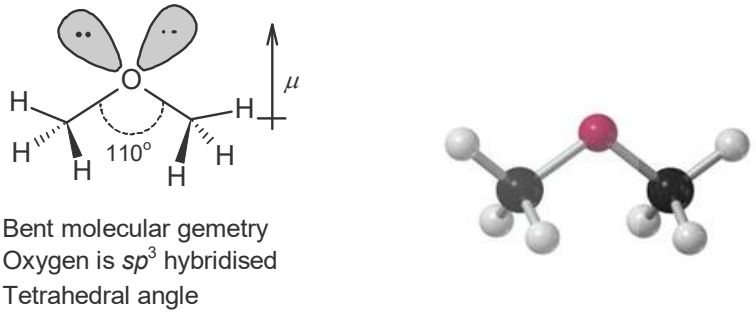
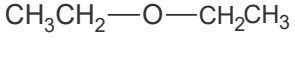
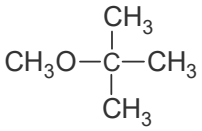


Fig. 17.1: Structure of dimethyl ether along with its Ball-and-Stick model. Here μ represents net dipole moment in the molecule.

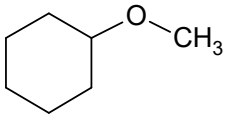
The groups bonded to the ether oxygen can be alkyl, aryl, ethenyl or any other carbon containing group. Aliphatic ethers may be simple or symmetrical in which both the alkyl groups are the same or mixed i.e. unsymmetrical in which the two alkyl groups are different. Just to recall, in IUPAC system of nomenclature, ethers are named by selecting the longer carbon chain as the parent alkane and namely the −OR group bonded to it as an alkoxy group. Common name are derived by listing the alkyl group bonded to oxygen in alphabetical order and adding the word ether. Now consider few examples of simple ethers (name given in brackets are common names):



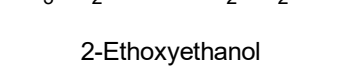
Ethoxyethane
(Diethyl ether)
Simple Ether



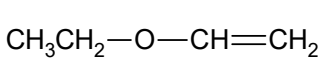
2-Methoxy-2-methylpropane
(*t*-Butylmethyl ether)
Mixed Ether



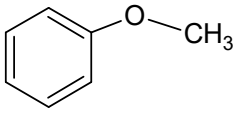
Methoxycyclohexane



2-Ethoxyethanol



Ethoxyethene

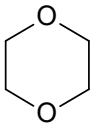


Methoxybenzene
(Anisole)

Ethers can be either open chain or cyclic. When the ring size (including the oxygen atom) is five or greater, the chemistry of the cyclic ether is similar to that of an open chain ethers. Three membered cyclic ethers are called oxiranes (IUPAC name), which are often known as epoxides. Because of Baeyer strain associated with small rings, epoxides are more reactive than other ethers.

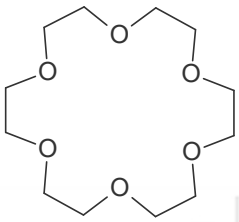
Oxirane
(Ethylene oxide)

Oxolane
(Tetrahydrofuran, THF)



1,4-Dioxane

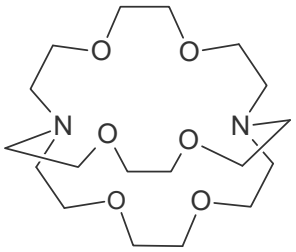
Large ring system with repeating $-OCH_2CH_2-$ units are called crown ethers. They are macro-monocyclic polyethers. These compounds are valuable reagents which can be used to help dissolve inorganic salts in organic solvents. Crown ethers are named as *x*-crown-*y*; where *x* is the total number of atoms in the ring and *y* is the total number of oxygen atom in the ring. For example,



18-Crown-6

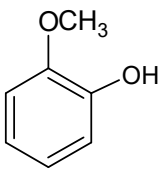
A crown ether with a total number of 18 atoms and 6 oxygen atoms in the ring

There is another class of compounds, similar to crown ethers, called cryptands. These are macro-polycyclic polymers having additional bridge(s). These compounds show higher complexing ability and selectivity towards a variety of metal ions in comparison with crown ethers. In the example of cryptand [2.2.2.] given below, the numbers in the brackets indicate the numbers of ether oxygen atoms in the chains between the bridgehead nitrogen atoms.

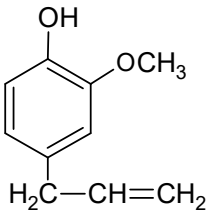


Cryptands [2.2.2]

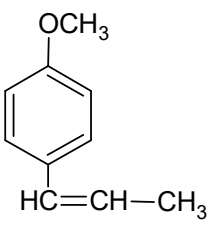
Ethers occur widely in nature, some examples of naturally occurring ethers are:



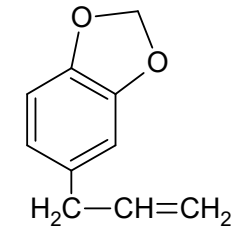
Guaicol
(Beech-wood tar)



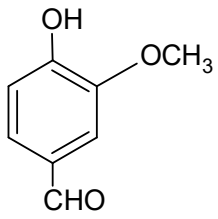
Eugenol
(Oil of cloves)



Anethol (Aniseed oil)



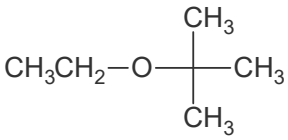
Safrole
(Camphol oil)

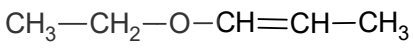


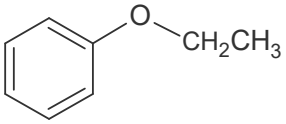
Vanilla
(Vanilla beans)

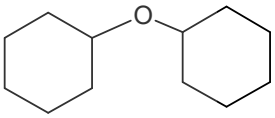
SAQ 1

Write IUPAC and common names for the following ethers:

a) 

b) 

c) 

d) 

17.3 PREPARATION OF ETHERS

In this section, we will discuss the preparation of open chain ethers and epoxides.

17.3.1 Preparation of Open Chain Ethers

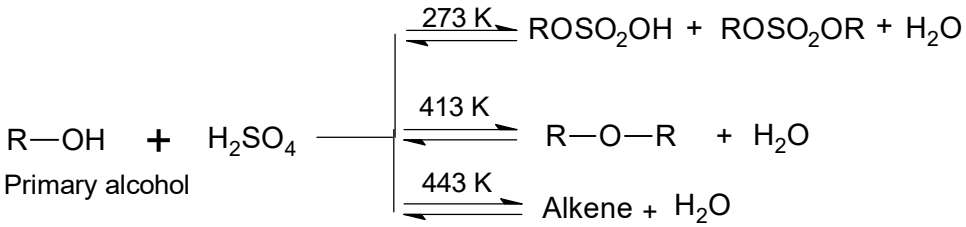
Ethers are commonly prepared from alcohols. There are two methods:

i) Acid catalysed dehydration

ii) Nucleophilic displacement (Williamson ether synthesis)

i) Acid Catalysed Dehydration

In precious Unit 15, we have described the conversion of alcohols to alkenes in the presence of sulphuric acid. When an alcohol is reacted with H_2SO_4, a series of reversible reactions occur under different reaction conditions. Which reaction product predominates depends on the structure of the alcohol, the relative concentration of reactants, and temperature of the reaction mixture.



As shown above, primary alcohols give alkyl hydrogen sulphate and dialkylsulphate at low temperatures, symmetrical ethers at moderate temperature and alkenes at high temperature.

In case of secondary alcohols, yields of ethers are lower because of competition from acid-catalysed dehydration. In case of tertiary alcohols, dehydration to an alkene is the only reaction.

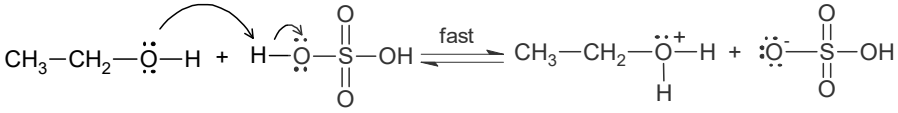
Diethyl ether is synthesised on an industrial scale by the acid-catalysed dehydration of ethanol.

$$2CH_3CH_2OH \xrightarrow[413\ K]{H_2SO_4} CH_3CH_2OCH_2CH_3 + H_2O$$

Reaction Mechanism: Acid-catalysed dehydration of ethanol:

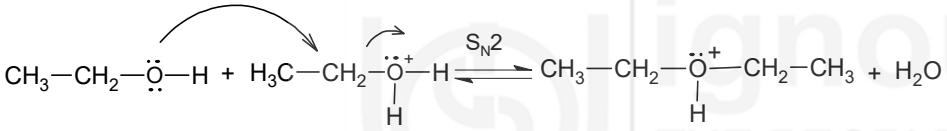
It follows the S_N2 mechanism. Detailed steps are as follows:

Step 1: Acid converts −OH, a poor leaving group into $-OH_2^+$ a better leaving group



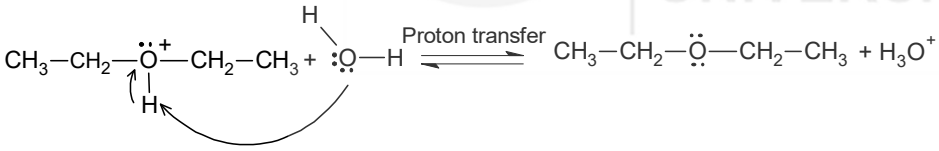
An oxonium ion

Step 2: The protonated ethanol is attacked by another molecule of ethanol (nucleophile) in an S_N2 process, thus, displacing H_2O.



An oxonium ion

Step 3: Deprotonation



Notice that a proton is used in the first step of the mechanism and then another proton is liberated in the last step of the mechanism. Therefore, in this reaction, the acids behave as a catalyst.

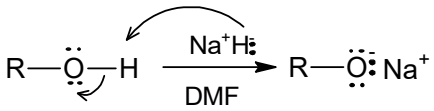
ii) Williamson Ether Synthesis

Ethers are also prepared by Williamson ether synthesis. This method is the most common general method for the preparation of ethers. This process is named after Alexander Williamson, a British scientist who first demonstrated this method in 1850 as a method of preparing diethyl ether. This method involves nucleophilic displacement of halide ion or other good leaving group by an alkoxide ion (S_N2 mechanism). If alcohols are starting material, one alcohol preferable primary alcohol is converted to alkyl halide (R−X), another alcohol is converted to alkoxide, using strong base such as sodium hydride (NaH), and then, the two products are heated together.

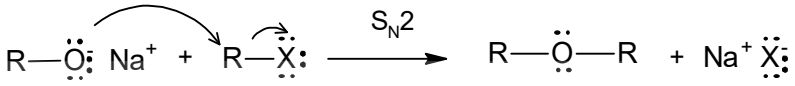
$$R{-}OH \xrightarrow[DMF]{NaH} R{-}ONa \xrightarrow[S_N2]{R{-}Cl} R{-}O{-}R + Na^+X^-$$

Mechanism: Williamson Ether Synthesis: This is a two step reaction.

Step 1: Hydride ion function as a base and deprotonates the alcohol.



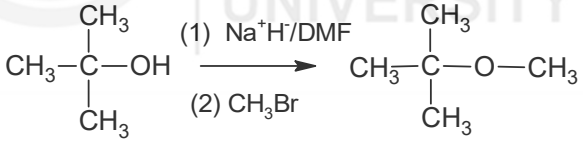
Step 2: The resulting alkoxide ion then functions as nucleophile and attacks the electrophilic carbon centre of alkyl halide and displacing halide ion.



As mentioned earlier, because of steric effect, the tendency for alkyl halide to undergo S_N2 reaction is primary>*sec*>*tert*. Therefore, this process works best with methyl or primary alkyl halides. Secondary alkyl halides are less efficient because elimination is favoured over substitution and tertiary alkyl cannot be used. This limitation must be kept in mind while designing a synthesis of ethers. For example consider the synthesis of *tert*-butylmethyl ether which is also known as methyl-*tert*-butyl ether (MTBE). There can be two possible routes, one by the reaction of butyl alcohol and bromomethane or other by the reaction of methanol with 2-bromo-2-methylpropane (*tert*-butyl bromide). The first route is efficient because it takes place through a primary alkyl halide i.e. bromomethane; which is suitable for S_N2 reaction. On the other hand; the second route does not work because it employs a tertiary alkyl halide which will undergo elimination reaction (E2) rather than substitution.

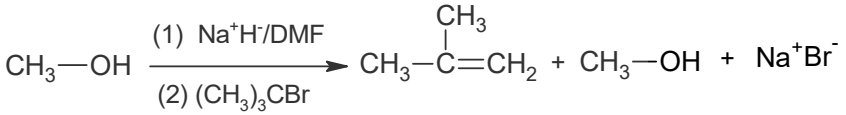
MTBE was used to improve octane rating of gasoline until it was observed the MTBE might contribute to ground water contamination.

Route 1:



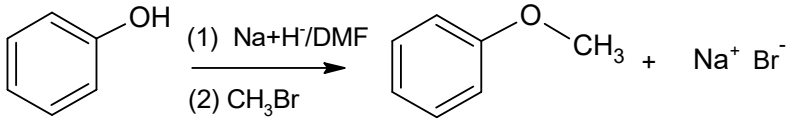
2-Methoxy-2-methylpropane
(*tert*-butylmethyl ether)

Route 2:



2-methylpropene

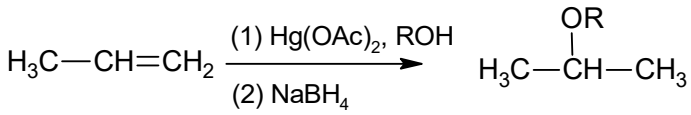
This method can also be used to prepare phenolic ethers.



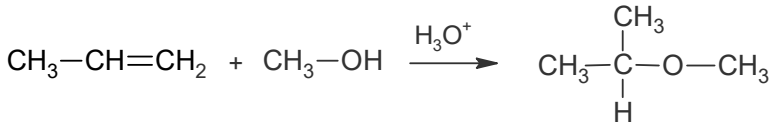
Methoxybenzen(Anisole)

If you wish to prepare methoxybenzene by the reaction of methanol and chlorobenezene in presence of strong base; this reaction does not work. Because the chlorine atom in chlorobenezene is attached to sp^2 carbon and S_N2 process does not occur at sp^2-hybridised centre.

Ethers can also be prepared by the reaction of alcohols with alkenes. Recall the oxymercuration-demercuration reaction of alkenes. If alcohol is used in place of water, the final product is ether which is result of the addition of alcohol across the alkene. This addition reaction follows Markovnikov mechanism.



Similar to above reaction, alcohol can also be added to alkenes in the presence of acid to give ethers.

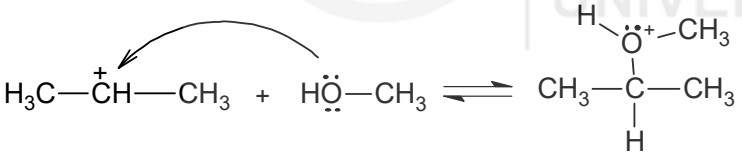


Mechanism: Acid catalyzed addition of an alcohol to an alkene.

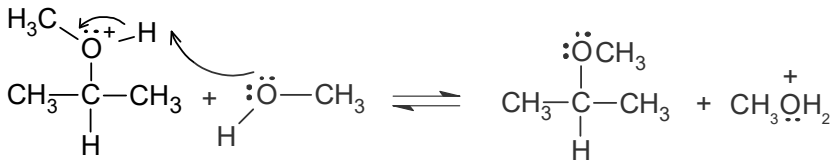
This reaction follows S_N1 mechanism.

Step 1: Proton transfer from the acid to the alkene gives a carbocation intermediate.

Step 2: Reaction of the carbocation intermediate (an electrophile) with the alcohol (a nucleophile) gives an oxonium ion.



Step 3: Proton transfer to solvent

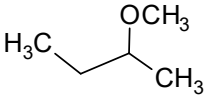


This method is used for the industrial production of MTBE. This method is only suitable for the reactions of alkenes which can produce stable carbocations with methanol or primary alcohols.

SAQ 2

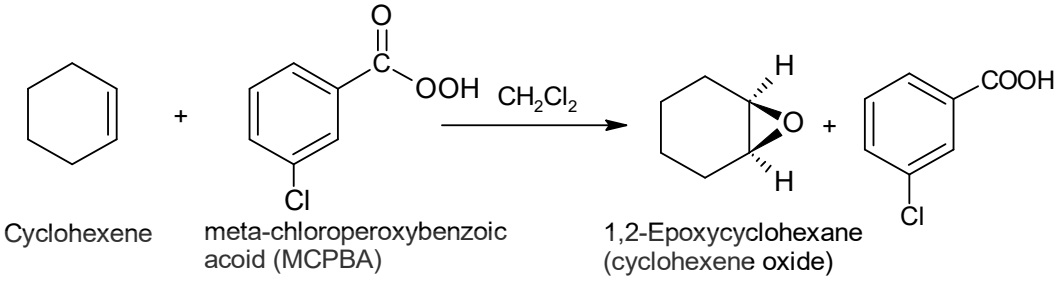
Show the reagents that can best be used to prepare following ethers by Williamson ether synthesis:

a) $CH_3CH_2—O—Ph$

b) 

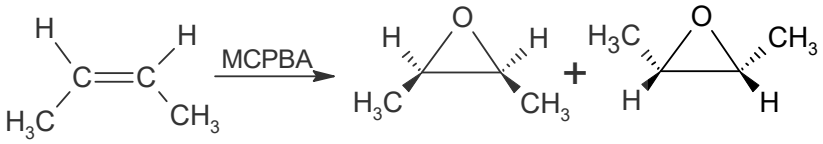
17.3.2 Preparation of Epoxides

Epoxides are obtained by the reaction of alkenes with peracids. This is most common method for synthesis of epoxides. Among per acids *meta*-chloroperoxybenezoic acid (MCPBA) is the most commonly used per acid.

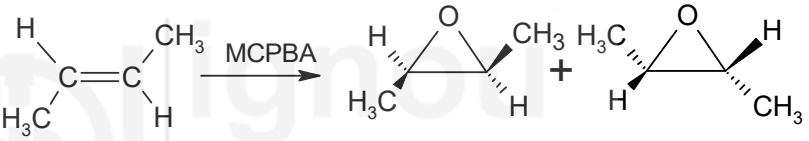


Cyclohexene | meta-chloroperoxybenzoic acid (MCPBA) | 1,2-Epoxycyclohexane (cyclohexene oxide)

This reaction is stereo specific (not entioselective); that is, the *cis* alkene give *cis* epoxides and *trans* alkene give *trans* epoxides.



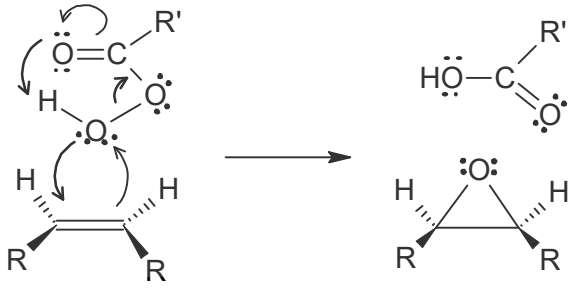
cis-2-Butene | *cis*-2,3-Dimethyloxirane (a pair of enantiomers)



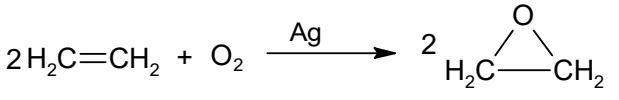
tans-2-Butene | *tans*-2,3-Dimethyloxirane (a pair of enantiomers)

Mechanism: Epoxidation of an alkene by peracids.

In this reaction, bond-making and band-breaking steps are taking place simultaneously i.e. in concerted way.



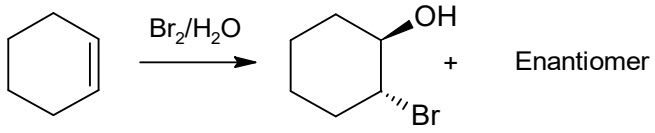
Industrial preparation of oxirane (ethylene oxide) is carried out by passing a mixture of ethylene and air (or oxygen) over a silver catalyst.



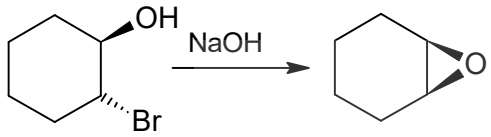
Oxirane (ethylenew oxide)

This method only works for the production of oxirane from ethylene. There are other methods also by which, we can prepare epoxides. In the previous Unit

15, we have seen that alkenes can be converted to halohydrins when they are treated with halogens in presence of water.



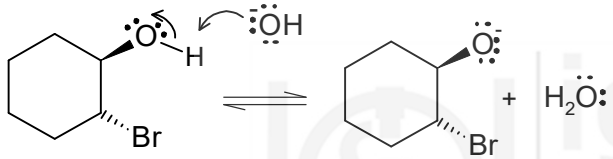
The halohydrin obtained from above reaction can be converted into epoxides upon treatment with a strong base.



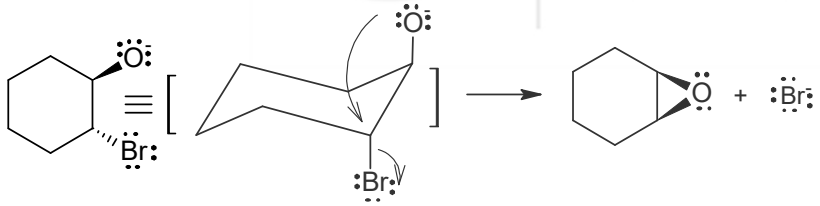
This reaction follows intra molecular S_N2 mechanism.

Mechanism: Epoxide formation from halohydrin.

Step 1: Hydroxide ion or other base abstract a proton from the hydroxyl group of halohydrin to form an alkoxide ion.

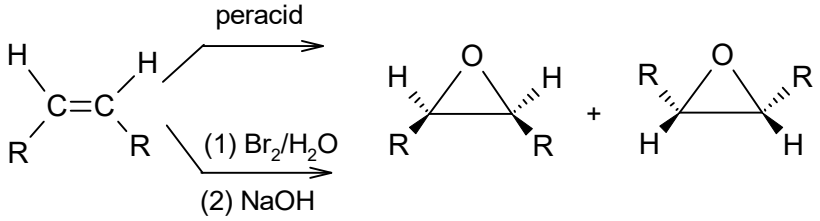


Step 2: Alkoxide ion formed in Step 1, functions as a nucleophile in an intramolecular S_N2 reaction, removing the halide as a leaving group.

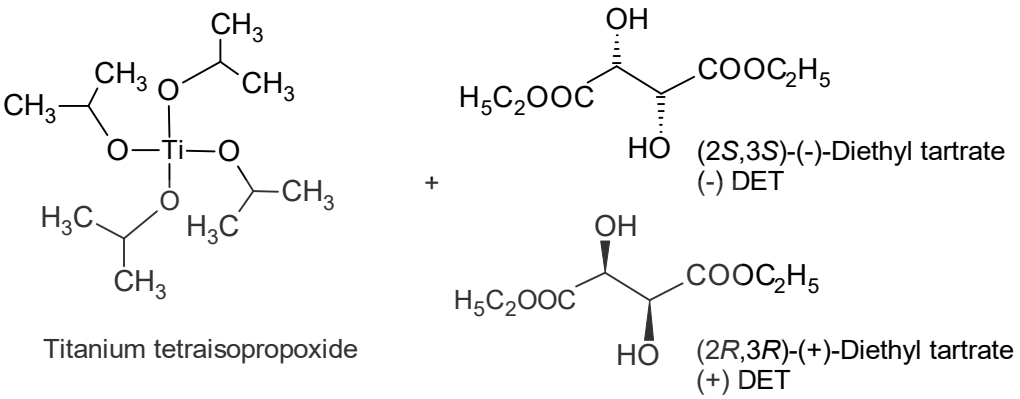


As with all S_N2 reactions, attack of the nucleophile is from the back side of the C – X bond and causing inversion of configuration at the site of substitution.

The stereochemical outcome of this conversion is the same as the reaction of peracids with alkene. That is, substituents that are *cis* to each other in the starting alkene remain *cis* to each other in the epoxide; and similarly substituents that are *trans* to each other in the starting alkene remain *trans* to each other in the epoxide.



Both the conversion routes provide a racemic mixture. In recent past, Prof. Barry Sharpless developed a catalyst for the **asymmetric (stereoselective) epoxidation of allylic alcohols**. The Sharpless' catalyst consists of titanium tetraisopropoxide [$Ti(O\text{-}iPr)_4$], and pure enantiomer of diethyl tartrate [(+) or (–) DET].



In the presence of any one of the above chiral catalyst, an oxidising agent such as *tert*-butylhydroperoxide converts an allylic alcohol to enantioselective epoxide. The stereochemical outcome of the reaction depends on whether the chiral catalyst used was (+) DET or (–) DET.

In Fig.17.2, we have shown that how oxygen is delivered to either the top face or the bottom face of the alkene, depending on which enantiomer of diethyl tartrate is used.

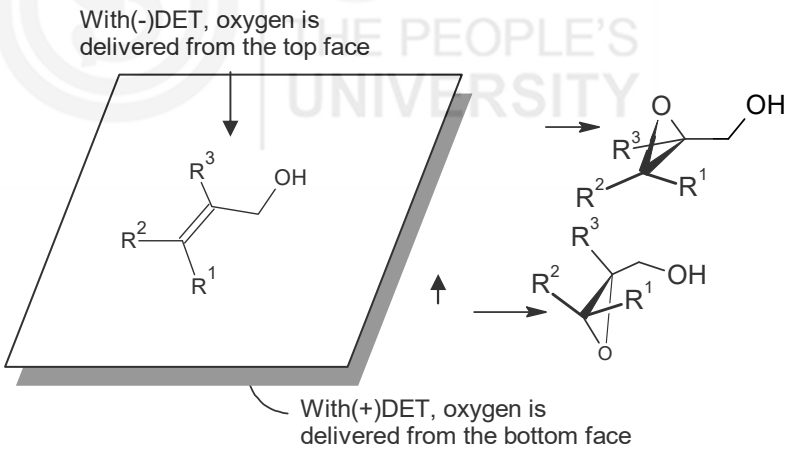
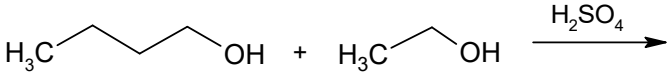


Fig. 17.1: Sharpless asymmetric Epoxidation.

Sharpless along with William Knowles and Ryoji Noyori received the 2001 Noble Prize in Chemistry for their pioneering work in the field of asymmetric synthesis.

SAQ 3

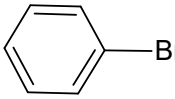
Explain why the following reaction is not preferred for the preparation of ether.



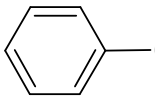
SAQ 4

Predict the major product of these reactions:

a) $CH_3CH_2OH + H_2SO_4 \xrightarrow[413]{\text{warm}}$

b) $CH_3CH_2ONa +$  $\longrightarrow$

c) $CH_3ONa + (CH_3)_3CCl \longrightarrow$

d)  $+ \; CH_3CH_2Br \longrightarrow$

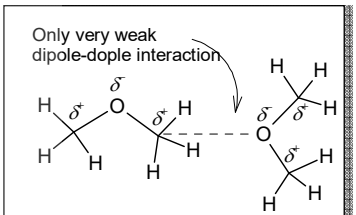
17.4 PROPERTIES OF ETHERS

Before studying the reactions of open chain ethers and epoxides in detail, let us first understand their physical properties.

17.4.1 Physical Properties

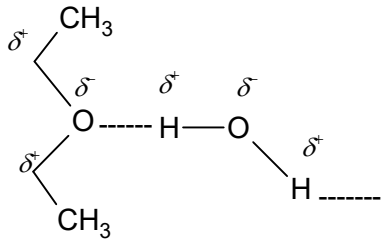
As discussed earlier, the geometry of the oxygen atom in ethers is similar to water and alcohols. Oxygen atom is sp^3 hybrised and the orbitals are arranged in a tetrahedral shape. Thus, similar to water and alcohols, due to the high electronegativity of oxygen atom, ethers are polar compounds with dipole moment 3.9×10^{-30} C m for diethyl ether. But they are not as polar as water, 6.0×10^{-30} C m and alcohols, 5.7×10^{-30} C m (for methanol). Because of the weak dipole – dipole interactions, ethers have lower building points as compared to those of alcohols containing the same number of carbon atoms and are close to those of hydrocarbons of having comparable carbon numbers. Another factor which also influences the boiling points of compounds is intermolecular hydrogen bonding, which is present in case of alcohols and not feasible in case of ethers because they do not have hydrogen attached to the oxygen and thus they cannot function as hydrogen bond donors.

	CH_3CH_2OH	$CH_3—O—CH_3$	$CH_3CH_2CH_3$
Boiling point	Ethanol 352 K	Dimethyl ether 249 K	Propane 273 K



Steric factor further weaken the dipole-dipole interaction

As ethers cannot act as hydrogen bond donors they are much less soluble in water than alcohols. However, they can act as hydrogen bond acceptors, which make them more soluble in water than hydrocarbons.



We are summarizing the physical properties of some of ethers in Table 17.1. For the comparison, boiling points of some alcohols are also given.

Table 17.1: Physical properties of some ethers

Name	Formula	Bp,K	Solubility in H_2O	Density kg/dm^3
Diethyl ether	CH_3OCH_3	249	Miscible	Gas
Ethanol	CH_3CH_2OH	351	(Highly soluble)	0.79
Diethyl ether	$C_2H_5OC_2H_5$	307.6	8 g/100 cm^3	0.71
1-Butanol	$CH_3(CH_2)_2CH_2OH$	380	8.3 g/100 cm^3	0.81
Methyl phenyl ether (anisole)	$C_6H_5-O-CH_3$	427		
Tetra hydro furan (THF)		339	Miscible	0.89
Oxirane		286.5	Miscible	8.88 (at 283 K)

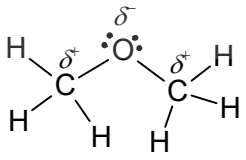
Before studying the reactions of ethers, try following SAQ.

SAQ 5

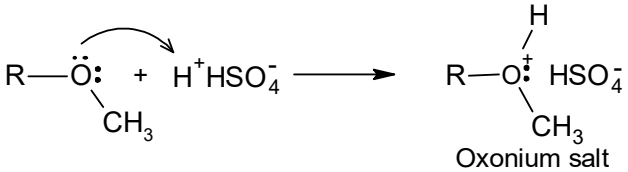
To what effect can you attribute for water solubility of ethers?

17.4.2 Reactions of Open Chain Ethers

Ethers are quite unreactive and behave more like alkanes than like organic compounds containing functional groups. As a result, they are ideal choice as solvent for many reactions. The bond between carbon and oxygen in ether is called the ether linkage. This ether linkage is not affected by even strong bases, oxidising agents such as potassium dichromate or potassium permanganate. However, due to the presence of highly electronegative oxygen atom in ether, the carbon atoms bonded to oxygen behave as electrophilic centres at which nucleophilic reaction can occur.

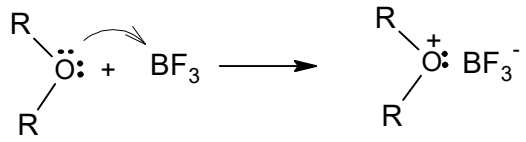


Further due to the presence of lone pair on oxygen, ethers behave as Lewis bases (electron-pair donors). Therefore, with strong acids, ethers give oxonium salts:

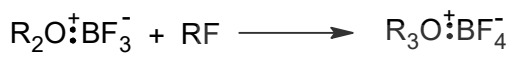


Oxonium salt

The solubility of ethers in sulphuric acid is, thus, a convenient method for distinguishing between ethers and hydrocarbons and alkyl halides. Similarly, ethers react with Lewis acid to form Lewis complexes.



Further, this Lewis complex treatment with alkyl fluoride gives a tertiary oxonium salt, trialkyloxoniumtetrafluoroborate.



The product of above reaction i.e. the, trialkyloxoniumtetrafluoroborates are powerful alkylating agents in many reactions.

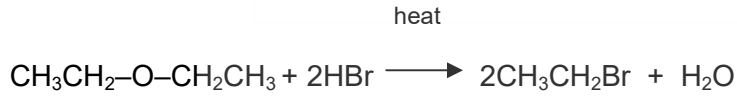
As shown above, ethers have two electrophilic centres. Therefore, ethers may undergo **nucleophilic substitutive reaction**. But in the case of ethers, nucleophilic substitution reaction can only be possible with a reagent that can react first with the oxygen atom of ether to form a good leaving group and then also provide a good nucleophile to displace it. The strong acids such as HBr and HI fulfill these criteria. In such reactions, cleavage of the ether linkage (C – O) takes place. These reactions are called acidic cleavage reaction of ethers.

If the ether is unsymmetrical, the nucleophile prefers to attack on less hindered electrophilic carbon centre of ether. Recall the order of reactivity of S_N2 reactions:

CH_3 > primary > *Sec* > *tert*

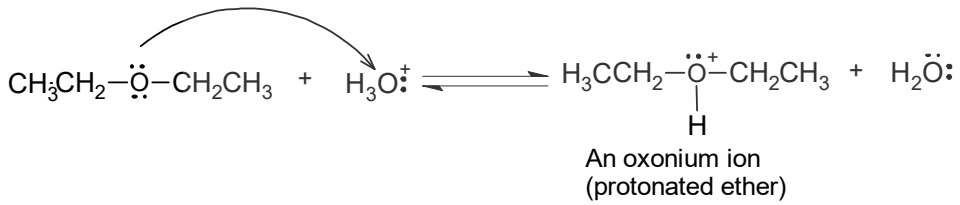
1. Acidic Cleavage

Ethers are cleared using hot, aqueous hydrobromic acid (48%) or hydroiodic acid (57%). For example diethyl ether reacts with hot concentrated HBr to give two molecules of bromoethane.

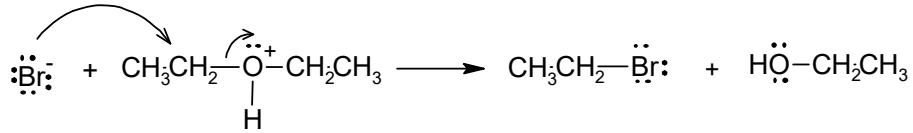


Mechanism: Acid cleavage of ethers:

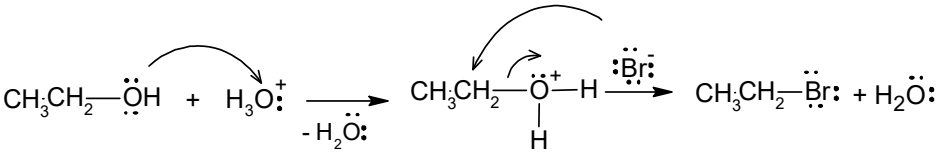
Step 1: Protonation of ether molecule leads to formation of a good leaving group.



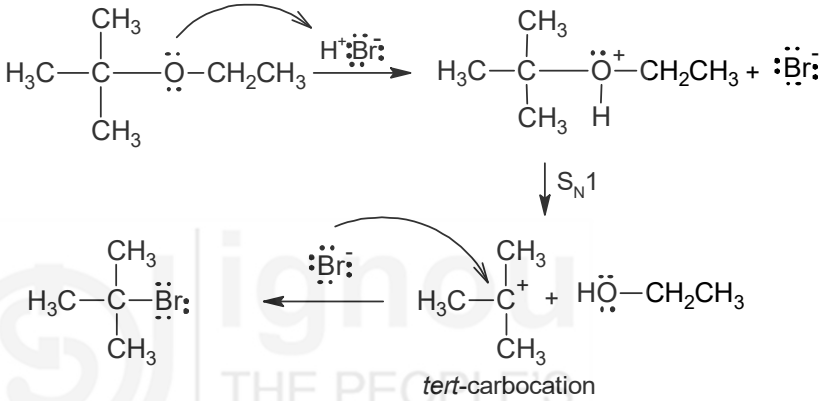
Step 2: Nucleophilic substitution reaction (S_N2): A bromide ion (Br^-) functions as a nucleophile and attacks at electrophilic centre of oxonium ion by displacing an alcohol as a leaving group.



This cleavage produces one molecule of bromoethane and one molecule of ethanol. In presence of excess concentrated HBr, ethanol is converted into second molecule of bromoethane by another S_N2 reaction:

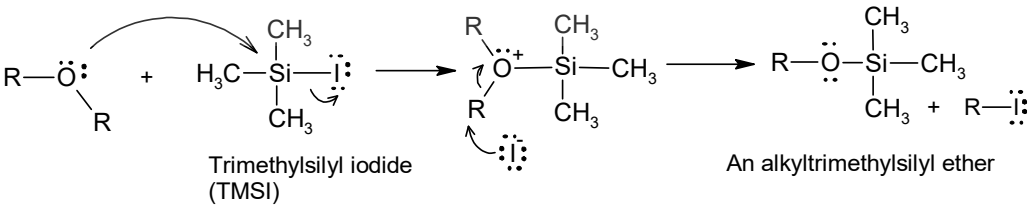


The acid cleavage of dialkyl ethers depends on the nature of the carbon bonded to oxygen. If both carbons are primary, cleavage involves an S_N2 mechanism as illustrated above. Otherwise cleavage is by an S_N1 mechanism. For example, tertiary butyl ethers, allylic and benzylic ethers follow S_N1 mechanism. These ethers require much milder reaction conditions. For example 2-ethoxy-2-methylpropane after protonation, cleaves to produce stable *tert*-carbocation.

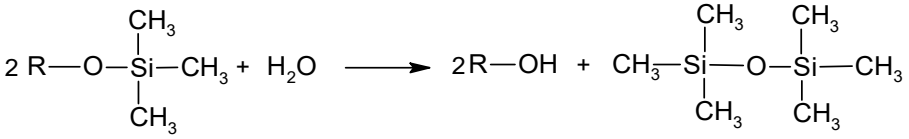


Finally, the reaction of carboction with nucleophile completes the reaction.

Acid cleavage reactions have great importance in synthetic chemistry. The hydroxyl group in a poly functional compound can be protected by converting it into ether and later, after completion of a chemical transformation, the molecule can be regenerated after treatment with concentrate dhydroiodic acid. As HBr and HI are strong acids, therefore, we generally prefer mild reagents such as iodotrimethylsilane or trimethylsilyl iodide (TMSI)[$(CH_3)_3SiI$] for ether cleavage. In first step, it reacts with ether and converts ether oxygen atom to a good leaving group.



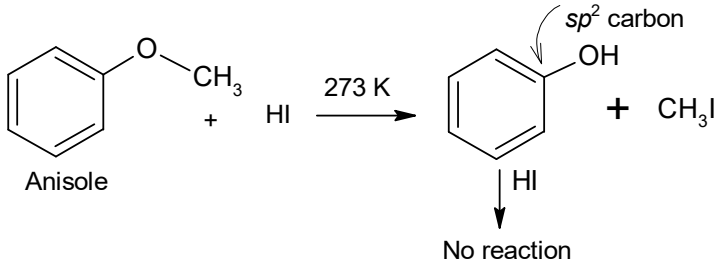
Alcohol can be obtained by the hydrolysis of alkylmethylsillyl ether.



The Zeisel procedure of estimation of the number of methoxyl (CH_3O-) or ethoxyl (C_2H_5O-) groups in alkyl and aryl ethers is based on acid cleavage reactions of ethers. This method consists of ether cleavage with excess of HI, followed by distillation of volatile iodomethane or iodoethane from the reaction mixture. Then, the iodoalkenes are treated with an ethanolic solution of silver nitrate and the silver iodide so formed is weighed.

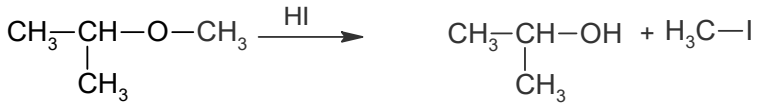
Both HI and HBr can be used to cleave ethers. HCl is less efficient and HF does not cause cleavage of ether. The reactivity is a result of the relative nucleophilicity of the halide ions.

Aromatic ethers, such as anisole, yield the alkyl halide and phenol, not halobenezene and alcohol. This is because; sp^2-hybridised carbon does not undergo reaction by an S_N2 or S_N1 path.



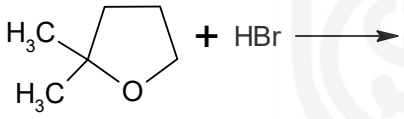
SAQ 6

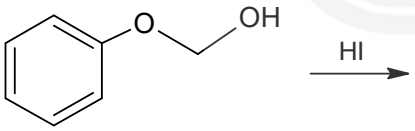
Account for the fact that following reaction gives CH_3I and $(CH_3)_2CHOH$ as the initial major product rather than CH_3OH and $(CH_3)_2CHOI$.

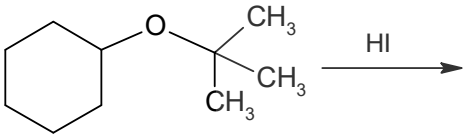


SAQ 7

Write detail mechanism pathway for the following reactions:

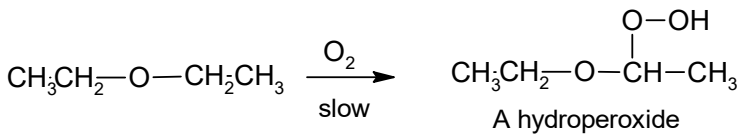
a) 

b) 

c) 

2. Autoxidation of Ethers

Ethers undergo autoxidation in the presence of atmospheric oxygen to form hydroperoxides:

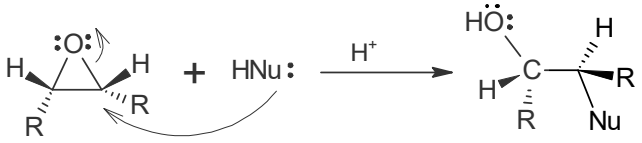


This process takes place via a free radical mechanism. The oxidised product, hydroperoxides decompose violently when heated. The presence of hydroperoxidein ether may cause laboratory explosion when ether is distilled for the purification. Therefore, it is important to know the concentration of hydroperoxide before distillation. To prevent the formation of peroxides, some

ethanol or a small amount of cuprous compound, e.g., cuprous oxide is added. It is also advised that never use ethers past their expiration date.

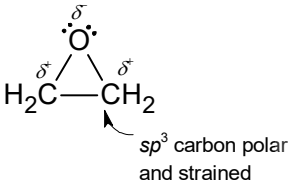
17.4.3 Reactions of Epoxides

It has been stated earlier that because of the strain associated with three-membered ring, epoxides are highly reactive compounds,. The characteristic reaction of epoxides is nucleophilic substitution reaction. In this reaction, ring opening takes place which can be initiated either by acid (acid-catalysed ring opening) or by nucleophile (nucleophilic ring opening). The general reaction can be written as:



Characteristic reaction of epoxides

An epoxide ring cannot have normal sp^3 bond angles of 109°; instead, the inter nuclear angles are about 60°, a geometric requirement of the three membered ring. The orbitals forming the ring bonds are incapable of maximum overlap. Therefore, epoxide ring are - strained. The polarity of the C−O bond, along with the ring strain, contributes to the high reactivity of epoxides compared to the reactivity of other ethers.

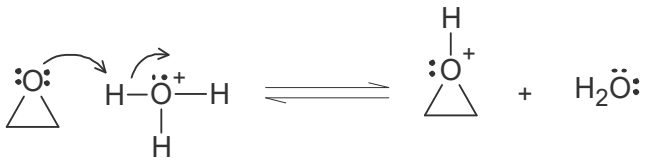


Acid-catalysed Opening

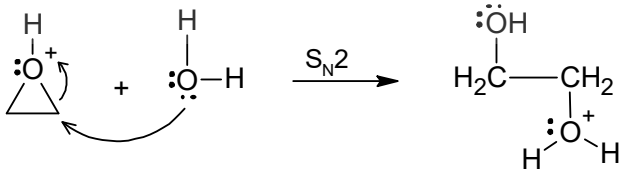
Like other ethers, epoxides undergo carbon-oxygen bond cleavage when treated with an acid. However, because of their high reactivity much milder acidic conditions are employed than for cleavage of open chain ethers. For example, acid-catalysed ring opening of oxirane gives 1, 2-ethane diol (ethylene glycol) when treated with aqueous sulphuric acid.

Mechanism: Acid-catalysed hydrolysis of an expoxide

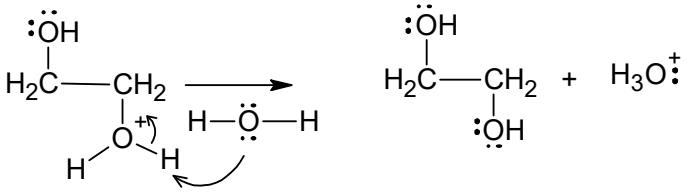
Step 1: Protonation: Proton is transferred from the acid to oxygen of the epoxide to give bridged oxonium ion intermediate



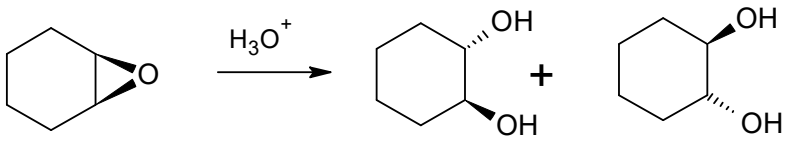
Step 2: Ring Opening: Nucleophile attacks from back side on a bridged oxonium ion and open the three membered ring.



Step 3: Proton Transfer: In this final step proton is transferred to solvent.



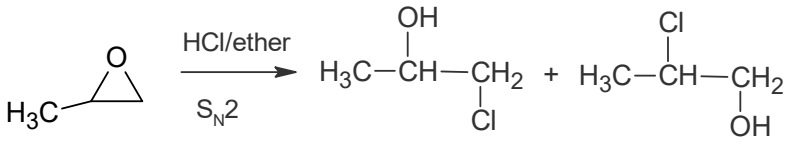
In these reactions, the attack of the nucleophile is anti to the bridge oxonium ion. Thus, the stereochemistry of acid-catalysed ring opening is S_N2 like.



1,2-Epoxy cyclohexane

trans-1,2-Cyclohexanediol
(Racemic mixture)

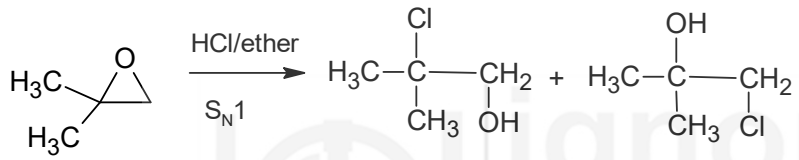
But regiochemistry of these reactions depends on the nature of the epoxides. For example, if one side is primary and other side is secondary, the nucleophile will attack on the less hindered primary position following predominantly S_N2 mechanism. On the other hand, if one side of the epoxides is a tertiary the nucleophile with attack on more substituted tertiary position rather on the primary following predominantly S_N1 process.



1,2-Epoxypropane

1-Chloro-2-propanol
90 %

2-Chloro-1-propanol
10 %

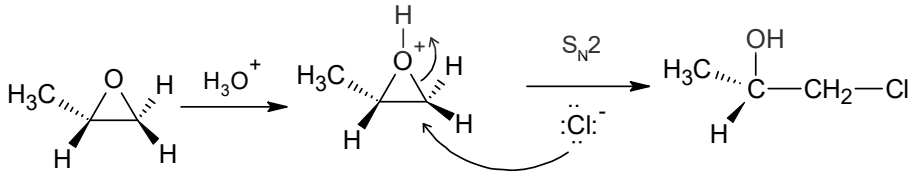


2-Methyl-1,2-Epoxypropane

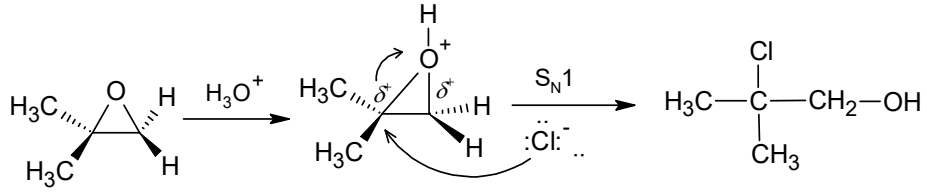
2-Chloro-2-methyl-
1-propanol
60 %

2-Chloro-2-methyl-
2-propanol
40 %

But in reality in S_N1 process, a pure carbocation does not form as we would expect for this process. Instead, an unshared electron pair on the oxygen atom maintains an interaction with the neighbouring carbon atom, which then bears only a partial positive charge. The tertiary position is significantly better at supporting a partial positive charge, so this position has significantly more partial carbocation character than the primary position or in other words more substituted carbon centre is better electrophile and therefore, more susceptible to nucleophilic attack. Because of the bridged carbocation stereochemistry of epoxides, reactions though following S_N1 process are S_N2 like. Above two acid catalysed reactions can now be illustrated as:



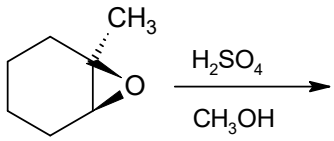
Dominatinf factor: Steric



Dominatinf factor:
electronic effect

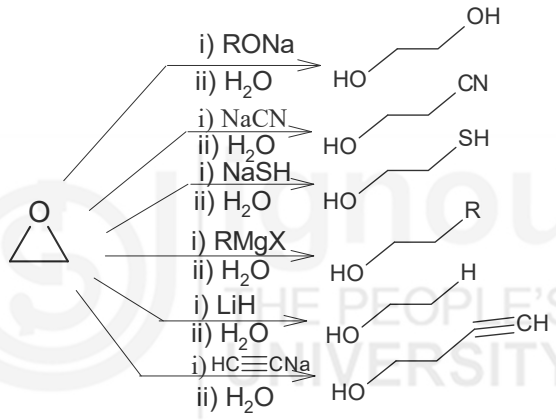
SAQ 8

Predict the product of the reaction below, and draw likely structure of oxonium ion intermediate.



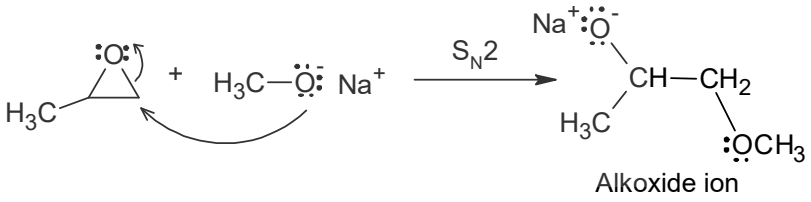
Nucleophilic Ring Opening

Unlike ethers, epoxides undergo ring-opening reaction with a variety of nucleophiles because of the strain associated with ring. Good nucleophiles attack on epoxides by an S_N2 mechanism and shows S_N2 like stereo selectivity and regioslectivity (inversion of configuration and nucleophile attacks the less substituted position).

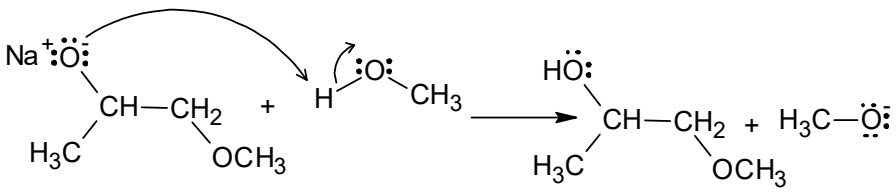


Mechanism: Nucleophilic opening of an epoxide ring

Step 1: Nucleophile attacks from backside on the less hindered carbon of the epoxide and opens the ring by cleaving the C−O bond.

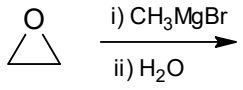


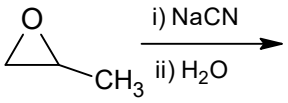
Step 2: The resulting alkoxide ion from Step 1 gets protonated by solvent system of reaction.

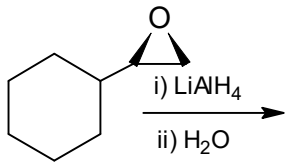


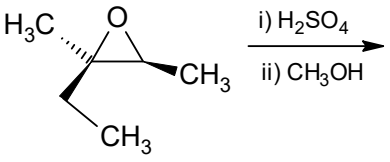
SAQ 9

For each of the following, predict the product:

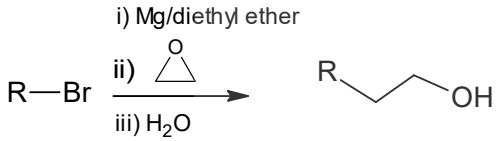
i) 

ii) 

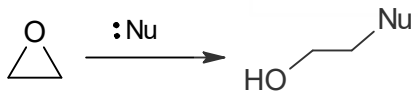
iii) 

iv) 

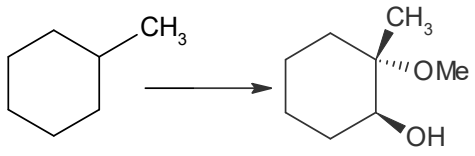
Epoxides play important role as building block in organic synthesis. Ethylene oxide can be used to introduce two carbons in a molecule. For example, consider an alkyl halide as starting material and by using an epoxide, we can introduce two carbon atoms in the structure of the alkyl halide:



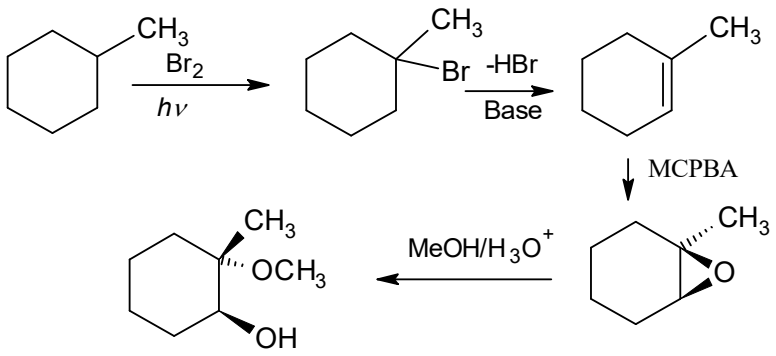
The −OH group of the product obtained from above reaction can be easily be modified by replacement with another nucleophile such as ammonia, halide, CN^-, N_3^-, SH^- etc. to get desired final or intermediate product. Epoxides can also be used for introducing functional group(s) in a molecule. You may have noticed that ring opening of an epoxide provides two functional groups on adjacent carbon centres.



For further understanding consider the following conversion:



Find product can be achieved by using following synthesis route:



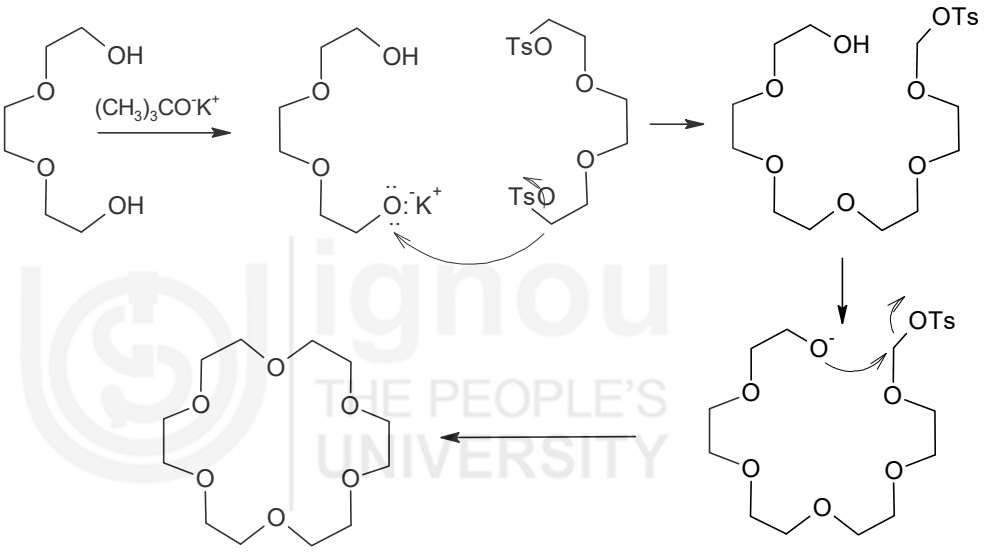
SAQ 10

How would you prepare 1-butanol from ethanol?

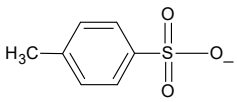
17.5 CROWN ETHERS AND CRYPTANDS

As mentioned earlier, structure of crown ethers are consisting of the repeating – OCH_2CH_2 – units. They are polymers of 1, 2-ethandiol. Crown ethers and cryptands have the ability to form complexes even with most reluctant alkali metal ions. This has made the coordination chemistry of alkali metals richer.

Crown ethers are prepared by a variant of the Williamson ether synthesis in which an alkoxide ion displaces a tosylate ion (It is a better leaving group than halide ions) by an S_N2 mechanism. A general procedure used for the synthesis of crown ethers is illustrated below.



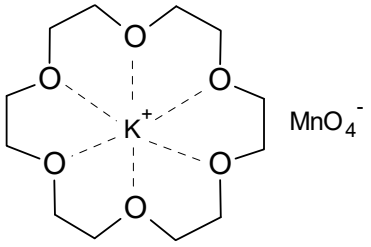
18-Crown-6
90 %



Tosylate ion,

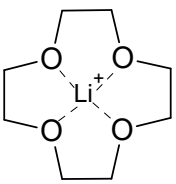
Tosylate ion is an excellent leaving group.

The unique feature of crown ether is that they can chelate metal ions and give metal complexes which are soluble in non-polar organic solvents. In this form, the crown ether is referred to as the host, while the metal ion is called guest. For example, purple benzene is a reagent in which $KMnO_4$, complexed by 18-crown-6, is dissolved in benzene. This is a very useful reagent for the oxidation of water insoluble organic compounds.

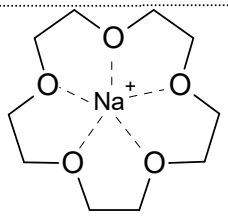


18-Crown-6 complex

Crown ethers are specific for the cation they bind, and this is related to the size of the cavity. As show above, 18-crown-6 binds K^+ preferentially, but smaller crown ethers can bind Li^+ or Na^+

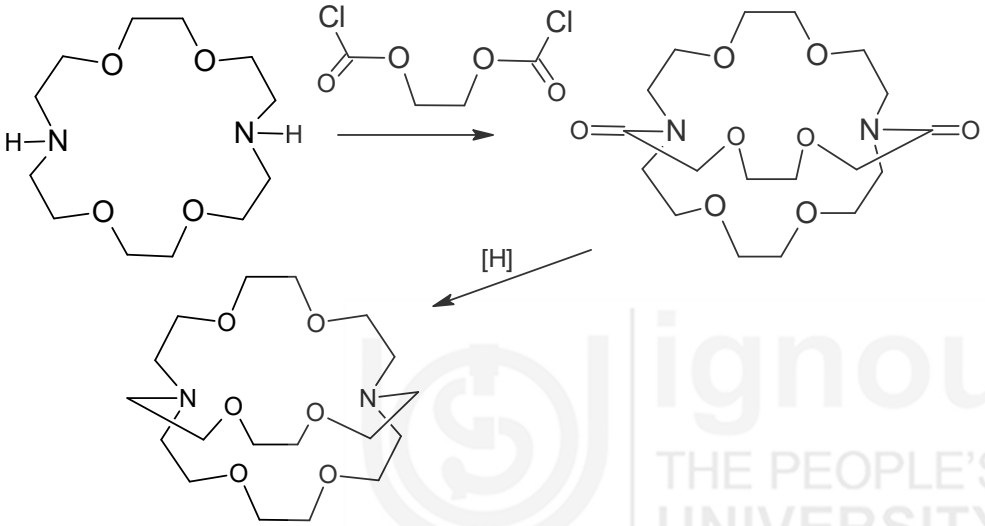


12-Crown-4



15-Crown-5

To further optimizing binding capabilities of crown ethers, Jean-Marie Lehan, who shared the 1987 Nobel Prize, developed double-cyclic crown ethers. He named them cryptands. These compounds are like crown ethers except they have addition 'bridge' which provides extra strength to hold the ion. In other words, if regular crown ether surrounds an ion, a cryptand locks it up. A typical cryptand is prepared by making a diamide from a diaza crown ether. The amide groups are subsequently reduced.



[2.2.2] Cryptand

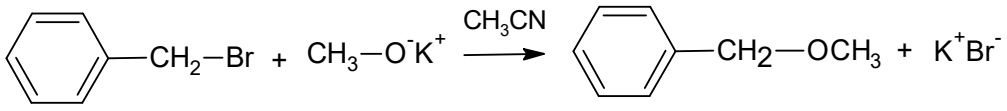
17.6 INDUSTRIAL USAGE

Ethers are widely used as solvents for oils, fats, gums, resins etc. Diethyl ether is used as refrigerant. It is also used as a solvent for extraction of organic matter, and in the laboratory for preparation of Grignard reagents. Diethyl ether was also used as inhalation anesthetic, but due to its side effects, it is now replaced by halogenated ethers such as enflurane [F_2CHOCF_2CHClF], isoflurane [$(F_2CHOCHClCF_3)$], sevoflurane [$CH_2FOCH(CF_3)_2$], etc. Dimethyl ethers are used as a catalyst in industrial polymerisation process, alternative fuel, a foam expansion agent, and as an aerosol propellent for a variety of products that include adhesives, sealants, foam in a can, coating, paints, automotive care products, tropical cooling spray, hair spray, sun screen and a variety of other personal care and household products.

Because of the inert nature of the ethers, many ethers such as tetra hydrofuran (THF), 1,4-dioxane, etc. are excellent solvents for carrying out many organic reactions. Epoxides are used as intermediates in the preparation and manufacturing of other basic organic chemicals.

Crown ethers have great advantages in synthetic organic chemistry. One is that an ionic reagent can be dissolved in an organic phase where it can react

with a water-insoluble organic compound. A second advantage is that the nucleophilicity of an ion such as CN^- or CH_3COO^- is greatly enhanced in non polar solvents, where the anion is poorly solvated, or naked. An example of how a crown ether increases the rate of substitution reaction in preparation of the benzyl methyl ether in acetonitrile (methyl cyanide) which does not dissolve ionic compound is shown below.



5 % yield with no crown ether
100 % yield with 18-crown-6 ether

Crown ethers generally form characteristic coloured complexes with metal ions, this property can be used for the detection of the metal ions.

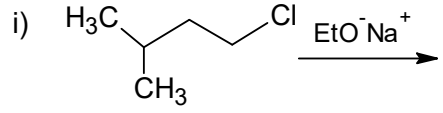
17.7 SUMMARY

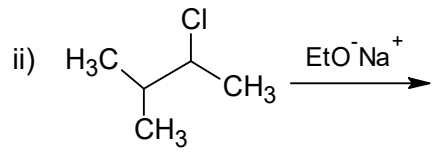
What we have studied in this unit, can be summarised as follows:

- Ethers can be prepared using the Williamson ether synthesis, which is an S_N2 reaction. On commercial scale, diethyl ether is prepared through the dehydration of ethanol in strong acid.
- Epoxides can be prepared by the reaction of peracid with alkenes or by the reaction of halohydrin with alkali.
- Ethers are less reactive than alcohols and they undergo ether cleavage by reaction with HBr and HI. This acid catalysed cleavage takes place via S_N2 or S_N1 mechanism. The exact mechanism being determined by the substituent on carbon atoms bonded to oxygen.
- Unlike ethers, epoxides are quite reactive and their ring opening reaction requires milder reaction conditions. The ring opening reaction may be initiated by acid or by nucleophile.
- The unique feature of crown ethers and cryptands is that they can selectivity chelate metal ions and give complexes which are soluble in non polar solvents.
- Ethers have many industrial uses.

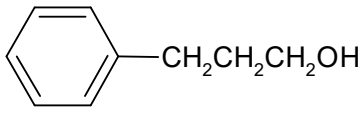
17.8 TERMINAL QUESTIONS

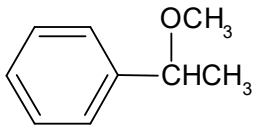
1. Among ethyl alcohol and diethyl ether, which will have greater solubility in water? Explain.
2. Write the major product obtained from the following reactions:





3. Write equation to show how would you prepare the following compounds?

i) 

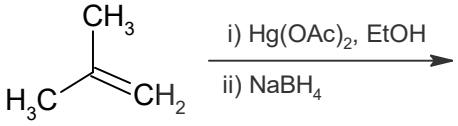
ii) 

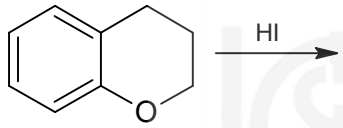
4. How are the methoxy and ethoxy groups estimated in a compound?

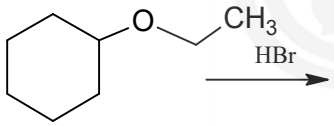
5. Give two important features of the crown ethers.

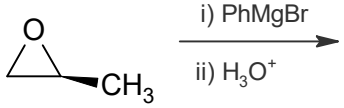
6. How would you prepare 1,4-dioxane from oxirane?

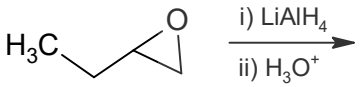
7. Predict the products for each of the following:

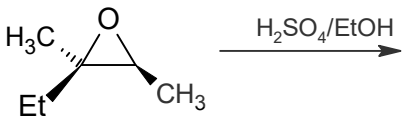
a) 

b) 

c) 

d) 

e) 

f) 

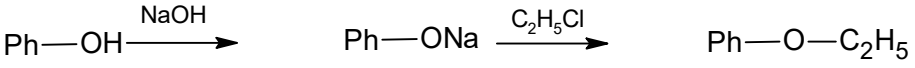
17.9 ANSWERS

Self Assessment Questions

1. a) 2-Ethoxy-2-methyl propane; b) 1-Ethoxypropene;

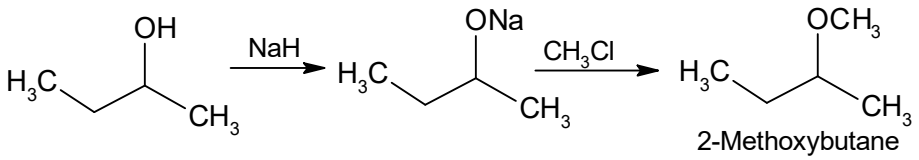
   c) Ethoxybenzene; d) Cyclohexyloxycyclohexane.

2. a) Following route will be followed:



Other route using ethanol and chlorobenzene does not work as replacement of chlorine from sp^2 is very difficult.

b) Following route will be preferred:

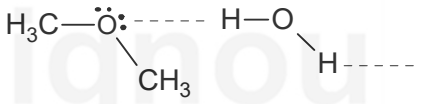


Other route using 2-chlorobutane and methanol gives considerably more elimination products.

3. From this reaction we expect a mixture of three ethers: diethyl ether, dibutyl ether and butyl ethyl ether. It is very difficult to separate these three ethers from reaction mixture in pure form.

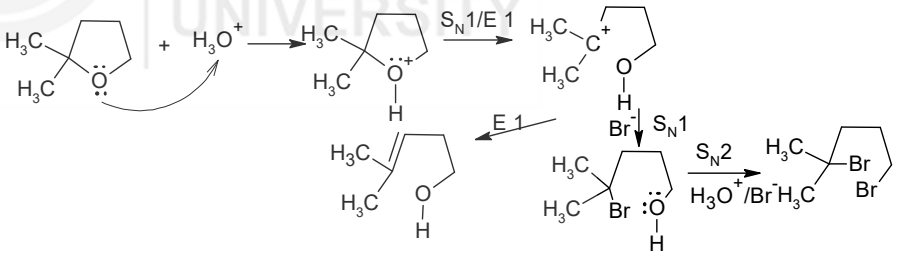
4. a) $CH_3CH_2OCH_2CH_3$; b) No reaction, c) $CH_3C(CH_3)=CH_2)$ CH_3; d) $PhOCH_2CH_3$.

5. Water solubility of ether can be attributed to hydrogen bonding between oxygen of ether with water.

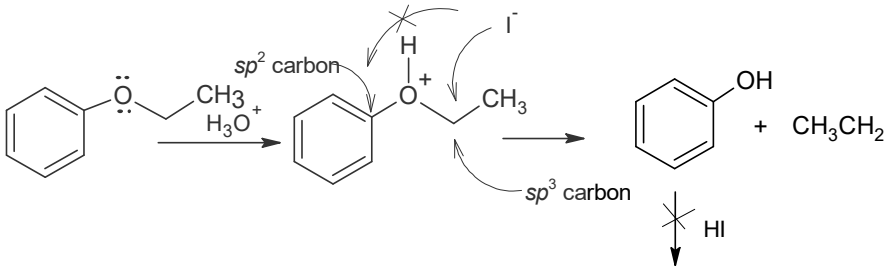


6. This reaction follows S_N2 pathway, therefore iodide ion prefers to attack on less hindered methyl carbon of 2-methoxypropane.

7. a)



b)



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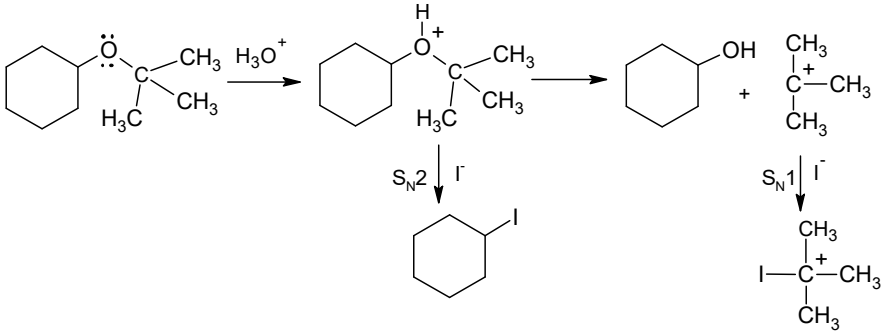
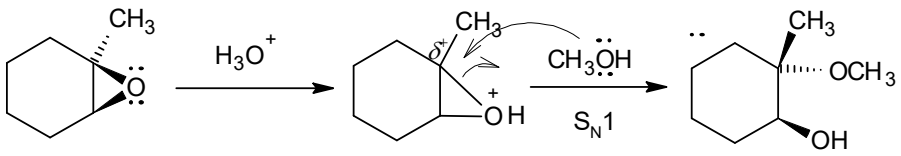
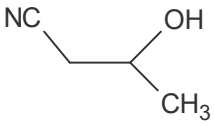


8. 

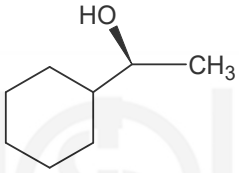
Nucleophile will attack from backside on *tert* carbon. This position is better at supporting partial positive charge. Therefore, this position has more carbocation character than *sec*. position.

9. i) $CH_3CH_2CH_2OH$

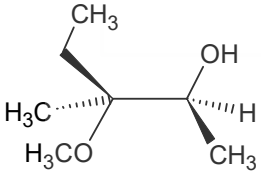
ii) Reaction will follow S_N2 pathway. Nucleophile will attack on less hindered position.

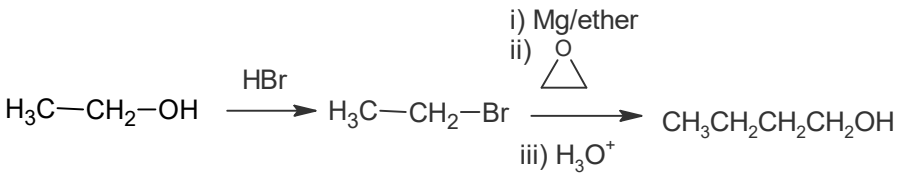


iii) Reaction will follow S_N2 pathway. Nucleophile will attack on less hindered position.



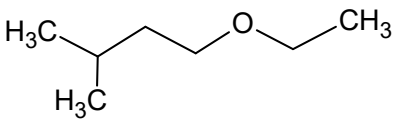
iv) Reaction will follow S_N1 pathway. Nucleophile will attack on *tert* position.

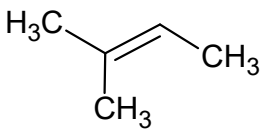


10. 

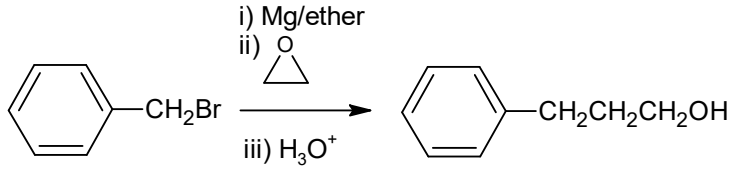
Terminal Questions

1. Ethanol has greater solubility in water as it is more polar than ether and ethanol molecules act both as hydrogen bond donor as well as hydrogen bond acceptor. Ether is less soluble in water as its molecules cannot act as hydrogen bond donor. It only acts as hydrogen bond acceptor.

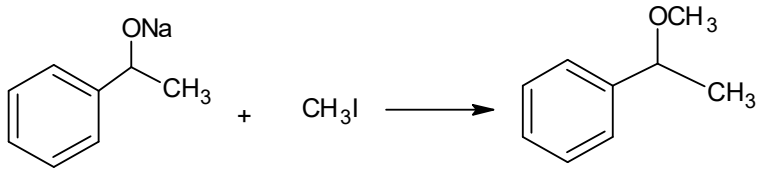
2. i) 

ii) 

3. i)



ii)

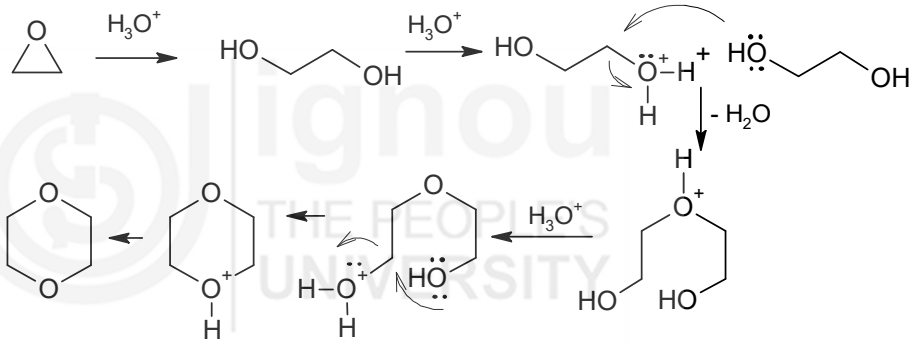


4. Methoxy or ethoxy group in an organic compound are estimated by the Zeisel method. In this method, the organic compound is first heated with excess of HI followed by distillation of volatile iodomethane or iodoethane from the reaction mixture. Then the iodomethane or iodoethane is treated with ethanolic solution of silver nitrate, and silver iodide so formed is weighed.

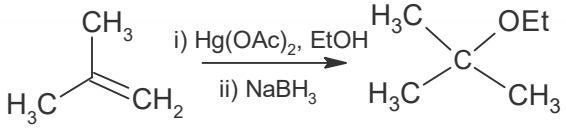
5. i) Crown ethers can selectively chelate metal ions and give metal complexes, which are soluble in non polar organic solvents.

   ii) Nucleophilicity of certain anions can be enhanced by the crown ethers and hence increased the rate of reactions of such reactions.

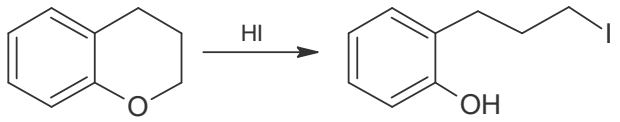
6.



7. a)



b)



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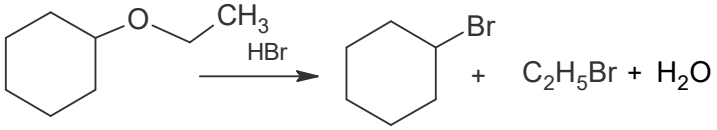

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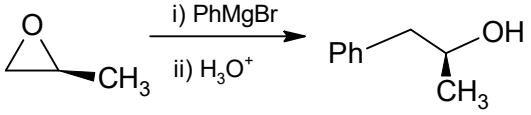

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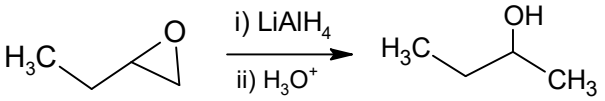

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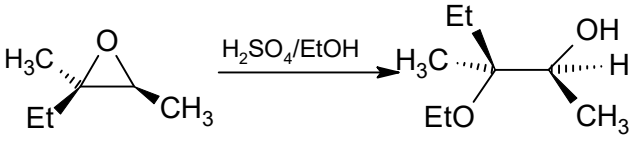


UNIT 18

ALDEHYDES AND KETONS

Structure

18.1 INTRODUCTION

In previous units, you have studied the chemistry of alcohols and phenols ethers. In this unit, we deal with aldehydes and ketones. Both these classes of organic compounds have a carbonyl group, >C=O. A ketone has two alkyl (or aryl) or one alkyl and one aryl groups attached to the carbonyl carbon, while an aldehyde has at least one hydrogen atom attached to the carbonyl carbon. The other group in an aldehyde can be alkyl or aryl.

The remarkable reactivity of the carbonyl group makes the chemistry of aldehydes and ketones the backbone of synthetic organic chemistry. The double bond between the carbon and oxygen atoms in these compounds serves as a model for the reaction of many other functional groups containing π bonds between dissimilar atoms. Although the reactions of carbonyl compounds are quite simple, their synthetic utility is enormous. Addition and substitution reactions are of major interest. In this unit, you will learn the basic principles which are responsible for the extreme reactivity of these compounds and on the basis of which reliable predictions can be made.

Here, we will first consider the preparation of aldehydes and ketones and then the characteristic reactions of the carbonyl-group. Finally, we will study industrial uses of aldehydes and ketones and the methods used for their detection. Aromatic aldehydes and ketones unlike aryl halides and phenols do not much differ from aliphatic aldehydes and ketones, you will study them in the next unit.

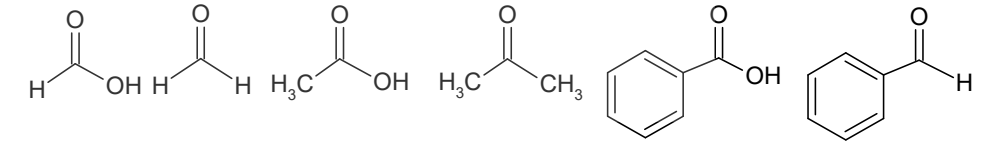
Expected Learning Outcomes

After studying this unit, you should be able to:

- explain the nucleophilic addition reactions of aldehydes and ketones on the basis of the structure of carbonyl group;
- describe the physical properties of aldehydes and ketones;
- list and discuss the preparation of aldehydes and ketones;
- describe the commercial methods of preparation of methanol, ethanol and propanone;
- explain the relative reactivity of aldehydes and ketones;
- describe the reactions of aldehydes and ketones;
- discuss the lab detection of carbonyl compounds and the test which distinguishes aldehydes from ketones; and
- state the industrial uses of aldehyde and ketones.

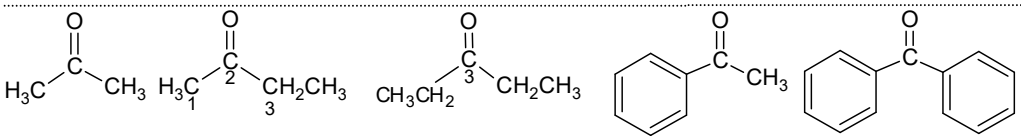
18.2 STRUCTURE AND PHYSICAL PROPERTIES

Before going in details of the chemistry of aldehydes and ketons, let us recall the nomenclature pattern of these compounds. The common names of aldehydes are derived from the common name of the corresponding carboxylic acid, with the ending **-ic** or **-oic** acid replaced by -aldehyde. In the IUPAC system, aldehydes are treated as derivatives of the alkanes, with ending **-e** replaced by **-al**. Thus, an alkane becomes an alkanal. Cyclic and aromatic aldehydes are named as cyclic alkane- or aryl-substituted carbaldehydes. In the examples given below, common names are written in parenthesis.



(Formic acid) Methanal (Formaldehyde) (Acetic acid) Ethanal Acetaldehyde) (Benzoic acid) Benzenecarbaldehyde (Benzaldehyde)

In the IUPAC system, ketones are called **alkanones**, the ending **-e** of the alkane replaced with **-one**. On the other hand, aromatic ketones are named as aryl-substituted alkanones. To indicate the position of carbonyl group in chain, the parent chain is numbered from the direction that gives the carbonyl carbon the smaller number regardless of the presence of substituents or the halogens, hydroxyl, C=C or C≡C functional groups. Cyclic ketones are simply called cycloalkanones and aromatic ketones are named as aryl-substituted alkanone.

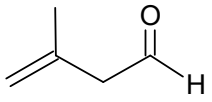


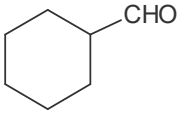
Propanone (Acetone) | 2-Butanone (Ethyl methyl ketone) | 3-Pentanone (Diethyl ketone) | 1-Phenylethanone (Acetophenone) | Diphenylmethanone (Benzophenone)

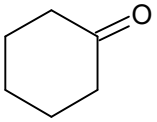
The IUPAC system still retains the common names for formaldehyde, acetaldehyde, bezaldehyde, acetone and benzophenone.

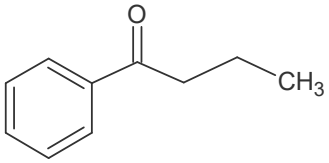
SAQ 1

Name of the following compounds:

a) 

b) 

c) 

d) 

18.2.1 Structure of the Carbonyl Group

In order to understand the chemistry of the carbonyl group, there is a need to look in to details of the structure of the carbonyl group. According to valence bond theory, the carbon-oxygen double bond consists of one σ bond formed by the overlap of sp^2 hybrid orbitals of carbon and oxygen and one π bond formed by the overlap of parallel 2*p* orbitals. The two nonbonding pairs of electrons (unshared electrons pairs) on oxygen lie in the remaining sp^2 hybrid orbitals of oxygen. The sp^2 hybridisation means that the carbonyl group has to be planar, and the angle between the substituent is close to 120°. Fig. 18.1 illustrates all these features for the methanal (CH_2O) molecule. You can notice that the orbital arrangements are somewhat similar to carbon-carbon double bond of alkenes. But when we compare electronic arrangement, we can notice two important differences. First, oxygen atom of carbonyl group bears two nonbonding pairs of electrons located in two sp^2 hybrid orbitals.

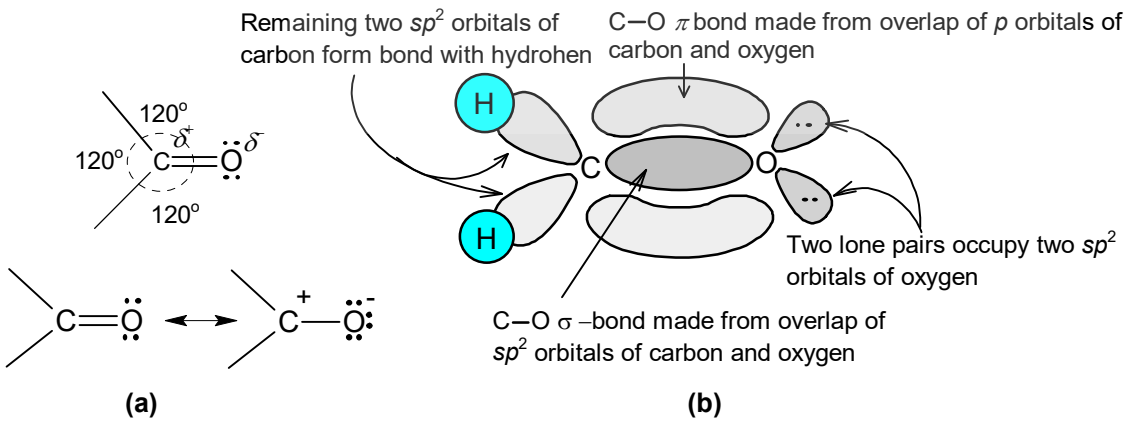
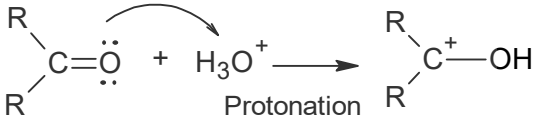


Fig.18.1: (a) Molecular structure of carbonyl group, (b) Orbital picture of methanal.

Second, carbonyl group oxygen is more electronegative than carbon [electronegativity of oxygen on the Pauling Scale = 3.44 and electronegativity of carbon on the Pauling Scale = 2.55]. Therefore, similar to ether group carbon-oxygen double bond is polar with oxygen bearing a partial negative charge and carbon bearing a partial positive charge. These two factors contribute to the high reactivity of the carbonyl group.

In addition, the resonance structures shown in Fig. 18.1(a) emphasise that carbon is an electrophilic site (electron deficient centre) and the oxygen is a nucleophilic site (electron rich centre). Thus, we can say that the carbonyl carbon acts as a Lewis acid and the carbonyl oxygen acts as a Lewis base. As a result, carbonyl carbon is susceptible to attack by a nucleophile. The electrophilicity of carbon centre is further enhanced when reaction is carried out in acidic medium due to the protonation of oxygen atom.



Now, we will apply molecular orbital approach to further understand the chemistry of the carbonyl group. A good approximation for reactivity can be found by looking at the frontier molecular orbitals [highest occupied molecular orbital (HOMO) and lowest unoccupied molecular orbital (LUMO)]. In case of carbonyl group, π and π^* are the HOMO and LUMO, respectively. Fig. 18.2 shows, how π and π^* orbitals are formed on mixing of two *p* atomic orbitals of carbon and oxygen.

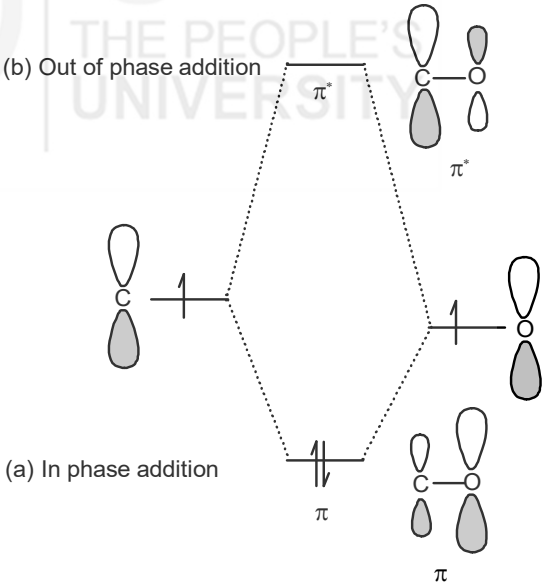


Fig. 18.2: Molecular mixing diagram for the creation of *π* bond in carbonyl group: (a) HOMO and (b) LUMO.

In the above diagram you can notice that *p* orbital of oxygen is lower in energy because oxygen is more electronegative than carbon. According to MO theory, when the two combining atomic orbitals are not equal in energy, the resulting molecular orbitals have a greater contribution from the atomic orbital that is closest in energy. Thus, the bonding π orbital has larger contribution from the oxygen, therefore has larger coefficient at the oxygen atom, and conversely, the anti-bonding π^* orbital has a larger contribution from the

carbon. Further, only the bonding orbital is occupied, the electron density in the bond is concentrated on oxygen. The resultant bond is said to be polarised. Polarisation of the bond means that there is an uneven distribution of electron density between the two combining atoms leading to the buildup of positive charge on the carbon and negative charge on the oxygen and of the carbonyl bond.

Conversely, unfilled antibonding π^* orbital, is polarised in the opposite direction, with larger coefficient at the carbon atom. Thus, when the carbonyl group reacts with a nucleophile, electrons move from the HOMO of the nucleophile into the LUMO of the electrophile, in other words π^* orbital of the carbonyl bond. The greater coefficient of the π^* orbital at carbon means a better HOMO-LUMO interaction. It can be concluded that larger coefficient on oxygen in the filled (bonding) orbital explains why the oxygen atom acts as Lewis base (nucleophilic centre). The larger coefficient on carbon in the empty antibonding, π^* orbital explains why it behaves as a Lewis acid (electrophilic centre).

It can now be summarised that all the concepts discussed above lead to the same conclusion, that is, in aldehydes and ketones, the carbon of carbonyl group is an electrophilic site and oxygen is a nucleophilic site. Thus, because of these structural features, these compounds undergo a wide variety of reactions with most involving nucleopholic addition.

The Angle of Nuecleophilic Attack

When a nucleophile (Nu^-) approaches the carbon atom, the electron pair in its HOMO starts to interact with the LUMO (antibonding, π^*) to form a new σ bond. This interaction leads to breaking of the π bond, leaving only the C–O, σ bond intact. The nucleophilic addition to carbonyl group can be illustrated as follows:

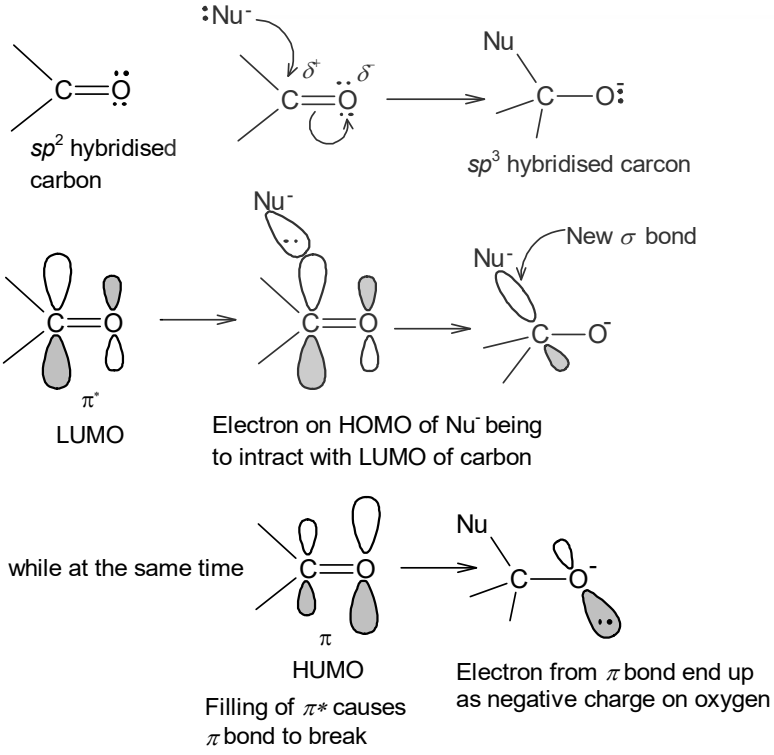
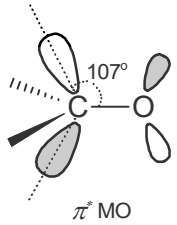


Fig. 18.3: Orbital interaction during nucleophilic attack.

Fig. 18.3 shows how the trigonal, planar sp^2 hybridised carbon atom of the carbonyl group changes to a tetrahedral sp^3 hybridised state in the product. Molecular orbital calculations also suggested that HOMO of the nucleophile approaches from a particular angle; that is, 107° to the plane of the carbonyl group. This approach route is known as the Burgi-Dunitz trajectory.

Burgi and Dunitz deduced this trajectory by examining crystal structures of compounds containing both a nucleophilic nitrogen atom an electrophilic carbonyl group.

The possible explanation for this angle of attack is that due to repulsion of the HOMO by the electron density in the carbonyl π bond, the lobs of LUMO, π^* are already at an angle as shown below.



Burgi-Dunitz angle

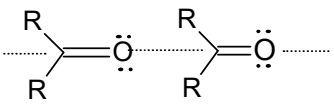
Any other portion of the molecule, that gets in the way of the Burgi-Dunitz trajectory, will greatly reduce the rate of nucleophilic addition to carbonyl group and this is the one of the reasons why aldehydes react faster than ketones in the nucleophillic reactions.

18.2.2 Physical Properties

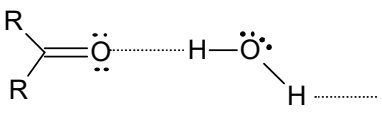
The bond dipole moment of a carbonyl group is 2.3 D

As we have mentioned above, the aldehydes and ketones are polar compounds due to presence of carbonyl group and these compounds possess intermolecular dipole-dipole attraction. Due to these interactions, molecules have higher boiling points than nonpolar compounds of similar molecular weight. The boiling points of aldehydes and ketones are, however, much lower than the boiling points of the corresponding alcohols. This is due to the fact that the molecules of aldehydes and ketones are held together by the much weaker electrostatic interaction between dipoles whereas alcohols are held together by strong hydrogen bonds.

The partial solubility and the formation of hydrates can be explained by the formation of hydrogen bonds between carbonyl compounds and water. The unshared electron pairs on oxygen are responsible for such hydrogen bonding. The carbonyl-carbonyl and carbonyl-water interactions are illustrated in the following structures:



Dipole-dipole intraction between the molecules of carbonyl compounds



Hydrogen bonding between carbonyl compound and water

As the hydrophobic hydrocarbon part of the molecule increases in size, water solubility decreases. The physical properties of some aldehydes and ketones are summarized in Table 18.2.

Table 18.2: Physical properties of some aldehydes and ketones

Aldehydes		Structure Formula	BP, K	Solubility in H_2O
IUAPC	**Common Name**			
Methanal	Formaldehyde	HCHO	252	miscible
Ethanal	Acetaldehyde	CH_3CHO	293	miscible
Propanal	Propionaldehyde	CH_3CH_2CHO	322	16 g/100 cm^3
Butanal	Butyraldehyde	$CH_3CH_2CH_2CHO$	349	7 g/100 cm^3
Benzaldehyde	Benzaldehyde	C_6H_5CHO	451	slightly
Ketones:				
Propanone	Acetone	CH_3COCH_3	329	miscible
2-Butanone	Methy ethyl ketone	$CH_3COCH_2CH_3$	353	26 g/100 cm^3
Phenylethanone	Acetophenone	$C_6H_5COCH_3$	475	insoluble
Diphenyl methanone	Benzophenone	$C_6H_5COC_6H_5$	579	insoluble

SAQ 2

Without consulting Tables given for physical properties of organic compounds, identify which compound in each pair would have the higher boiling point.

a) 1-Pentanal or 1-pentanol

b) 3-Methyl-2-butanone or 2-methylbutane

c) 2-Pentanone or 2-pentanol

d) Cyclohexanone or cyclohexane

e) Pentane or 1-pentanal

18.3 PREPARATION

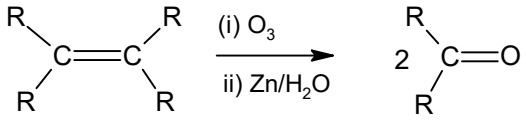
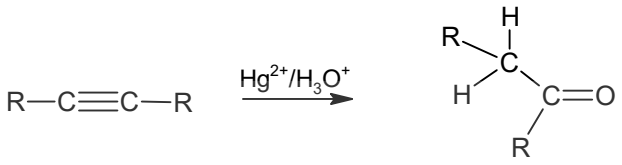
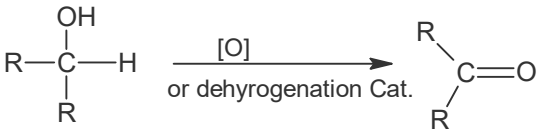
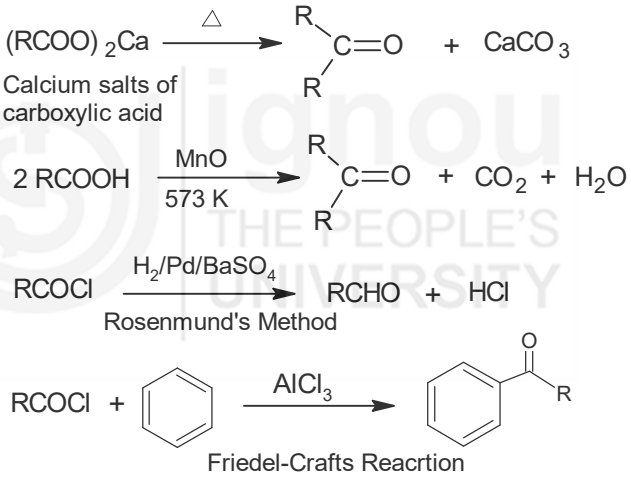
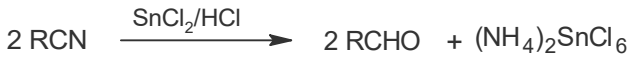
We have already learned several reactions that can be used for the preparation of aldehydes and ketones. Recall the oxidation of alkenes with ozone, hydration of alkynes and oxidation or dehydrogenation of alcohols.

In this section, we will first consider the general methods for the preparation of aliphatic aldehydes and ketones and then follow them up with industrial methods for the production of methanal, ethanal and propanone.

18.3.1 General Methods of Preparation of Aldehydes and Ketones

Aldehydes and ketones can be prepared from alkenes, alkynes, alcohols, carboxylic acids and their derivatives. We are summarising the general reactions of these methods of preparation in Table 18.3.

Table 18.3: Preparation of Aldehydes and Ketones

From Alkenes: Ozonolysis of alkenes

From Alkynes: hydration of alkynes

From Alcohols

From Carboxylic Acids and their Derivatives

From the Stephen's Method


The preparation of aldehydes and ketones from alkenes and alkynes has been discussed in Unit 7 and Unit 8, respectively. Here, we will consider preparation of these compounds from alcohols, and carboxylic acids and their derivatives.

i) From Alcohols

As mentioned in Unit 12, primary alcohols give aldehydes and secondary alcohols give ketones on dehydrogenation/oxidation. The tertiary alcohols are resistant to dehydrogenation/oxidation because the carbon bearing the –OH group is already bonded to three carbon and, therefore, cannot form any additional carbon-oxygen bond. This is the most common way of synthesising aldehydes and ketones in the laboratory. We generally use the following oxidising agents for the oxidation of alcohols:

i) alkaline potassium permanganate solution

ii) hot, concentrated HNO_3

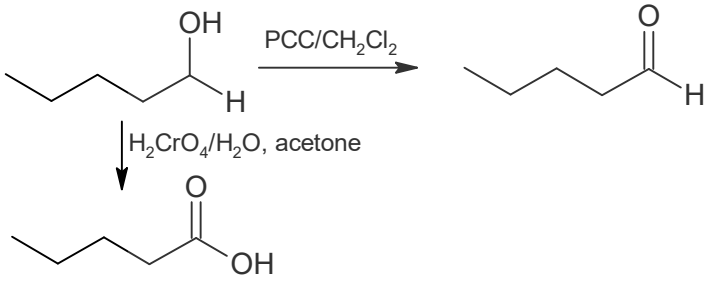
iii) chromic acid (H_2CrO_4)

iv) chromium trioxide (CrO_3) complex with pyridine or with pyridine and HCl (PDC and PCC)

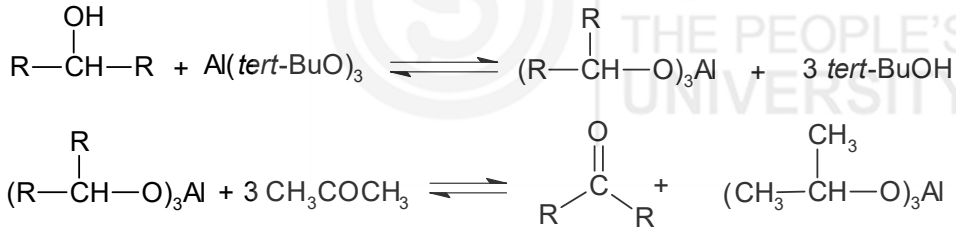
A solution of chromic acid in aqueous sulphuric acid is known as the **Jones reagent**. This reagent is used to distinguish between aldehydes and ketones. Aldehydes give a positive test, but ketones do not. Primary and secondary alcohols also give positive test with Jones reagent but tertiary alcohols do not.

This regent is also selective and does not oxidise alkene and alkyne units if present in same molecule.

The first three methods generally lead to over oxidation of primary alcohols to carboxylic acids. The chromium trioxide complex is most commonly used for oxidation of a primary alcohol to an aldehyde. This reagent is prepared by dissolving CrO_3 in aqueous HCl and adding pyridine to precipitate pyridinium chlorochromate (PCC) as solid. PCC oxidation is carried out in aprotic solvent such as dichloromethane.



Another reagent used for oxidation of secondary alcohols is alumimium tertiary-butoxide. It is used in the **Oppenauer oxidation**. In this method, the reaction mixture is first heated and then propanone (acetone) is added:

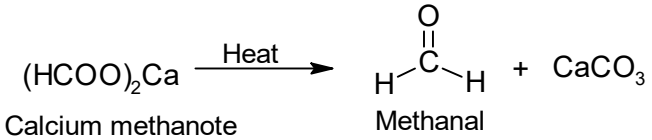


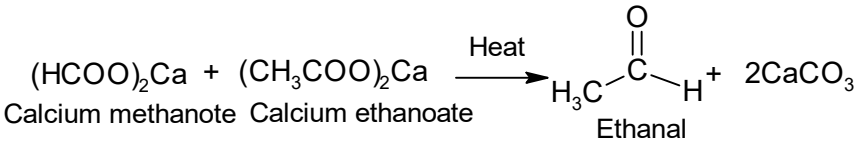
Oppenaure oxidation is reversible and the reverse reaction is known as the Meerwein-Ponndorf-Varley reduction.

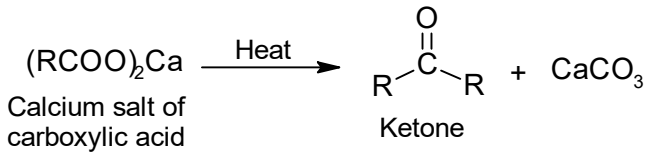
ii) From Carboxylic Acids and their Derivatives

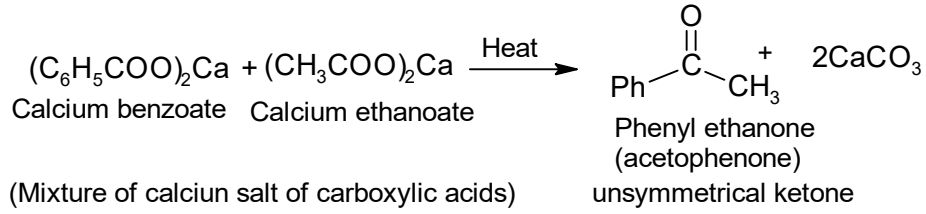
Carboxylic acids can be converted into aldehydes and ketones either by heating their calcium salts or by passing vapours of the acid over heated manganous oxide or by reduction of acid chlorides with hydrogen in the presence of palladium over barium sulphate **(Rosenmund's method)**. We will consider these reactions in more detail in third semester course. General equations for these reactions are given below:

From Calcium Salts of Carboxylic Acids

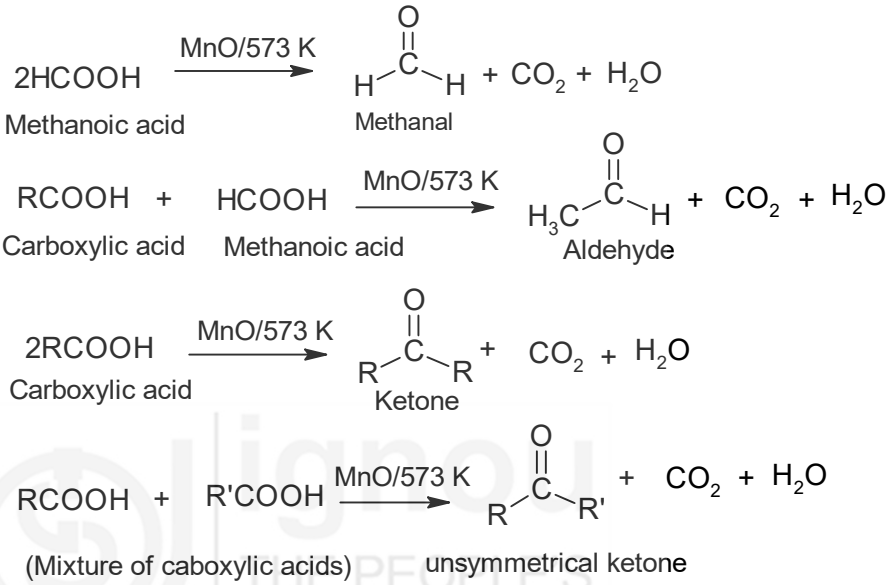






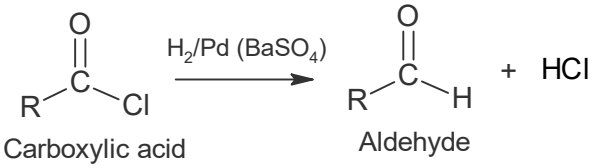


From the Reaction of Carboxylic Acids with Manganese(II) oxide



Please note that for aldehydes other than methanal and for unsymmetrical ketones, a mixture of acids and their calcium salts in molar proportion is taken.

From Acid Chlorides by the Rosenmund's Method

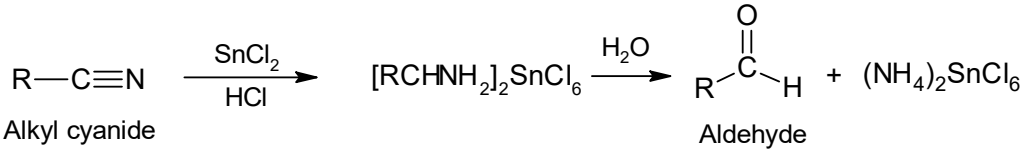


where R = CH_3 or C_6H_5

$BaSO_4$ poisons the catalyst and helps to stop the reduction at the aldehydes stage.

iii) From the Stephen's Method

Reduction of an alkyl cyanide with stannous chloride and hydrochloric acid followed by hydrolysis with steam gives aldehydes **(Stephen's method)**:



where R = CH_3 or C_6H_5

SAQ 3

An organic compound A (molecular formula C_3H_7Cl) was treated with aqueous sodium hydroxide and the vapours of the product obtained were passed over heated copper to give propanone (acetone). A is

a) 1-chloropropane b) 2-chloropropane c) chlorocylclopropane

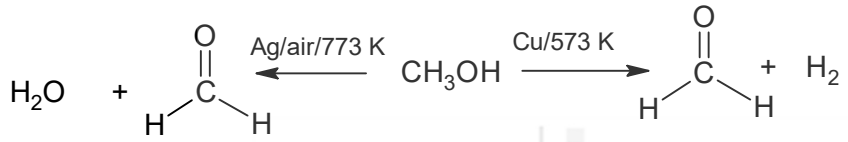
18.3.2 Industrial Methods of Preparation of Aldehydes and Ketones

The industrial preparation of some common carbonyl compounds are described below:

Methanal

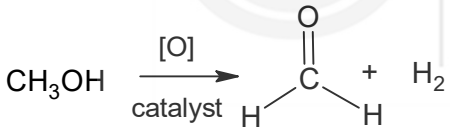
It is manufactured from methanol by following two processes:

i) Oxidation of methanol using silver or copper catalyst.

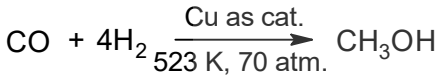


Although the silver catalyst is expensive no silver is lost and catalyst is easily regenerated and can be recycled.

ii) Oxidation using zinc-chromium or iron-molybdenum oxide catalyst.



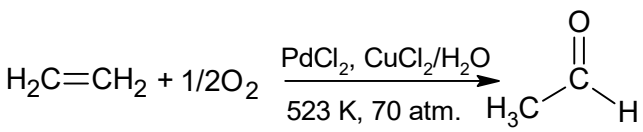
Methanol itself is made from enriched water gas.



Ethanal

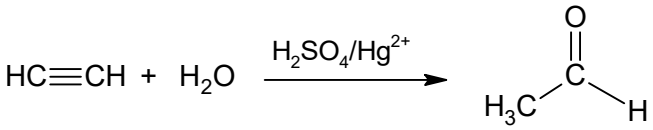
The following methods can be used for the manufacture of ethanol:

i) By passing a mixture of ethene and oxygen under pressure over palladium (II)/Cupric chloride catalyst in water at 323 K, ethanal is produced:

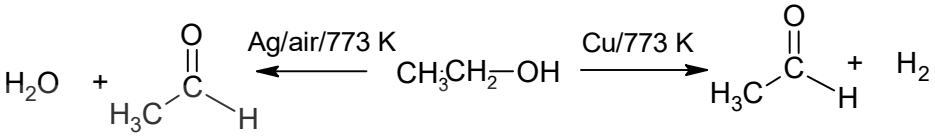


This process is called **Wacker process**. Since ethene is cheaper than ethyne, this process has superseded the two older routes outlined below:

ii) By passing ethyne through dilute sulphuric acid, with mercury(II) sulphate as catalyst at 336 K.

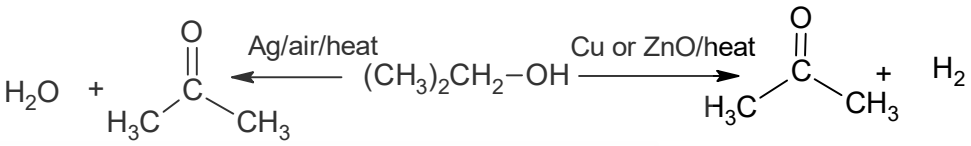


iii) By the oxidation of ethanol (which is manufactured from ethene) in the gas phase over a silver or copper catalyst:

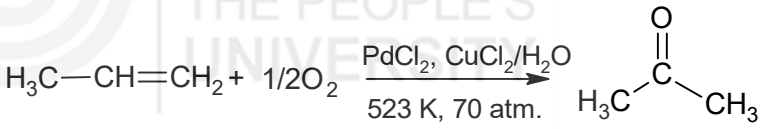


Propanone

Dehydrogenation of 2-propanol over heated copper or zinc oxide or air oxidation over heated silver gives propanone. 2-Propanol is obtained from propene.



Propanone can also be manufactured by the direct oxidation of propene from natural gas with oxygen or air, catalysed by a mixture of palladium and cuprous chlorides (**The Wacker Process**).



We have already seen in Unit 16 that propanone is obtained as a by-product in the oxidation of cumene to phenol.

SAQ 4

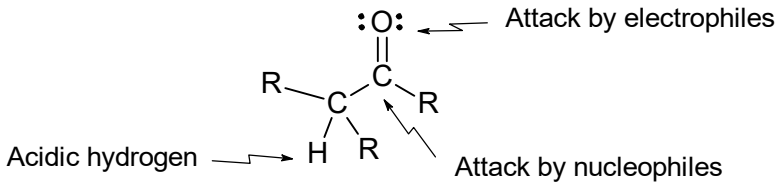
How will you convert propene to acetone?

18.4 REACTIONS OF ALDEHYDES AND KETONES

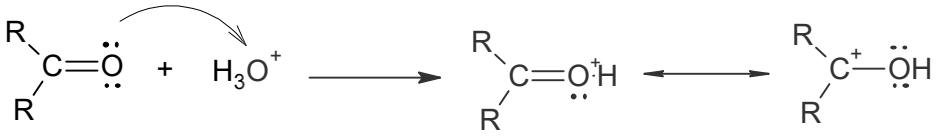
We can group together the reactions of aldehyde and ketones into four categories (a) reactions of the carbonyl group, (b) reactions of the 'α' hydrogen (acidic hydrogen) attached to the carbon adjacent carbonyl group, (c) oxidation reactions and (d) reduction reactions.

As stated earlier, the carbon-oxygen double bond is polar which leads to ionic addition to the carbonyl π bond. A carbonyl compound may first be attacked either by a nucleophile or by an electrophile. Therefore, with most reagents, carbonyl additions show the same overall course, i.e., addition of the negative,

nucleophilic part of the reagent to the carbon atom and addition of the positive electrophilic part to the oxygen atom.

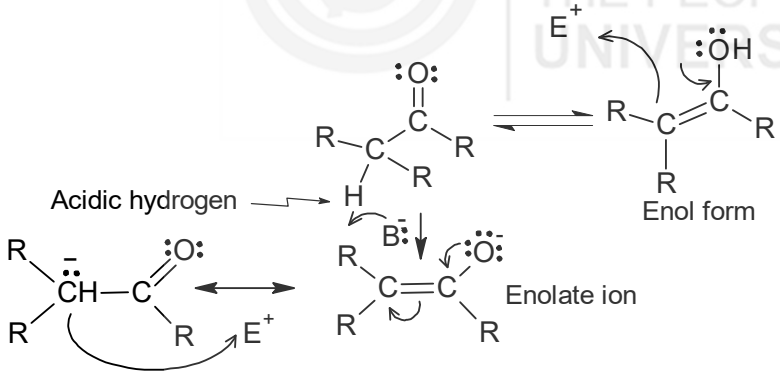


In acidic medium, the proton first adds to the carbonyl oxygen. This further increases the electrophilic nature of the carbonyl carbon.



Resonance structures of protonated carbonyl group

Hence, nucleophilic additions to the carbonyl compounds are very often catalysed by acids. We turn now our attention on the nature of *α* hydrogen atoms attached to carbon next to carbonyl group. The carbonyl group induces enhanced acidity of these hydrogens. Moving or removing these *α* hydrogens may lead to either of two electron-rich species: enols or enolate ions. Both enol and enolate ion behave as nucleophiles and are capable of attacking electrophilic species such as protons, halogens and even carbon centre of carbonyl compounds. A brief description of the reactions due to *α* hydrogen is included in this unit.

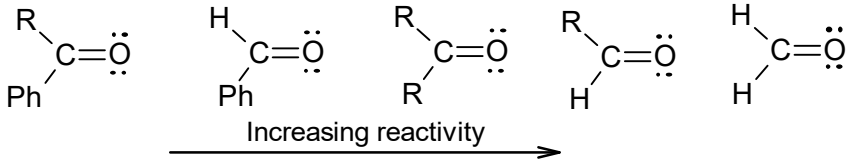


Before going into details of the reactions of carbonyl compounds, let us study the relative reactivity of aldehydes and ketones.

The relative reactivity of aldehydes and ketones in addition reactions may be attributed partly to the extent of polarisation on the carbonyl carbon. The more polarised the carbonyl group the greater the positive charge on the carbonyl carbon. A greater positive charge means higher reactivity. If this partial positive charge is dispersed throughout the molecule, then the carbonyl compound is less reactive.

As you already know the alkyl group is electron releasing (+*I* effect). Therefore, in ketones, due to the presence of two alkyl groups, the carbon of the carbonyl group will be less electron deficient than in aldehydes. Hence, ketones will be less reactive than aldehydes. Further, methanal with no alkyl

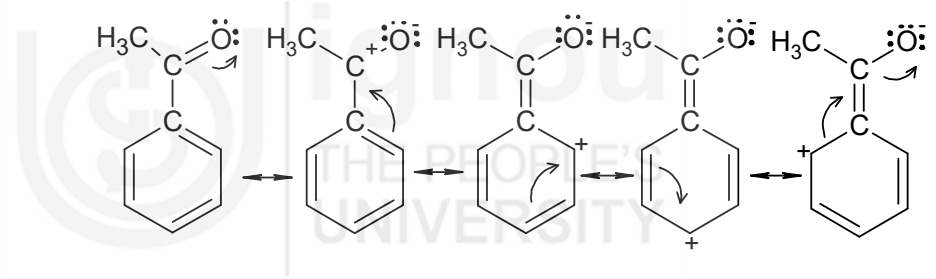
groups attached to the carbonyl carbon is more reactive than ethanal and other susbstituted aldehydes.



The most reactive aldehyde is trichloroethanal (chloral), Cl_3CCHO, in which electron withdrawal by the three chlorine atoms depletes the electrons density on the carbonyl carbon so much that it forms stable hydrates.

Steric factors also play a role in the relative reactivity of aldehydes and ketones. Since hybridisation of the carbonyl carbon changes from sp^2 in the starting material to sp^3 in the addition product, ketones are less reactive than aldehydes because of the un-favourable steric interaction between the two alkyl groups and the other two groups in the product. Lack of such steric hindrance in the product is another reason for the higher reactivity of methanal.

A carbonyl group attached to an aromatic ring is less reactive in addition reactions than it is in aliphatic aldehydes and ketones. This can be attributed to resonance interaction in between the carbonyl group and the aromatic ring:



Resonating structures of phenylethanone (acetophenone)

The result of this interaction is a weakening of the positive charge on the carbonyl carbon atom through dispersal of the charge into the ring.

With the above general ideas, it will be easier to understand the reactions of aldehydes and ketones. Many of the reactions given below are shown by all aldehydes and ketones, but some members show exceptional behaviour which we will take up separately.

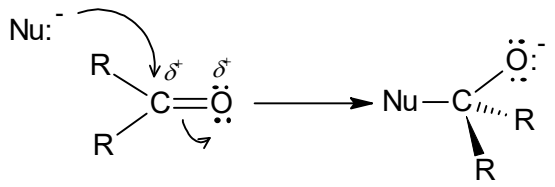
18.4.1 Nucleophilic Addition Reactions

The main reaction of aldehydes and ketones is **nucleophilic addition** to the partially positive carbon of the carbonyl group. This addition can take place by two pathways: i) nucleophilic addition-protonation and ii) electrophilic protonation or addition of other Lewis acid –nucleophilic addition. We will now take up the mechanism of both the pathways in detail.

The Mechanism of Nucleophilic Addition-Protonation

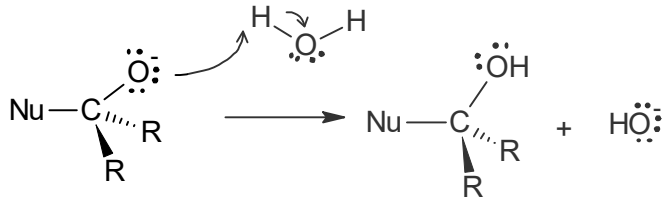
Necleophilic addition reactions in neutral or more commonly in basic condition follow the mechanism as shown below:

Step 1: Nucleophilic attack



Notice how the nucleophile approaches the electrophilic carbon and breaks the π bond of carbonyl group. This also results in rehybridisation of carbonyl carbon from sp^2 to sp^3 and the electron pair of the π bond moves over the oxygen, thereby producing an alkoxide .

Step 2: Protonation

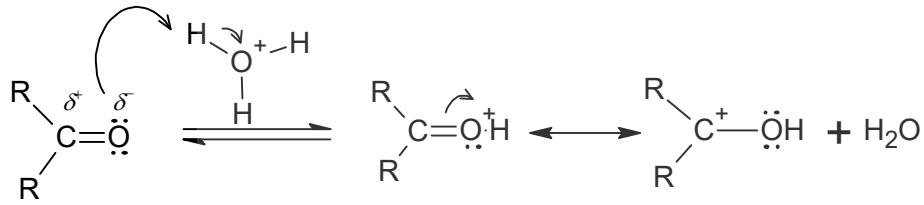


In second step, alkoxide ion abstracts a proton from protic solvents such as water or alcohol to yield the final addition product.

Protonation - Nucleophilic Addition

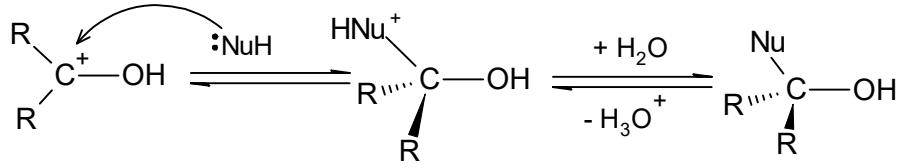
This mechanism predominates under acidic condition and begins with the attack of a electrophilic proton or other Lewis acid on nucleophilic oxygen (Lewis base) of carbonyl group. Protonation increases the electron deficiency of the carbonyl carbon and makes it more reactive toward nucleophile.

Step 1: Protonation

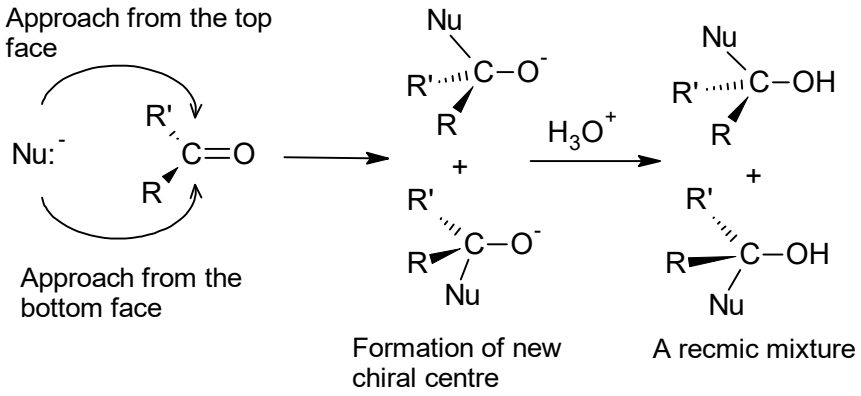


Step 2 and 3: Nucleophilic attack and deprotonation

The carbocation formed in step 1 reacts with the nucleophile, followed by loss of a proton which completes the addition process.



Weakly basic nucleophiles follow this mechanism. The acidic conditions are not suited for strong basic nucleophile. It is also important to note that in normal situation, in both the mechanisms the nucleophile can approach the carbonyl carbon from either side with equal probability. As a result, the carbonyl addition product will consist of racemic mixture if it is a chiral rectant.



But in recent past, many stereoselective neucleophilic addition reactions have been designed. The stereoslectivity of such reactions are either substrate controlled or reagent controlled or controlled by a catalyst. Details of such types of reactions will be studied in higher classes.

A wide variety of nucleophiles can attack the carbonyl group of aldehydes and ketones. We can categories the nuclephilic addition reactions on the basis of the nature of attacking atom in the following groups:

i) Addition of carbon nucleophiles

ii) Addition of oxygen nucleophiles

iii) Addition of sulphur nucleophiles

iv) Addition of nitrogen nucleophiles

v) Addition of hydrogen nucleophile

i) Addition of Carbon Nucleophiles

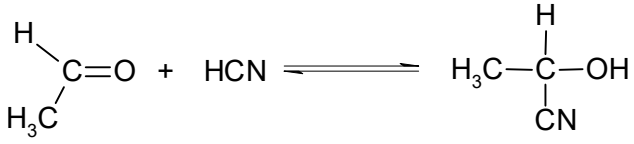
Following types of carbon nucleophiles undergo addition reaction with aldehydes and ketones:

$^{-}$:C≡N:	RC≡C:$^{-}$	RMgX	RLi
Cyanide ion	**An anion of a terminal alkyne**	**Grignard reagent**	**Organolithium reagent**

Additions of such nucleophiles have lot of significance in synthetic organic chemistry because a new carbon-carbon bond is formed in the process. These reactions are carried out in neutral conditions or basic conditions and they follow two step nucleophilic addition-protonation mechanism.

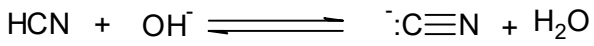
Addition of Hydrogen Cyanide

Aldehydes and ketones react with hydrogen cyanide to form nitriles (cyanohydrins), for example, HCN adds to ethanal to form 2-hyroxypropanenitrile (acetaldehyde cyanohydrin).



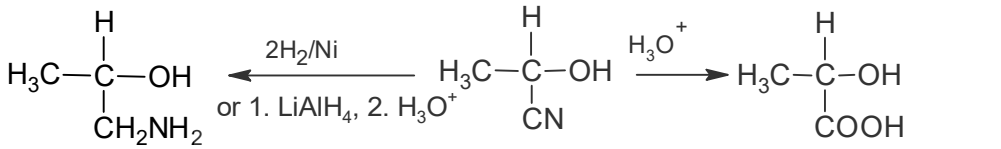
2-Hydroxypropanenitrile
75 % yield

These reactions are reversible and occur very slowly as cyanide ion is a poor electron donor (weak nucleophile), but their rates are greatly increased by the addition of alkali. This is because added alkali increases the concentration of the cyanide ion,



It is difficult to handle HCN because it is volatile nature (b.p. = 26 °C) at room temperature and is also toxic in nature. Therefore, appropriate mixture of KCN/NaCN and HCl is used in place of HCN. For aldehydes and simple ketones, the position of equilibrium favours nitrile formation. Nitrile formation is not a useful reaction for aromatic ketones and sterically hindered aliphatic ketones as the position of equilibrium for these compounds favours starting materials.

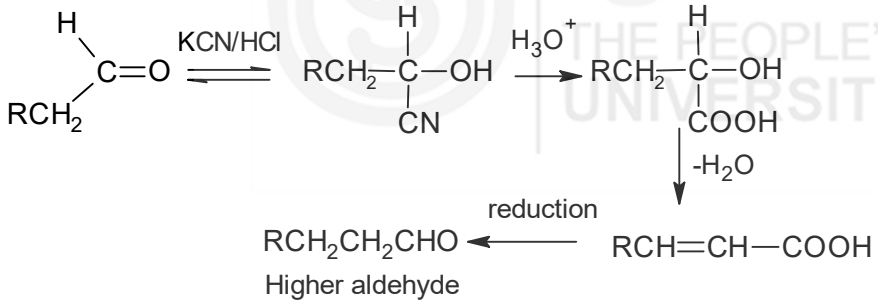
Nitriles are useful in synthesis as they can be modified by further reactions. Hydrolysis of nitriles gives α-hydroxyacids and their reduction gives primary amines:



1-Amino-2-propanol

2-Hydroxypropanoic acid

An important consequence of the hydrogen cyanide addition reaction is that one more carbon atom is added to the carbon chain. For example,



Higher aldehyde

Thus, nitriles are valuable intermediates for the synthesis of other useful organic compounds.

SAQ 5

Arrange the following carbonyl compounds in order of favourability of formation of nitriles:

Propanal, propanone, methanal and 1-phenylethanone

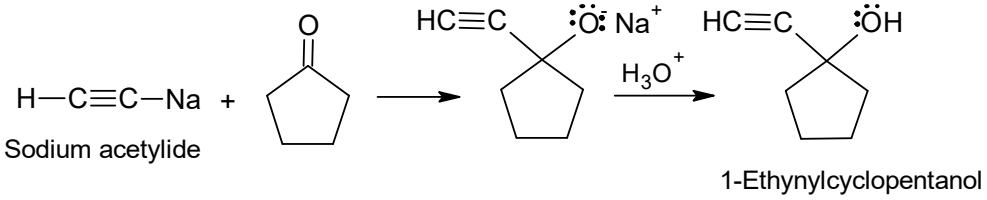
SAQ 6

How will you prepare butanal from propanal?

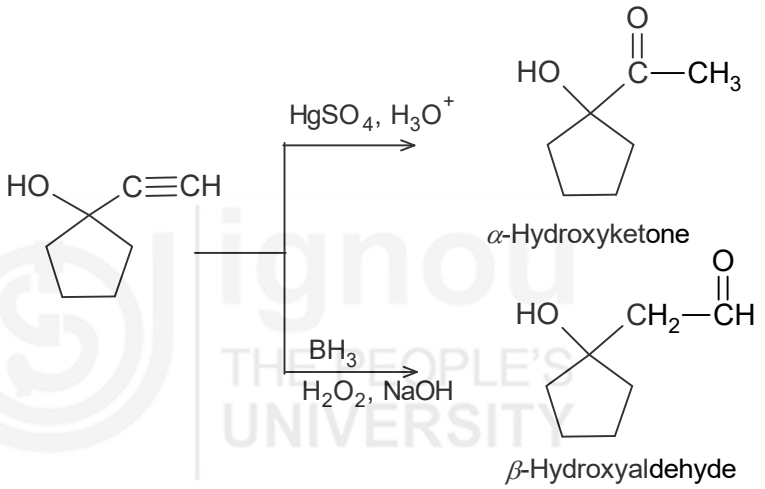
Addition of Anions of Terminal Alkynes

As discussed earlier that the hydrogen atom of a terminal alkyne is weakly acidic, and it reacts with a suitable base to generate a conjugate base, the

alkyne anion. Alkyne anions are carbanions and classified as strong nucleophiles. Alkyne ions undergo addition reactions with the carbonyl group of aldehydes and ketones. In the following example, addition of the sodium acetylide to cyclopentanone followed by hydrolysis in aqueous acid gives 1-ethynylcyclopentanol.

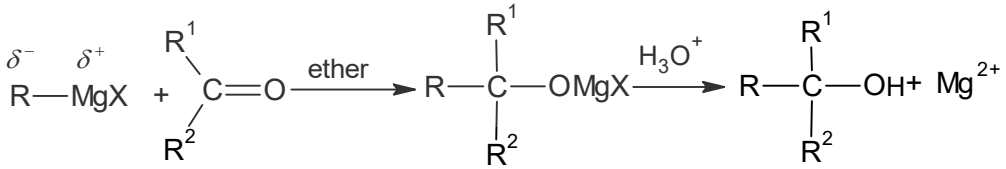


This reaction is also very useful in synthesis as both the functional groups of adduct (alkynyl alcohol) can be further modified. For example, acid catalysed hydration of 1-ethynylcyclopentanol gives an *α*-hydroxyketone and its hydroboration followed by oxidation with alkaline hydrogen peroxide gives a *β*-hydroxyaldehyde.



Addition of Grignard Reagents

The special significance of the addition of the Grignard reagents on a carbonyl group of aldehydes and ketones is that they provide excellent way to form new carbon-carbon bond. General reaction of the addition of Grignard reagent to aldehydes or ketone is that



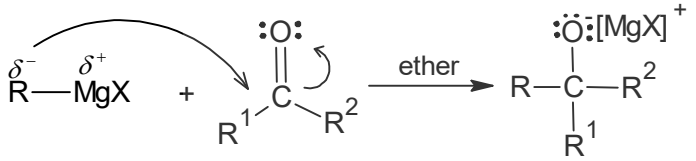
This reaction was discussed in earlier unit. As mentioned earlier, the carbon-magnesium bond of a Grignard reagent is polar in nature because of the difference in electronegativity between carbon and magnesium (2.5 – 1.2 = 1.3). In this bond, carbon bears a partial negative charge and magnesium bears a partial positive charge. Therefore, Grignard reagent is a good nucleophile and adds to carbonyl group of the aldehydes and ketones to form adduct, which on protonation in aqueous acid gives an alcohol. The reaction of Grignard reagent with methanal (formadehyde) gave primary alcohol, with other aldehydes gave secondary alcohols and with ketones gave

tertiary alcohols. Grignard reactions must be performed in dry ether. Even traces of moisture can be neutralised the reagent. Let us study the mechanism of the reaction of Grignard reagent with carbonyl compounds.

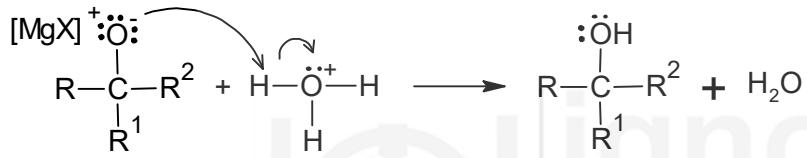
Mechanism: Reaction of Grignard reagent with aldehydes and ketones

When a Grignard reagent is mixed with an aldehyde or ketone, the negative hydrocarbon group quickly attacks the positive carbonyl carbon and provides the two electrons needed for the new carbon-carbon bond. The π electrons are displaced to the oxygen, forming alkoxoide ion in the form of alcohol salt ($-O^-[MgX]^+$. The alkoxide ion is strong base and when treated with an aqueous acid such as HCl during work up, it is protonated to form alcohol.

Step 1: New bond formation between a nucleophile and an electrophile



Step 2: Protonation

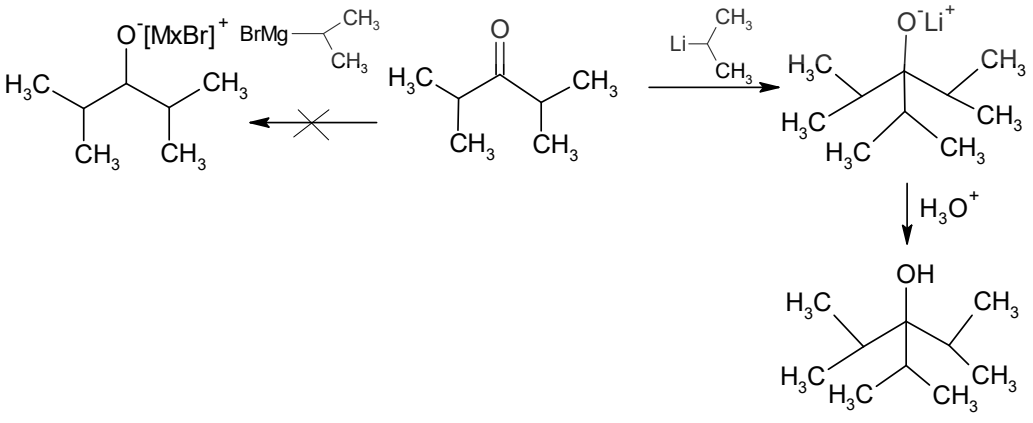


SAQ 7

How will you prepare primary, secondary and tertiary alcohols from same Grignard reagent?

Addition of Organolithium Compounds

Because of high electropositivity of lithium atom, organolithium compounds have greater negative charge on carbon. Therefore, they are generally more reactive in nucleophilic addition reactions than organomagnesium compounds. These compounds are very useful in addition reactions to sterically hindered ketones. In the following example, the Grignard reagent does not react with ketone but the organolithium does since it is stronger nucleophile.



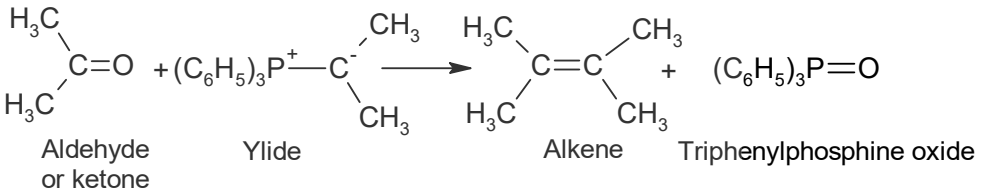
SAQ 8

Write the reaction mechanism of the following reaction:

PhCHO + BuLi → PhCH(Bu)OH

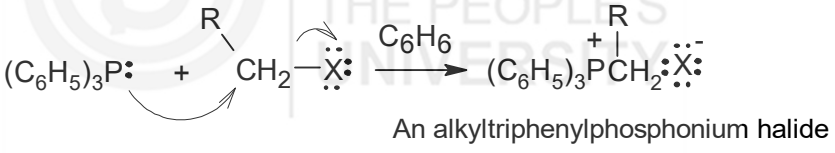
Wittig Reaction

A very important method of synthesis of alkenes known as Wittig reaction involves the reaction between an aldehyde or ketone and a phosphorus ylide. Phosphorus ylides contain a carbanion which is stabilised by an adjacent positively charged phosphorus group.

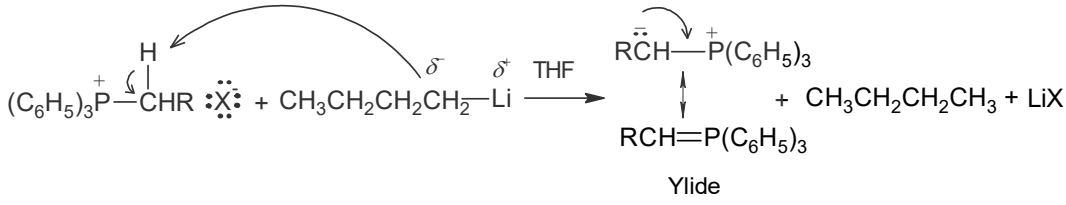


In this reaction, the oxygen of the carbonyl group is substituted by an alkene group, triphenyl phosphine oxide being the other product.

Phosphorus ylides are prepared from haloalkanes by two step sequence: the first step is the S_N2 displacement of halide by triphenylphosphine [$(C_6H_5)_3P$] to give an alkyltriphenylphosphonium salt.



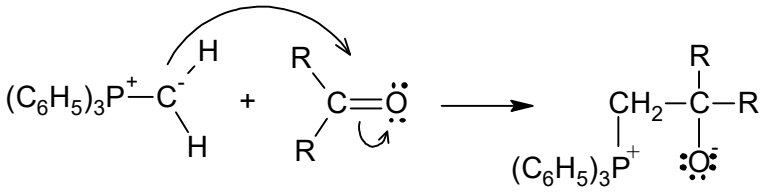
α-Hydrohen atoms on the alkyl group of an alkyltriphenylphosphonium ion now become weakly acidic in nature due to the presence of adjacent positively charged phosphorus atom and can be removed by very strong base such as butyllithium (BuLi) or sodium hydride. (NaH) to give ylide.



Mechanism

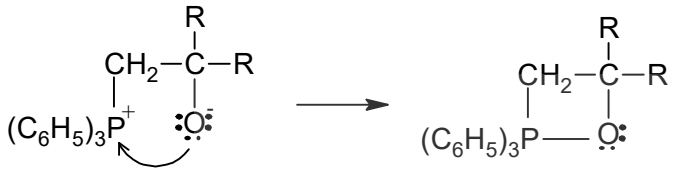
The carbanion in the ylide is nucleophilic and can attack the carbonyl group. The result is a dipolar intermediate called a betaine. The betaine is short lived and collapses to a four membered oxaphosphacyclobutane (oxaphosphetane) ring. This substance finally breaks to give alkene and triphenylphenylphosphine oxide. The driving force for the last step is the formation of very strong phosphorus-oxygen double bond.

Step 1: Bond formation between a nucleophile and an electrophile

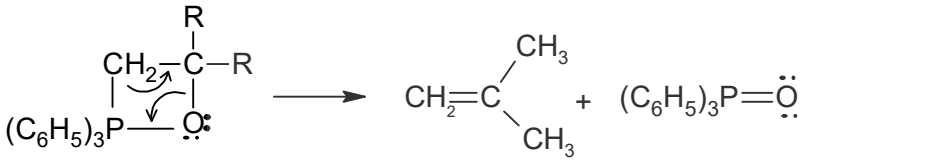


A betaine

Step 2: Formation of four membered ring



Step 3: Braking of four membered ring to more stable products

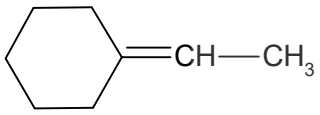


An alkene Triphenylphosphine oxide

Wittig reactions display useful steroselectivity. The reaction of non-conjugated ylides (unstabilised ylides) and aldehydes typically results in *Z* (*cis*) alkenes as major product and conjugated ylides (stabilised ylides) frequently result in trans products. Because of this, Wittig reaction is of considerable importance in industrial synthesis. Much of the synthetic vitamin A is manufactured by a reaction sequence involving Wittig reaction.

SAQ 9

Show how the following alkene can be synthesised by the Wittig reaction:

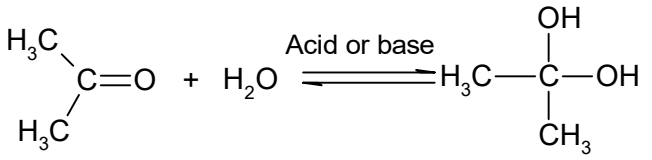


ii) Addition of Oxygen Nucleophiles

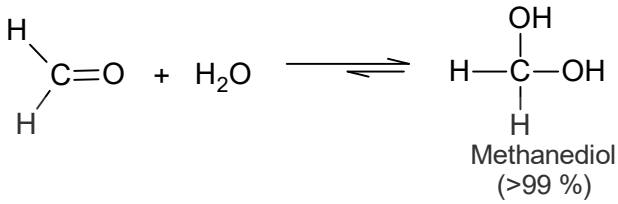
In this section, we examine nucleophilic addition reactions of aldeydes and ketones with water and alcohols. Both water and alcohols are very weak nucleophiles. Therefore, these reactions are reversible and the position of equilibrium depends on the reactivity of carbonyl group of aldehydes and ketones.

Addition of Water

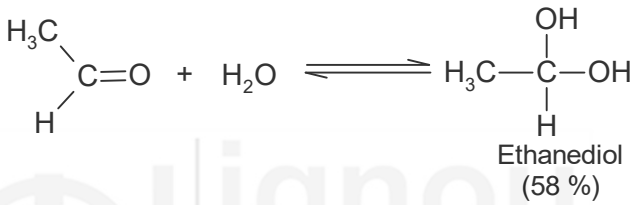
Aldehydes and ketones react with water to form 1,1-diols (Geminal diol) or hydrates. These compounds are unstable and are rarely isolated. The reaction is catalysed by acid or base. Hydration reaction is reversible and in most cases, equilibrium strongly favous the carbonyl group.

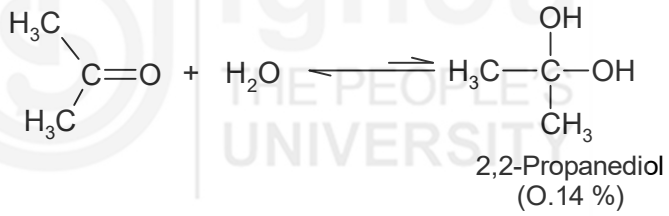


Stable hydrates are known in few cases but they are rather exceptions, For example, hydrates of 2,2,2-trichloroethanal (chloral) methanal (formaldehyde).

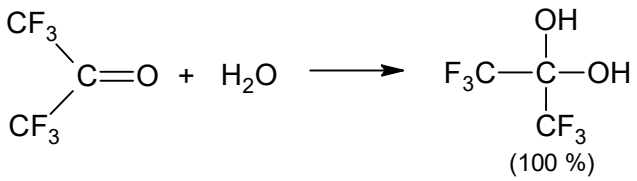


The position of equilibrium depends on the reactivity of the carbonyl group and is influenced by a combination of electronic and steric effects. With increase in size of alkyl substituent on carbonyl group, the reactivity of the carbonyl compounds decreases, For example,





As discussed earlier, the carbon atom of carbonyl group has carbocation character. Methanal has no alkyl substituent to stabilise its carbonyl group and is converted almost completely into corresponding diol. The carbonyl group of ethanal is stabilised by one alkyl substituent and carbonyl of propanone by two alkyl substituents. Thus ethanal gives 58 % of 1,2-ehanediol while propanone gives 0.15 % of 2,2-diol product. The reactivity of carbonyl group can be increased by increasing carbocation character of carbon atom of carbonyl group. This can be done by attaching electron withdrawing group to carbonyl group. For example, in contrast to almost negligible hydration of propanone, hexafluoroproanone is completely hydrated.



Above observations can also be explained on the basis of steric factor. The carbon atom that bears two hydroxyl groups is sp^3 hybridised. Its substituents are more crowded than are in the starting aldehyde or ketone. Increased crowding can be better tolerated when the substituents are hydrogen than when they are alkyl groups. Thus, diol of methanal is least crowded and hence

formed in larger amount. Diol of propanone on the other hand is more crowded, therefore, is formed in a lesser amount. The amount of diol of ethanal is formed between the above two limits. In real situation, the reactivity of aldehydes and ketones for the formation of diol depends on the combined effect of electronic and steric factors.

SAQ 10

Which of the following compounds do you predict would form hydrates and why?

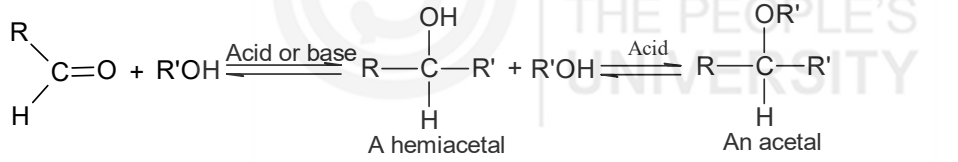
$Cl_3CCOCCl_3$, $CH_3CH_2COCH_3$

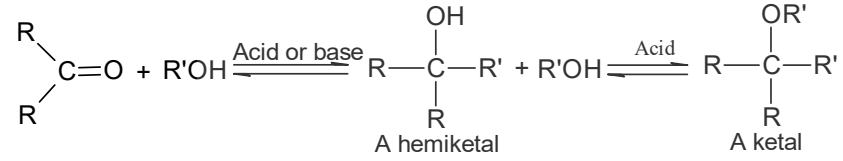
SAQ 11

Write the mechanism of both acid and base catalysed hydration reactions.

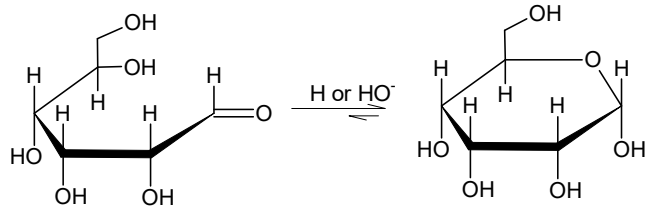
Addition of Alcohols

We have seen above that the addition reactions of water are reversible and the equilibrium is generally unfavourable. Therefore, addition reactions of water to aldehydes and ketones are generally not of much significance. On the other hand, alcohols undergo appreciable nucleophilic addition reactions to aldehydes and ketones. Let us study these reactions in some more detail. Aldehydes and ketones give first hemi-acetals (half-acetal) and hemiketals on reaction with an alcohol, respectively. With excess of alcohol, they give acetals and ketals. All these reactions are catalysed by acid or base.





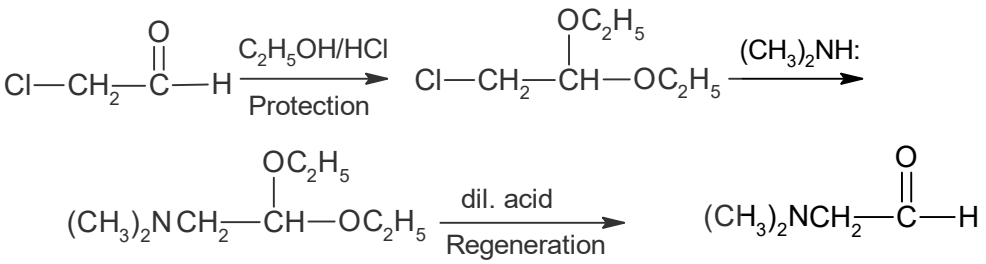
Hemiacetals are generally unstable and exist only in minor concentration in the equilibrium mixture. Exception are those from reactive carbonyl compounds such as methanal or 2,2,2-trichloroethanal.Five and six membered cyclic hemiacetals also are quite stable. Such hemiacetals are common in sugar chemistry. For example in aqueous solution, the cyclic forms constitute more than 99% of the mixture.



Aldehyde form (0.003 %)

Cyclic hemiacetal (two stereoisomers) (90 %)

Hemiacetals are generally not stable relative to starting materials, but they react further with alcohols to form acetals. Acetals are more stable than hemiacetals and can be isolated in good yield under the proper conditions. Like other ethers, acetals are good solvents. They are stable to bases and oxidising agents, but are cleaved even by dilute acids. The mechanism of cleavage reaction is just the reverse of that for the formation of the acetals. This property of acetals is used in synthesis to protect the carbonyl function from reacting while a substitution or addition reactions is carried out elsewhere in the molecule. After the reaction the acetal is then hydrolysed back to the aldehyde. The example below illustrates the utility of such protection in synthetic reactions,

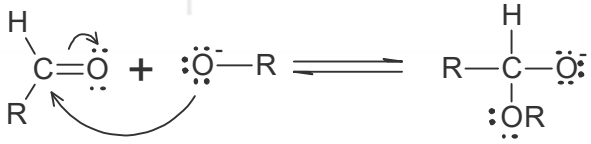


Let's study the mechanism of base-catalysed and acid-catalysed formation of a hemiacetal.

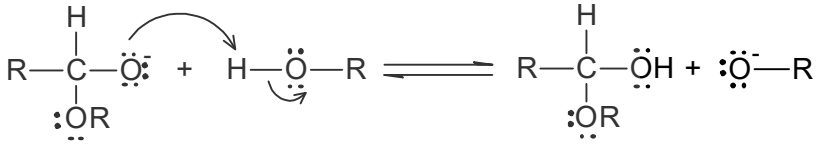
Mechanism: Base catalysed formation of hemiacetals

Step1: Alkoxide ion is formed by the proton transfer from ROH to the base.

Step 2: Nucleophilic attack on the elctrophilic carbon of carbonyl group.

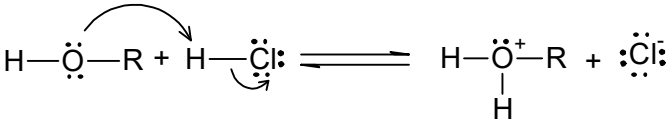


Step 3: Protonation of above addition compound.

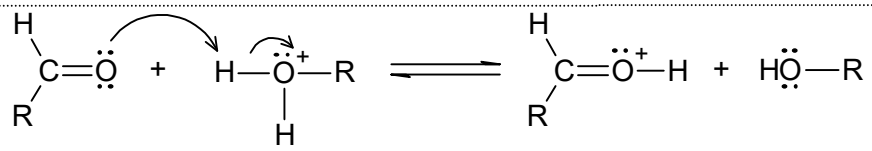


Mechanism: Acid Catalysed formation of hemiacetals

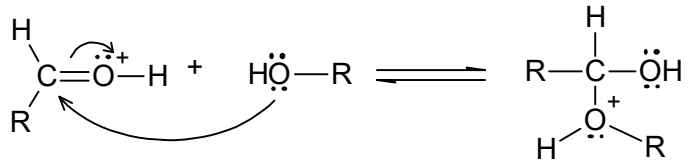
Step 1: In presence of strong acids such as HCl or sulphuric acid, alcohol molecules get protonated and this protonated alcohol will act as proton source in next step.



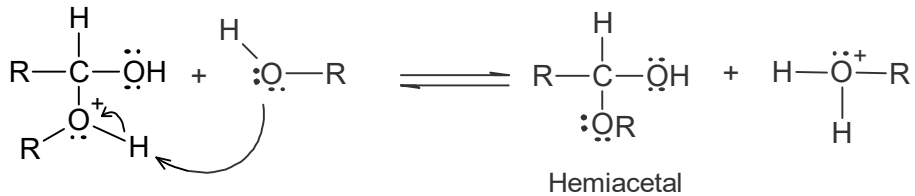
Step 2: Proton from protonated alcohol is transferred to the oxygen of carbonyl group.



Step 3: Attack of a nucleophile (alcohol molecule) to the protonated carbonyl group.



Step 4: Transfer of proton from oxonium ion to an alcohol molecule.



Hemiacetal

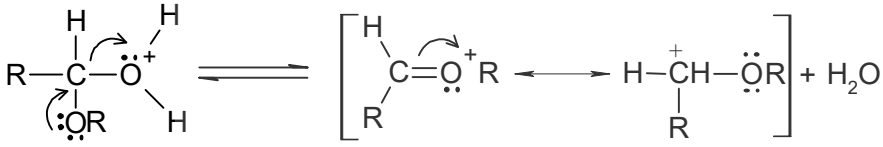
Formation of acetal from hemiacetal is catalysed by acid, not by base as it is difficult to displace, poor leaving group like −OH directly by a nucleophile. The mechanism of this reaction is as followed.

Mechanism: Acid catalysed formation of an Acetal

Step 1: Protonation of hydroxyl group of hemiacetal to form oxonium ion.

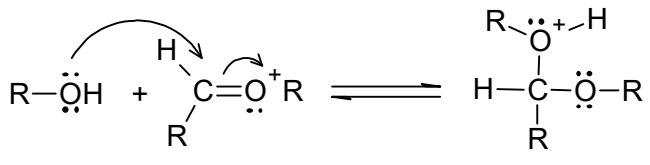
Hemiacetal An oxonium ion

Step 2: Loss of water molecule to form resonance stabilised carbocation.



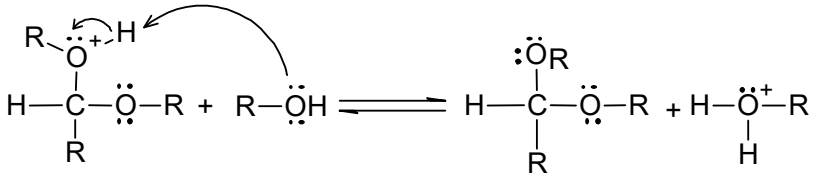
A resonance stabilised carbocation

Step 3: Nucleophilic attack on positively charged carbon atom of the carbonyl group to form protonated acetal.



A protonated acetal

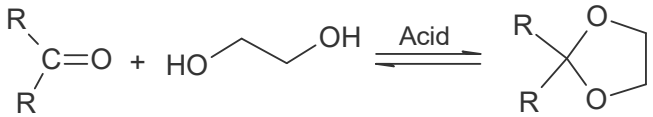
Step 4: Proton transfer from protonated acetal to alcohol molecule.



An acetal

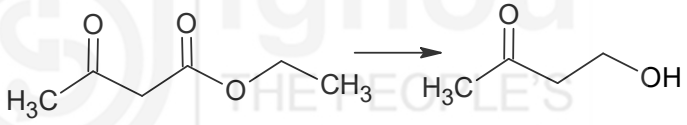
It is much more difficult to obtain ketals from ketones, as in most of cases the equilibrium favour reactants rather than products. In such situation, formation of acetal/ketal is favoured by the removing one of products, water from reaction mixture using special distillation technique.

Notice that acetal/ketal formation requires one mole of aldehyde or ketone and two moles of the alcohol. Alternatively, alcohols having two hydroxyl groups can be used in equimolar ratio to prepare cyclic acetals/ketals. Cyclic acetals or ketals are often used for protecting carbonyl group because they are easy to prepare. Sulphuric acid and *p*-toluinesulphonic acid (TsOH) are commonly used acids for the preparation of hemiacetal/hemiketals and acetals/ketals.



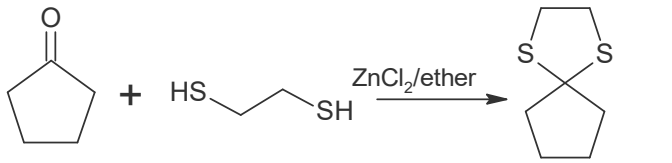
SAQ 12

How will you accomplish the following conversion?



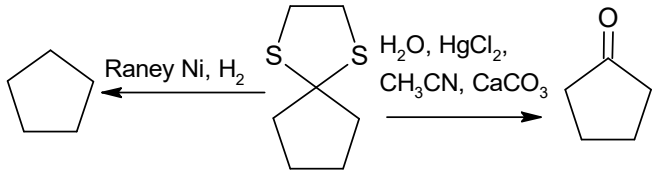
iii) Addition of Sulphur Nucleophiles

Thiols and sulphur analogs of alcohols react with aldehydes and ketones by the mechanism identical with the one discussed above for alcohols. These reactions can be catalysed by Lewis acids such as BF_3 or $ZnCl_2$. Reactions are generally carried out in ether solvent. Cyclic thioacetals/thioketals are particularly easy to prepare.



Cyclic thioketal

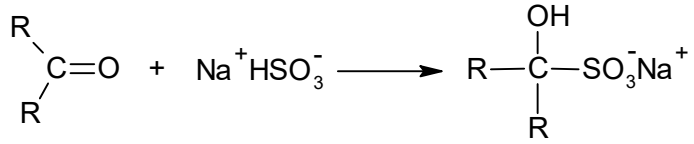
Thioacetals/thioketals are stable in aqueous acids. Their hydrolysis is carried out using mercuric chloride in aqueous acetonitrile. Thioacetals/thioketals can be desulphurised to the corresponding alkanes by the treatment with Raney nickel.



Cyclic thioacetal

Addition of sodium bisulphate ($NaHSO_3$)

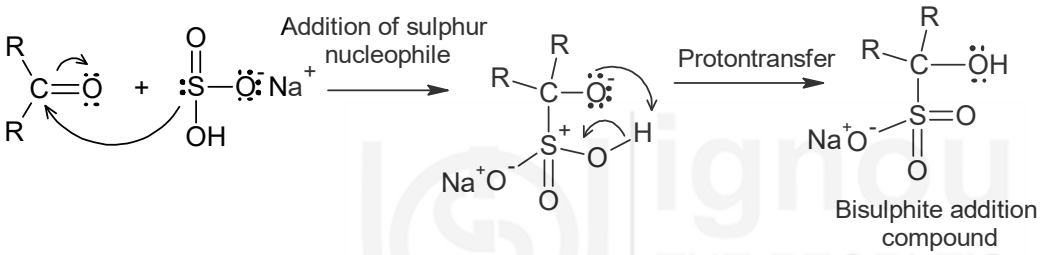
The reaction with sodium bisulphate (sodium hydrogen sulphite) gives the bisulphite adduct.



The bisulphite adducts are crystalline solids. On heating with dilute acid or aqueous sodium carbonate, they regenerate the carbonyl compound. This reaction is often used for separation and purification of aldehydes and ketones. The mechanism of this reaction is given below:

Mechanism: Formation of bisulphite a dduct

The reaction occurs by nucleophilic attack of the lone pair of sulphur on the carbonyl carbon of aldehde or ketone, just like the attack of cyanide. This leads to a positively charged sulphur atom and a simple proton transfer leads to the product.



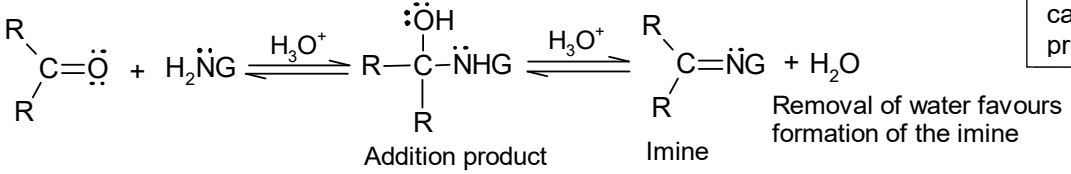
iv) Addition of Nitrogen Nucleophiles

Nitrogen nucleophiles such as ammonia and its derivatives may be regarded as nitogen analog of water and alcohols. They add to carbonyl group of aldehydes and ketones in same fashion. However, in certain cases addition products lose water, furnishing either of two new dehydrated products: imines (Schiff bases) and enamines.

Addition of Ammonia and its mono substituted derivatives (GNH_2)

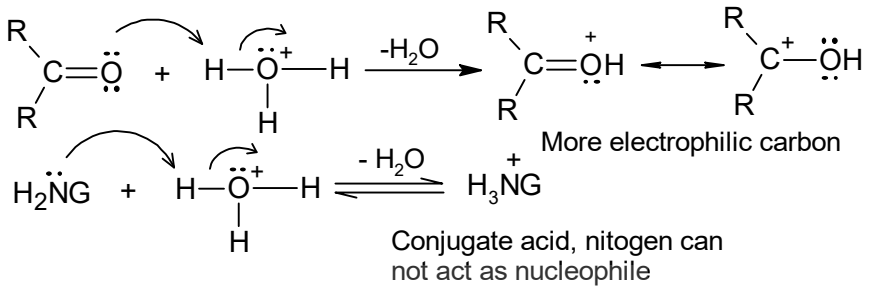
Addition of ammonia is a reversible reaction with an unfavourable equilibrium. However, certain mono substituted ammonia derivatives are added to carbonyl compounds to give imines or Schiff bases. Imine is a **condensation product** in which the initial addition is followed by dehydration to form a carbon-nitrogen double bond. The net result is substitution of oxygen by nitrogen group. Imines are generally unstable unless C=N group is part of an extended system of conjugation and are difficult to isolate from reaction mixture. The general reaction can be summed up as follows:

Organic reactions in which two molecules of starting materiel react together to form a main product plus a byproduct of considerably lower molecular mass such as H_2O or CO etc. are referred to as condensation reactions and the main product is called condensation product.



G = Groups mentioned in Table 18.5

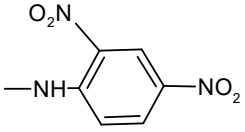
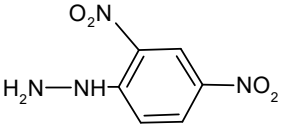
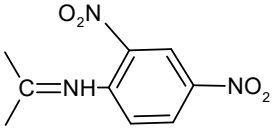
These reactions are catalyzed by acids. While protonation of carbonyl compounds increases their reactivity towards nucleophiles. But on the other hand, protonation of the reagent, H_2NG will lower its nucleophilic character as depicted below:



Therefore, an optimum pH has to be maintained during the reaction. The optimum pH for the reaction depends on the nature of G in H_2NG. It is to be adjusted such that all of H_2NG is not converted to H_3N^+G and at the same time there is sufficient concentration of the conjugate acid of the carbonyl compound to activate it.

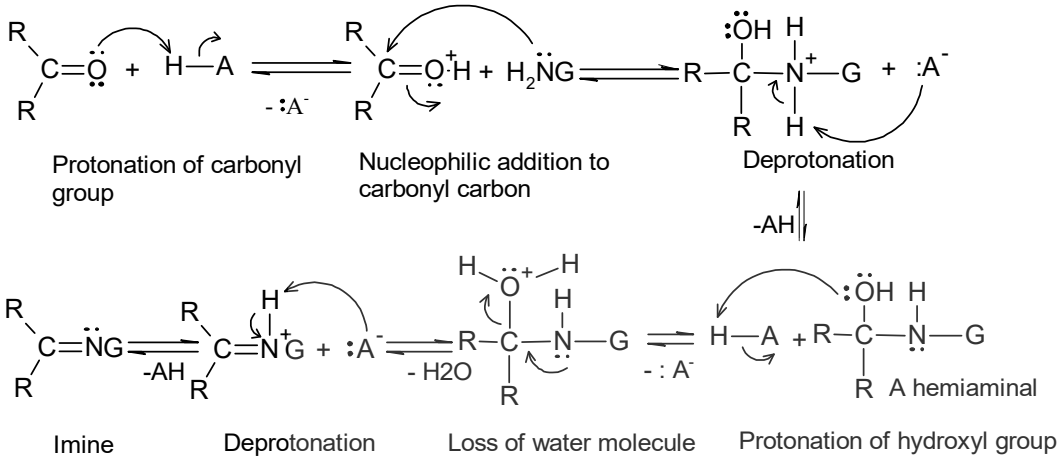
The names of reactants with different G, general condensation products and their class are given in Table 18.5. Many of these condensation products are crystalline solids with sharp melting points. For this reason they are frequently employed for the preparation of aldehyde and ketone derivatives needed for identification.

Table 18.5: Addition of ammonia derivatives

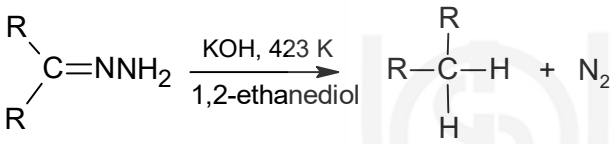
G of product	Ammonia derivative	Condensation product	Class
-R/-Ar Alkyl/aryl	RNH_2,/$ArNH_2$ Primary aliphatic amine/aromatic amine	>C = NR/.C= NAr	Imine (Schiff base)
-OH	NH_2OH Hydroxylamine	>C =NOH	Oxime
$-NH_2$	H_2NNH_2 Hydrazine	>C =NNH_2	Hydrazone
$-NHC_6H_5$	$H_2NNHC_6H_5$ Phenyl hydrazine	>C= $NNHC_6H_5$	Phenylhyrazone
$-NHNHCONH_2$	$NH_2NHCONH_2$ Semicarbazide	>C= $NNHCONH_2$	Semicarbazone
	 2,4-Diphenylhyrazine		2,4-dinitrodiphenylhyrazone

Mechanism: Formation of imine from an Aldehyde or Ketone

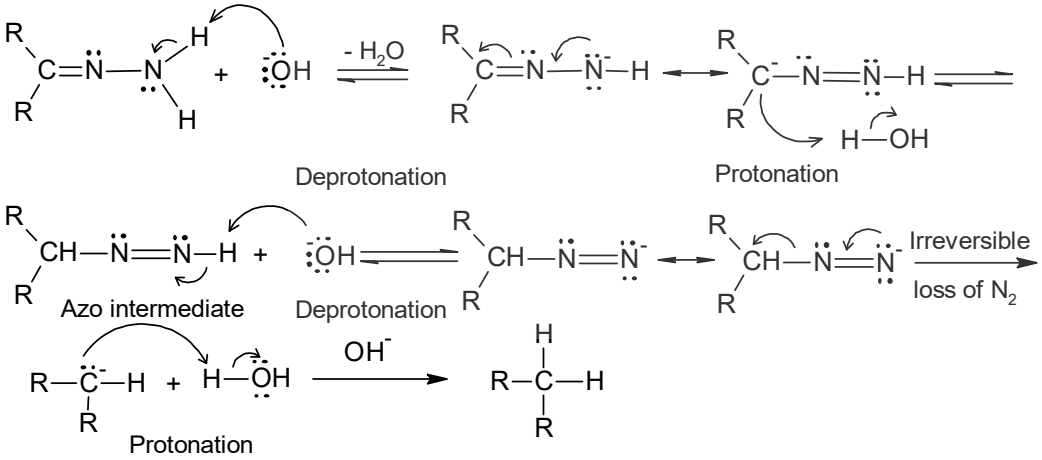
A six step mechanism for the formation of imine is shown below. The first three steps produce intermediate hemiaminal (carbinolamine) and last three steps convert this intermediate to imine.



Imines are useful compounds both in synthetic organic chemistry and in biological systems. They are used for the synthesis of complex amines. When the hydrazones are heated with potassium hydroxide or sodium ethoxide, alkanes are formed with the loss of nitrogen:



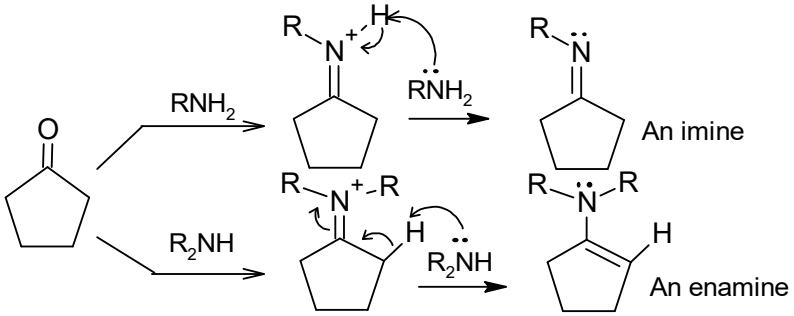
Thus the carbonyl group is converted into a methylene group via a hydrazine. This reaction is known as the **Wolff Kishner** reaction or Wolff Kishner reduction. In this reaction, base mediates hydrogen shifts. The detailed mechanism is given below.



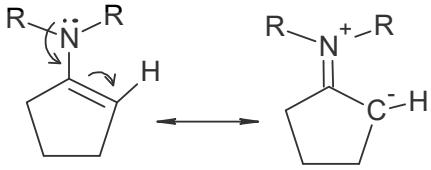
Like hydrazones, semicabozones can also be used in the above reaction.

Addition of Secondary Amines:

Secondary amines react with aldehydes and ketones to form enamines (*en* = carbon-carbon double bond, *amine* =amino group). The mechanism for the formation of an enamine is very similar to that for the formation of an imine except last step:



Enamines behave as carbon nucleophiles during organic reactions because of following resonance structures.

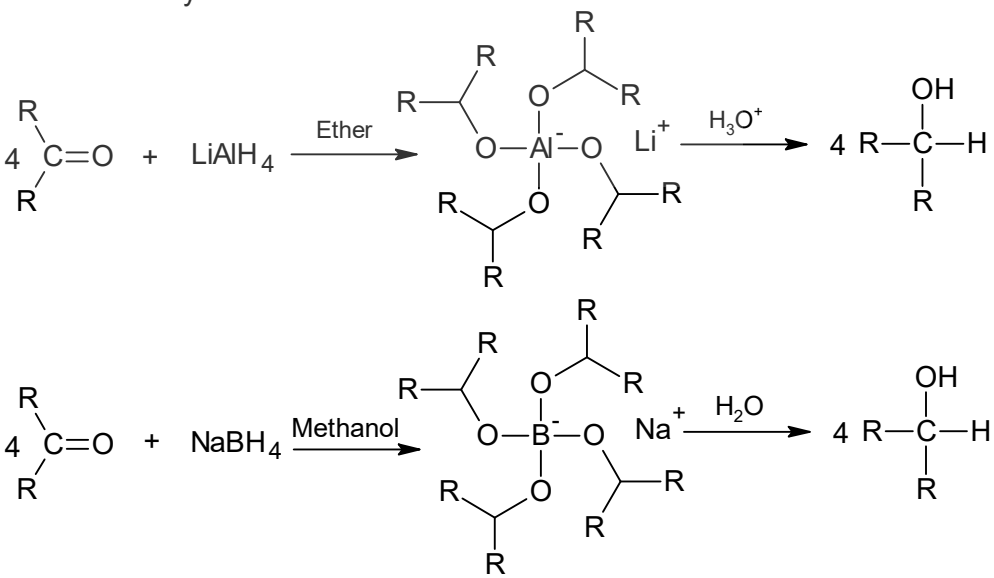


We will further go in detail of enamine chemistry and their use in synthetic organic chemistry at higher level.

v) Addition of Hydrogen Nucleophiles

Addition of hydride donors such as lithium aluminum hydride ($LiAlH_4$) or sodium borohydride ($NaBH_4$) or LiH to aldehydes and ketones gives alcohols. This addition reaction is also called a redox reaction as the reduction of a carbonyl compound to an alcohol takes place. In this unit, our discussion is only focussed on the addition reaction of lithium aluminum hydride and sodium borohydride. Both these reagents function as delivery agent of hydride (H^-).

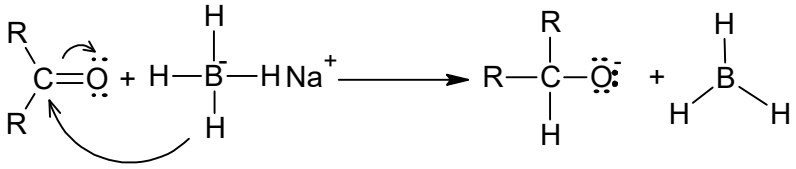
Lithium aluminum hydride is a very powerful donor of hydride. It reduces not only the carbonyl group of aldehydes and ketones rapidly but also those of carboxylic acid and their other functional derivatives. On the other hand, sodium borohydride is less reactive and, therefore a much more selective reagent, reducing only the carbonyl group of aldehydes and ketones. Because of high reactivity of lithium aluminum hydride, non protic solvents such as diethyl ether or tetrahydrofuran (THF) are used for carrying out the reaction and protic solvents such as methanol or alcohols are used for the reactions of sodium borohydride.



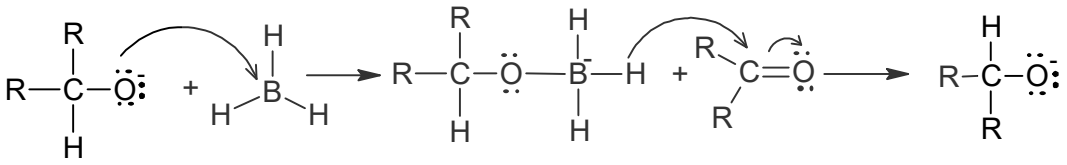
A tetraalkyl borate

Mechanism: Addition of Hydride using Sodium Borohydride

Step 1: Nucleophilic hydride ion adds to the electrophilic carbonyl carbon atom.



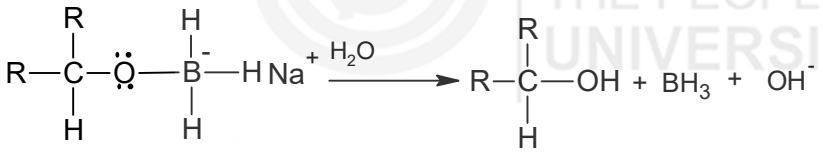
Step 2: The alkoxide ion produced in the first step can help stabilise the electron-deficient BH_3 molecule by adding to its empty *p* orbital. Now we have a tetravalent boron anion again, which could transfer a second hydride to another carbonyl group.



Second molecule of carbonyl compound

This process can continue so that, in principle, all four hydrogen atoms could be transferred to molecules of aldehyde to form tetraalkyl borate.

Step 3: Reaction is completed with the addition of proton. Water or alcohol solvent provides the proton needed to form the alcohol from the alkoxide ion.

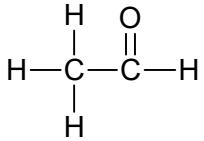


SAQ 13

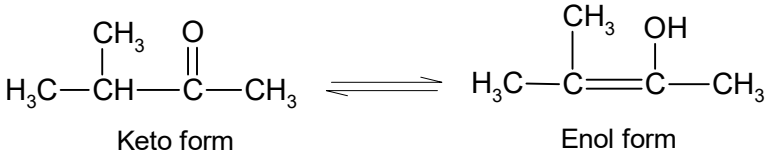
Write the mechanism for the addition of hydride to a carbonyl compound using $LiAlH_4$.

18.4.2 Reactions Involving α-Hydrogen

Another important characteristic of carbonyl compounds is the acidity of hydrogen atoms on carbon atom alpha to the carbonyl group, called α-hydrogens. We have already encountered C−H acidity in the alkynes in earlier Unit of first semester course. Propanone is about 100,000 times stronger as acid compared to ethyne. Because of the reactivity of the α-hydrogens, aldehydes and ketones may exist as equilibrium mixtures of the two isomeric forms, a keto from and an enol form.



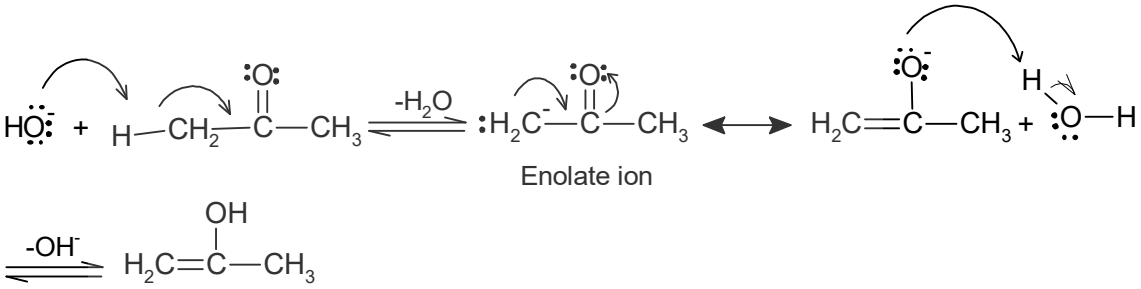
Ethanal has three α hydrogens



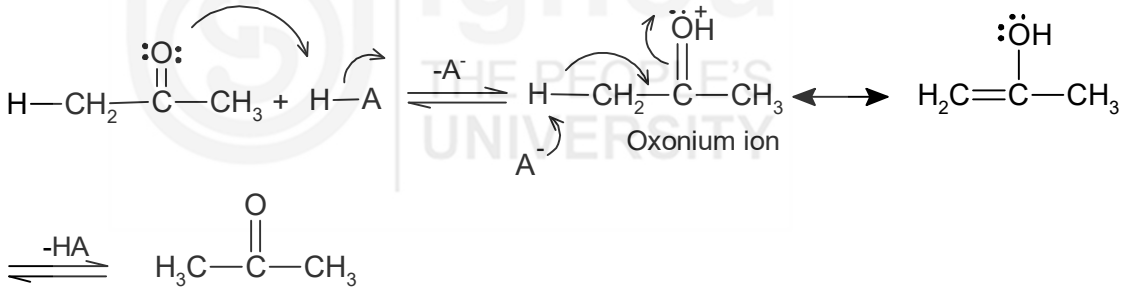
This type of isomerism in which there is dynamic equilibrium between the two forms is called tautomerism, and the isomers are called tautomers. In the pure liquid state or in neutral solutions, only traces of the enol form are present since enol form is less stable than the keto form.

Conversion of keto form to enol form is called enolisation. This conversion can be achieved by catalytic reaction with both acids and bases as shown in the following equations.

Base-catalysed enolisation



Acid-catalysed enolisation



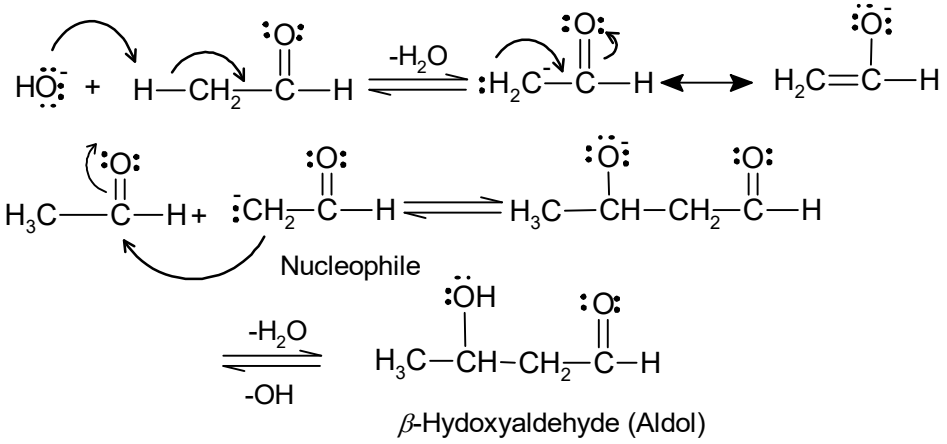
Strong acids give rise to weak conjugated bases on ionisation. The ionisation of propaone produces $^{-}CH_2COCH_3$ in which the negative change is delocalised and hence, it as a weak base. On the other hand, ionisation of CH_4 produces $^{-}CH_3$ which is a very strong base and, therefore, CH_4 is a very weak acid. The stabilisation of the anion by resonance is responsible for the greater acidity of propanone relative to methane and ethyne.

Enols and enolate ions are important reaction intermediates because they react further as nucleophiles on electrophilic carbon centres to create new carbon-carbon bonds. We will now discuss those reactions of the carbonyl compounds in which α-hydrogens are involved.

Aldol Reaction

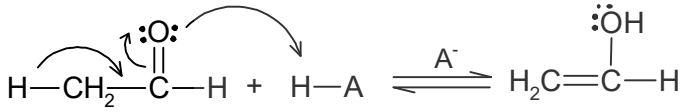
Aldol is a composite word for aldehyde + alcohol.

When an enol or enolate ion adds to another molecule of the aldehyde or the ketone, the reaction is called the **aldol**. This reaction is either base- or acid-catalysed. The mechanism of the aldol raction involving self-condensation of two molecules of ethanal in presence of a basic catalyst is shown as an example:



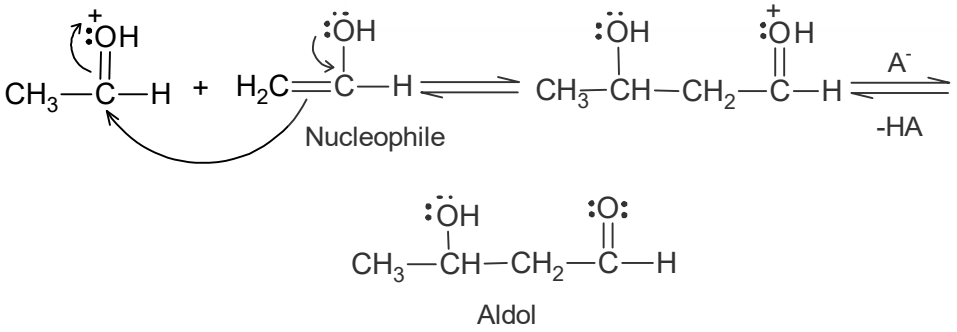
The mechanism of acid catalysed aldol reaction involves following steps;

Step 1: Acid catalysed enol formation



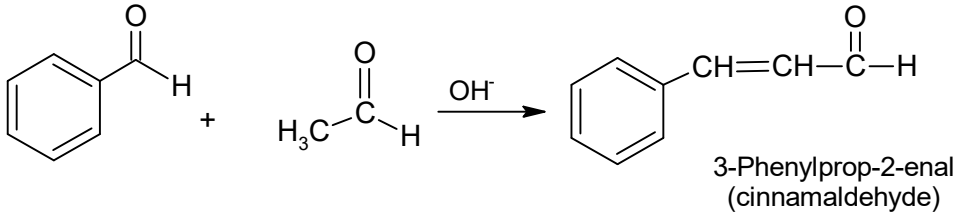
Step 2: Oxonium ion formation of second molecule of an aldehyde or a ketone.

Step 3 and 4: Nucleophilic enol attacks on electrophilc carbon atom of the oxonium ion and oxonium ion transfer its proton to conjugate base, A^- of acid HA.



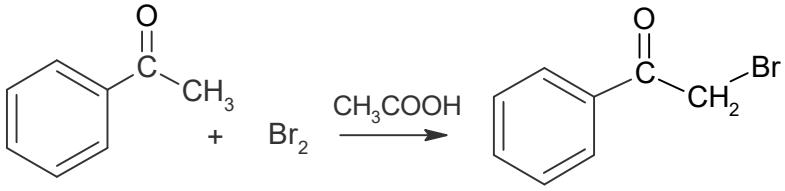
Ketones containing α-hydrogen are also capable of aldol-type of reaction. In the aldol reaction, one chiral centre is created so we expect two stereoisomers are produced as two 1:1 mixture of enantiomers. Chemists have been trying to carry out aldol and other enolate reactions in such manner that they give enantioselective products. You may study such reactions in your higher classes.

Aldehydes lacking α-hydrogens enter into a mixed aldol condensation with other aldehydes having α-hydrogens. They do this by acting as the carbanion acceptors. For example, benzaldehyde reacts with acetaldehyde to produce cinnamaldehyde, an α, β-unsaturated aromatic aldehyde used as a flavouring agent:



α-Halogenation

Aldehydes and ketones having α-hydrgen react at the α-carbon with halogens such as bromine or chlorine to form α-haloaldehydes and α-haloketones.. e.g.,



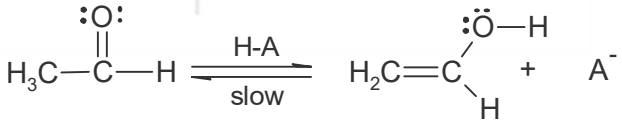
1-Phenylethanone (acetiphenone)

2-Bromo-1-Phenylethanone (α-bromoacetophenone)

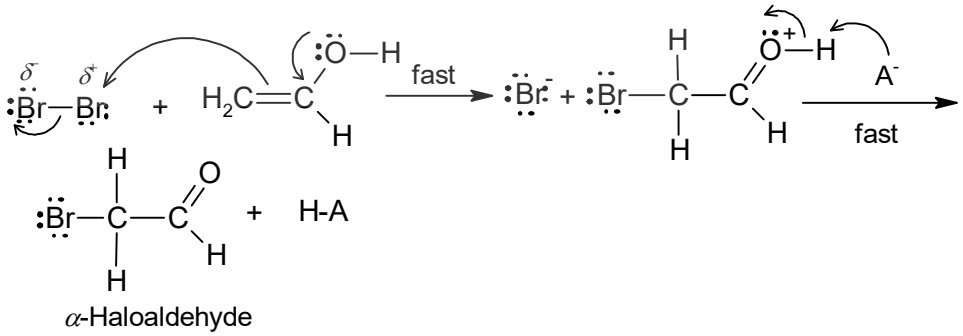
Halogenation reactions on α-carbon can be catalysed by both acid and base. Acid catalysed halogenations are generally stopped at single halogen substitution. But in the case of base catalysed halogenation, α-substituted halogen increases acidity of remaining α-hydrogens; thus, they can be removed by base with much more ease and, therefore, successive halogenations are more rapid.

Mechanism: Acid catalysed α-halogenation of an aldehde or a ketone

Step 1: Enol is formed by catalytic reaction of acid with an aldehyde or a ketone.



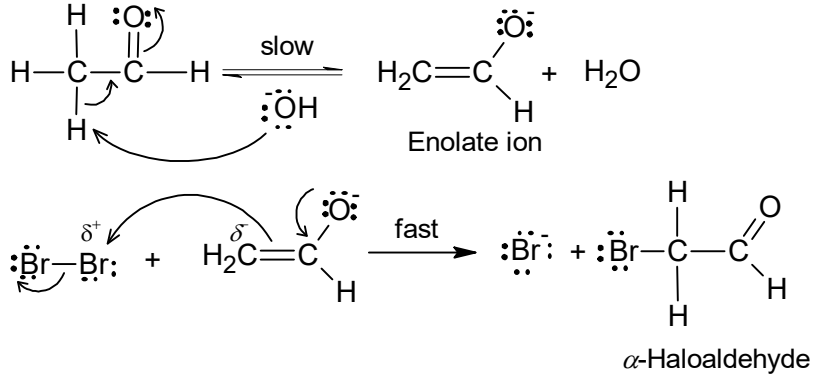
Step 2 and 3: The nucleophilic enol then attacks on electrophilic end of polarised halogen molecule and gives α-substituted intermediate which in final step transfer its proton to conjugated base of acid to gives an α-haloaldehyde or an α-haloketone.



α-Haloaldehyde

Mechanism: Base catalysed α-halogenation of an aldehyde or a ketone

In the first step, base removes an α-hydrogen from an aldehyde or a ketone to form enolate ion. In next step, this enolate ion attacks on electrophilic halogen to gives an α-haloaldehyde or an α-haloketone.

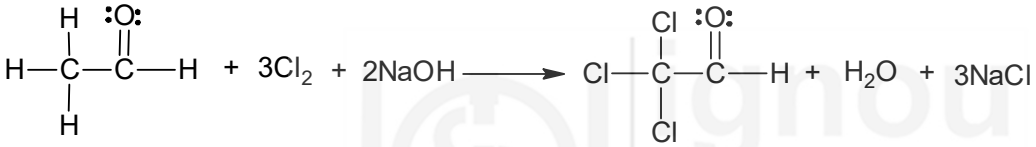


α-Haloaldehyde

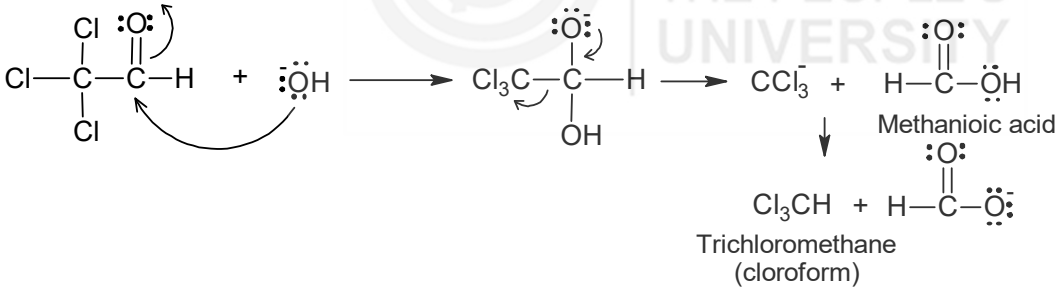
Because of high reactivity of the remaining *α* hydrogens, base catalysed halogenation tends to give polyhalogenation products. For this reason base catalysed halogenations have less synthetic use.

Furthermore, when ethanal or methyl ketones are warmed with an alkalie solution of chlorine, bromine, or iodine, the product is trichlromethane (chloroform), tribrimomethane (bromoform), or tri-iodomethane (iodoform), respectively. This reaction is called the haloform (trihalomethane) reaction and appears to take place in two stages:

Stage 1: Halogenation



Stage 2: Cleavage

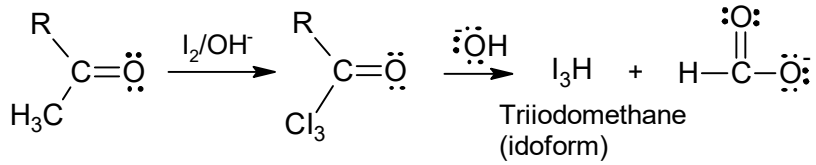


The first step is polyhalogenation *via* the enlolate ion. The second step is cleavage of the polarised Cl_3C-C bond by base through an addition elimination mechanism. The haloform reaction is useful not only as a preparartive method for the haloforms but also as a diagnostic test for the presence of the methyl ketone group or a group capable of giving methyl ketone group under the dehydrogenation. In practice, a solution of iodine is added to the aqueous alkaline solution of the compound to be tested. A positive reaction will yield tri-iodomethane (iodoform), CHI_3, a bright yellow solid which may be identified by its sharp pungent odour and its melting point. Trichloromethane and tribromomethane are liquids.

Ethanol or 2-propanol also gives idoform test as these compounds are oxidised by iodine during reaction to ethanal and propanone, respectivily.

$2CH_3CH_2OH + I_2 \rightarrow CH_3CHO + 2HI$

$2CH_3CHOHCH_3 + I_2 \rightarrow CH_3COCH_3 + 2HI$



SAQ 14

A carbonyl compound does not form iodoform on being heated with iodine and sodium hyroxide. It is:

a) ethanal

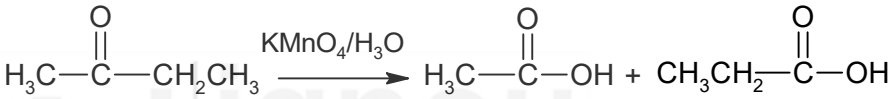
b) propanone

c) benzaldehyde

d) phenylethanone

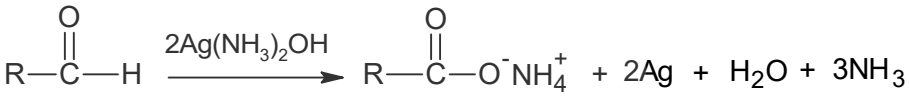
18.4.3 Oxidation

Aldehydes are oxidised so easily that even the mildest oxidising reagents will serve to bring about their conversion to acids. Ketones, on the other hand, are fairly resistant to oxidation. The oxidation of ketones, when forced by the use of strong oxidizing reagents and heat, results in the rupture of carbon-carbon bonds to produce acids.

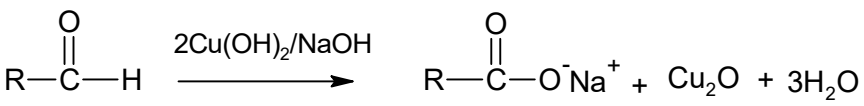


The ease with which oxidation of aldehydes takes place, provides a simple method for distinguishing between aldehydes and ketones. Mild oxidising agents may be used for this purpose. **Tollen's reagent,** an ammonical solution of silver oxide, $Ag(NH_3)_2OH$, **Fehling's solution,** an alkaline solution of cupric ion complexed with sodium potassium tartrate and **Benedicts solution,** an alkaline solution of cupric ion complexed with sodium citrate, are the three reagents commonly used to detect the presence of an aldehyde group.

When Tollen's reagent is used to oxidise an aldehyde, the silver ion is reduced to the metallic form and, if the reaction is carried out in a clean test tube, a silver mirror is formed.



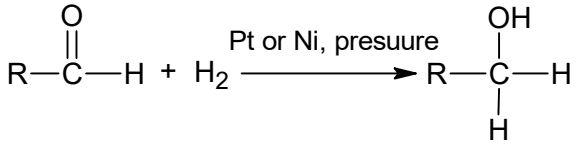
When Fehling's and Benedict's solutions are used to oxidise an aldehyde, the complexed deep blue cupric ion is reduced to red cuprous oxide.



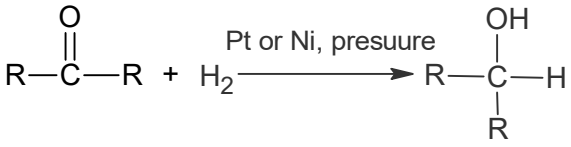
Aromatic aldehydes react with the Tollen's reagent but do not react with either Fehling's or Benedict's solution. A method of distinguishing aliphatic aldehyde from aromatic aldehydes is thus provided by this difference in reactivity between the two types of reagents.

18.4.4 Reduction

Both aldehydes and ketones undergo reduction and the nature of the product depends on the reagent used for the purpose. Catalytic hydrogenation of aldehydes and ketones gives primary and secondary alcohols, respectively. Reduction with dissolving metals (e.g., sodium-alcohol) gives alcohols similar to metallic hydrides (lithium aluminium hydride or sodium borohydride).

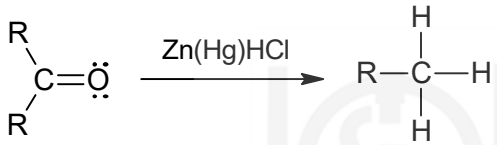


Primary alcohol

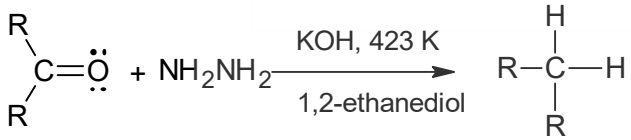


Secondary alcohol

Alkanes are formed when carbonyl compounds are reduced with zinc amalgam and hydrochloric acid. This reaction is known as the **Clemmensen reduction**.



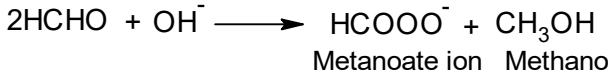
An alternative to the Clemmensen reduction for an acid sensitive ketone is the Wolff-Kishner reduction. As mentioned earlier, this employs hydrazine (NH_2NH_2) and potassium hydroxide. The solvent is 1, 2-ethanediol (glycol).



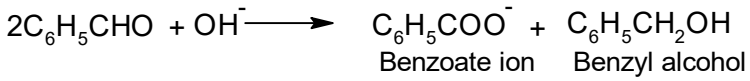
18.4.5 Specific Reactions of Aldehydes and Ketones

Methanal

Methanal (formaldehyde) gives many of the general reactions of carbonyl compounds above but as it does not have α hydrogens and therefore, it does not undergo those reactions in which α-hydrogens are involved. Thus, for example, it does not undergo base-catalysed self condensation. On treatment with aqueous sodium or potassium hydroxide it forms methanol and methanoate ion. This reaction is known as the **Cannizzaro reaction.**

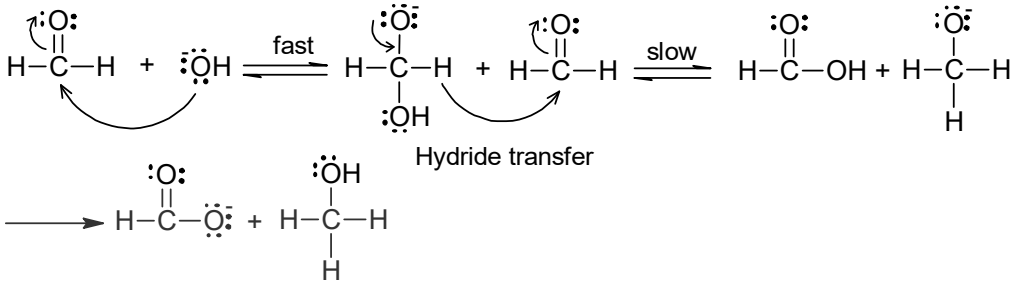


Benzaldehyde which also does not have any α-hydrogen undergoes the Cannizzaro reaction as well, e.g.,

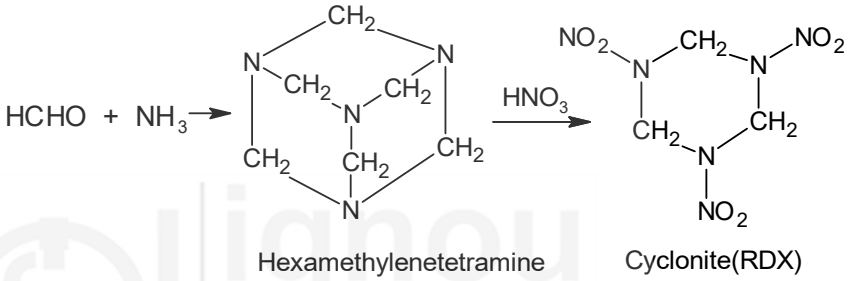


Mechanism: Cannizzaro reaction

Reaction is initiated by the addition of hydroxide ion to the carbonyl carbon to form an addition intermediate, which transfers a hydride to a second molecule of methanal in the rate determining step. After the proton transfer in final step, final product are methanol and eathanoate ion.



Treatment of methanal with ammonia gives hexamethylenetetramine: Hexamethylenetetramine is also called **urotropin** and has following cyclic structure.



Hexamethylenetetramine is medicinally useful as a urinary antiseptic (urotropine) and is also oxidized by nitric acid to the important military explosive cyclonite (RDX).

Methanal is also used as a methylating agent:

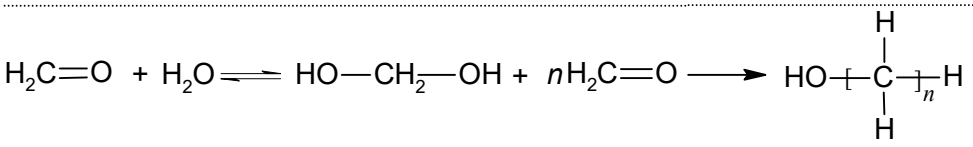
$$C_2H_5NH_2 + HCHO + HCOOH \longrightarrow C_2H_5NHCH_3 + CO_2 + H_2O$$

Aldehydes

Here we will consider reactions which are given by aldehydes only and not by ketones. Aldehydes restore the magenta colour of Schiff's reagent (aqueous rosaniline hydrochloride solution whose magenta colour has been discharged by sulphur dioxide).

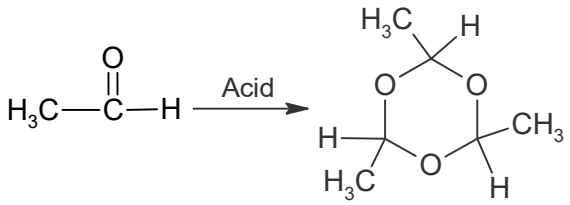
As mentioned earlier, aldehydes are very easily oxidised. Hence, they reduce Tollens' reagent to metallic silver, and Fehling's and Benedict's solutions to cuprous oxide.

Aldehydes (except methanal) on being warmed with concentrated sodium hydroxide solution, undergo aldol condensations and dehydration. Methanal and ethanal polymerise readily, propanone does not. The polymer of formaldehyde is known as **paraformaldehyde**, $HO(CH_2O)_nH$, with *n* having an average value of 30. Paraformaldehyde is an amorphous white solid which is prepared by slowly evaporating **formalin** (a 37-40% aqueous solution of methanal) under reduced pressure.



Depolymerisatin of paraformaldehyde is brought about by heating. This facile change of state from solid to gaseous allows methanal to be easily stored and used.

When treated with acid at a low temperature, ethanal undergoes addition to give a cyclic trimer, paraldehyde (b.p. 389 K). Paraldehyde, when warmed, is depolymerised to regenerate ethanal. Like methanal, ethanal can also be easily stored and is used in the form of paraldehyde.



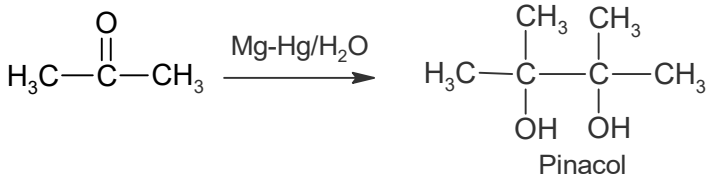
Paraldehyde

Finally in the following subsection, we will see the reactions which are given by ketones only and not by aldehydes.

Ketones

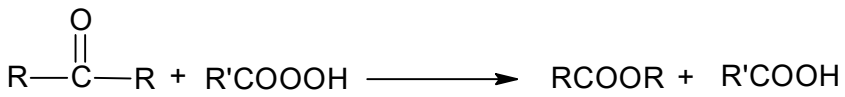
Ketones react with ammonia to give complex condensation products. Treatment with nitrous acid converts ketones to oximino derivatives, e.g.,

When reduced with magnesium amalagam and water, ketones give dimers. The dimer from propanone is called pinacol.



Pinacol

Treatment of ketones with preacids gives esters. This reaction is known as **Baeyer-Villiger oxidation**:



18.5 INDUSTRIAL USE

Methanal is perhaps the most important member of the aldehyde family. Its industrial importance lies principally in its ability to copolymerise with phenol and with urea to produce bakelite and urea methanal resins, respectively.

Methanal is also an antiseptic and disinfectant. As formalin, it is used to preserve anatomical specimens, in the manufacture of dyes, gelatin and casein.

Ethanal is used for preparing ethanol, ethanoic acid, phenolic resins, synthetic drugs and rubber accelerators. Its trimer, paraldehyde $(CH_3CHO)_3$, is used in medicine as a hypnotic.

Propanone is used as a solvent for celluloid, lacquers, cellulose acetate and nitrate and in the preparation of sulphonal and ketene ($CH_2=C=O$) for synthesis of organic compounds. Other ketones are used as solvents for resins and synthetic rubber.

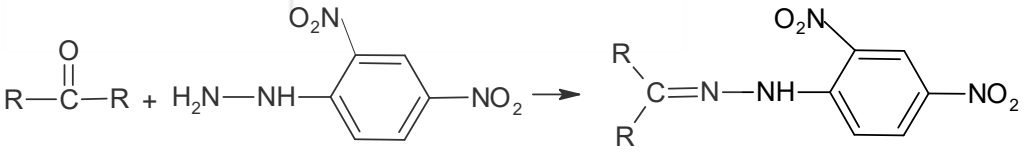
Benzaldehyde is used in perfumery, for preparation of dyes for flavouring purposes and for the preparation of α, β-unsaturated derivatives.

Phenylethanone (acetophenone) is used in perfumery and as hypnotic (hypnone). It is also used in the preparation of many organic compounds which are used in synthesis such as, phenacyl halides 1, 3-diketones, etc.

Some insecticides are prepared from the condensation of carbonyl compound, e.g., DDT (Unit 11) is obtained by heating trichloroethanal (chloral) with chlorobenzene in the presence of concentrated sulphuric acid.

18.6 LAB DETECTION

Both aldehydes and ketones on heating with an alcoholic solution of 2,4-dinitrophenyl hydrazine (DNP) in acidic medium give orange red crystalline hydrazine derivatives which are identified by their characteristic melting points.



Aldehyde or Ketone 2,4-Dinitrophenyl hydrazine 2,4-Dinitrophenyl hyrazone

Aldehydes reduce Tollens' reagent and Fehling or Benedict solutions, while ketones do not. These tests provide methods for distinguishing between aldehydes and ketones. Glucose (an aldehyde) when heated with Fehling solution gives red precipitate. This test is both qualitative as well as quantitative. It is used to estimate the amount of glucose in a sample of urine of diabetic patients. As mentioned in Section 18.4.2, ethanal and methyl ketones are characterised through the tri-iodomethane test (iodoform test).

SAQ 15

How might you use simple test tube reactions to distinguish between:

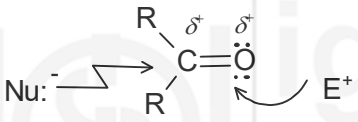
a) Benzaldehyde and ethanol

b) Ethanal and propanone

18.7 SUMMARY

In this unit, we have described the chemistry of aldehydes and ketones. We summarise below what we have studied so far:

- Aldehydes and ketones have carbonyl (> C=O) group which is quite reactive. Ketones can be regarded as alkyl or aryl derivatives of aldehydes.
- Aldehydes and ketones are prepared by oxidation or dehydrogenation of alcohols, decomposition of calcium salt of carboxylic acids or catalytic decomposition of carboxylic acids, Rosemund's method and Stephen's method.
- Methanal is commercially obtained by the catalytic oxidation of methanol. Ethanal and propanone are prepared industrially either by hydration of alkynes or catalytic oxidation of alkenes. Propanone is also obtained from oxidation of natural gas and as a by-product in the oxidation of cumene.
- The > C = O function in aldehydes and ketones undergoes addition reaction. As it has a polarized caron oxygen double bond, nucleophiles add to the carbonyl carbon atom and electrophiles add to the carbonyl oxygen atom.



Carbonyl group is attached by a variety of reagents such as HCN, $NaHSO_3$, ROH, ammonia derivatives, RMgX etc. to give addition products.

- The reaction of aldehydes and ketones with phosphorous ylildes gives alkenes (Wittig reaction). In certain aldehydes and ketones, where α-hydrogens are present, acid or base catalysed enolisation, base-catalysed halogenation, haloform reaction and aldol condensation, etc., are observed.
- Aldehydes can be oxidised to carboxylic acid; ketones cannot be oxidised without breaking carbon-carbon bonds. The carbonyl group of an aldehyde or ketone can be reduced to alcohol by either catalytic hydrogenation or metallic hydrides. They can also be reduced to alkanes by either the Wolff-Kishner or Clemmensen reduction.
- Methanal reacts with aq. NaOH to give a mixture of alcohol and carboxylate ion (Cannizzaro reaction). Methanal reacts with ammonia to form hexamethylenetetramine. Methanal and ethanal readily polymerise.
- Ketones from oximino derivatives with HNO_2, are oxidised to esters with peracids and form pinacols with magnesium amalgam water.
- Detection of carbonyl group is achieved by the formation of crystalline 2, 4-dinitrophenyl hydrazones. Aldehydes are detected by the reduction of ammoniacal silver nitrate or Fehling solution and by Schiffs' reagent.

18.8 TERMINAL QUESTIONS

1. Predict the products in the following reactions:

   a) $RCH_2OH \xrightarrow[\text{Pyridine}]{CrO_3}$

   b) $HC{\equiv}CH \xrightarrow[Hg^{2+}]{H_3O^+}$

   c) $H_3C{-}\overset{\overset{O}{\|}}{C}{-}Cl \xrightarrow{H_2/Pd(BaSO_4)}$

   d) $H_3C{-}C{\equiv}N \xrightarrow[2.\ H_2O]{1.\ SnCl_2/HCl}$

2. Write a mechanism for the reaction of:

   a) addition of methanol to propanal.

   b) addition of hydrazine to cyclohexanone.

3. Predict the products:

   a) $H_3C{-}\overset{\overset{O}{\|}}{C}{-}CH_3 + H_2NNH_2 \xrightarrow{H_3O^+}$

   b) $CH_3CH_2{-}\overset{\overset{O}{\|}}{C}{-}CH_3 + CH_2P(C_6H_5)_3 \xrightarrow{DMSO}$

   c) $CH_3CHO + Ag(NH_3)OH \longrightarrow$

   d) $H_3C{-}\overset{\overset{O}{\|}}{C}{-}CH_3 + Br_2 \xrightarrow{OH^-}$

   e) $CH_3CH_2CH_2{-}\overset{\overset{O}{\|}}{C}{-}CH_3 \xrightarrow[1,2\text{-ethanediol}]{H_2NNH_2,\ NaOH}$

   e) $H_3C{-}\overset{\overset{O}{\|}}{C}{-}CH_3 \xrightarrow{Zn(Hg),\ HCl}$

4. Show how to bring about the following conversions using Wittig reaction:

   a) acetone to 2-methyl-2-butene

   b) cyclohexanone to methylenecyclohexane

5. Write equations for the following named reactions.

   a) Oppenaur oxidation

   b) Cannizzaro reaction

   d) Aldol condensation

   e) Baeyer-Villiger oxidation

18.9 ANSWERS

Self-Assessment Questions

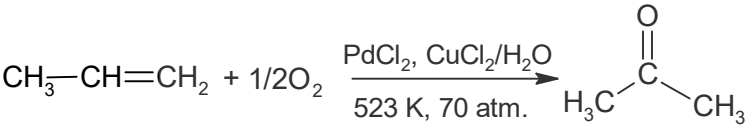
1. a) 3-methyl-3-butenal; b) cyclohaxanecarbaldehyde;

   c) cyclohexanone; d) 1-phenylbutanone

2. a) 1-pentanol; b) 3-methyl-2-butanone; c) 2-pentanol; d) cyclohexanone; e) 1-pentanal

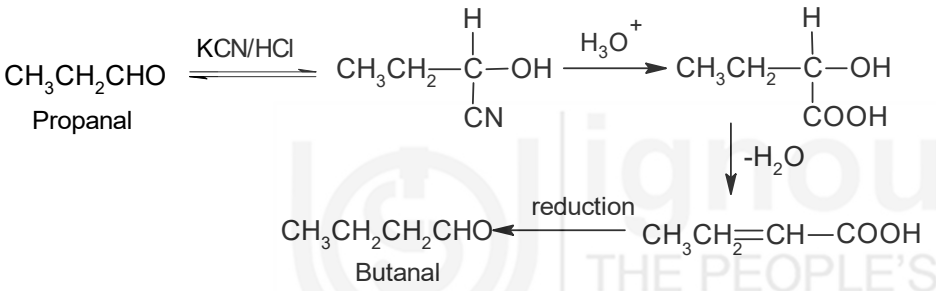
3. 2-Chloropropane

4. Propanone can be manufactured by the direct oxidation of propene from natural gas with oxygen or air, catalysed by a mixture of palladium and cuprous chlorides (**The Wacker Process**).



5. Methanal > propanal > propanone > 1-phenylethanone

6.



7. Reaction of a Grignard reagent with methanal gives primary alcohol, reaction with other aldehydes gives secondary alcohols and reaction with ketones gives tertiary alcohols.

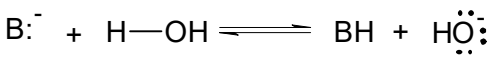
8. The mechanism will be same as for the reaction of Grignard reagent with aldehydes and ketones.

9. It can be prepared using cyclohexanone and ylide prepared from chloroethane.

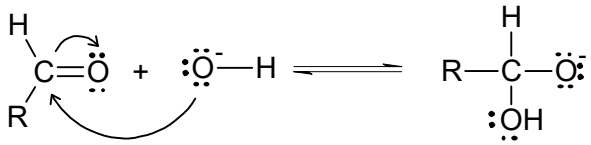
10. As discussed in text, reactivity of carbonyl group can be increases by increasing carbocation character of carbon atom of carbonyl group. $Cl_3CCOCCl_3$ has electron withdrawing group ($-CCl_3$) attached to carbonyl group. Therefore this will form hydrates.

11. Mechanism of base catalysed hydration reaction:

    Step 1



    Step 2



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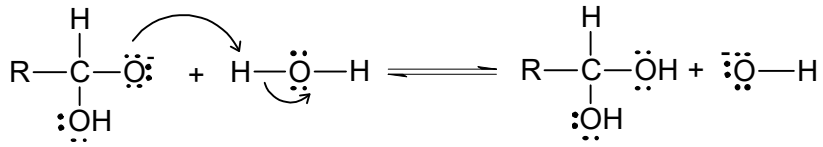
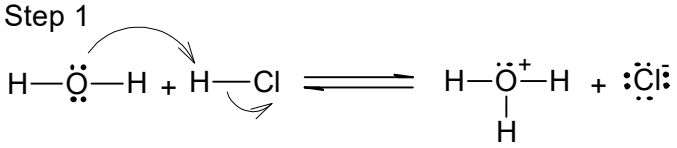


Mechanism of Acid catalysed hydration reaction:

Step 1



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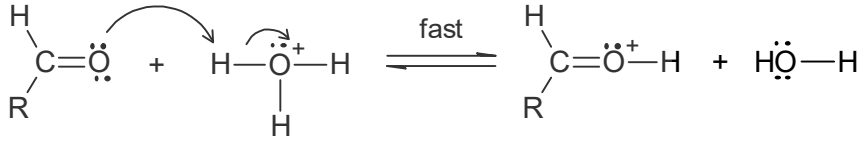

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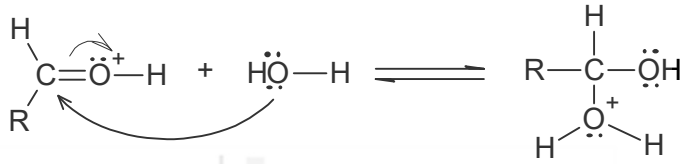
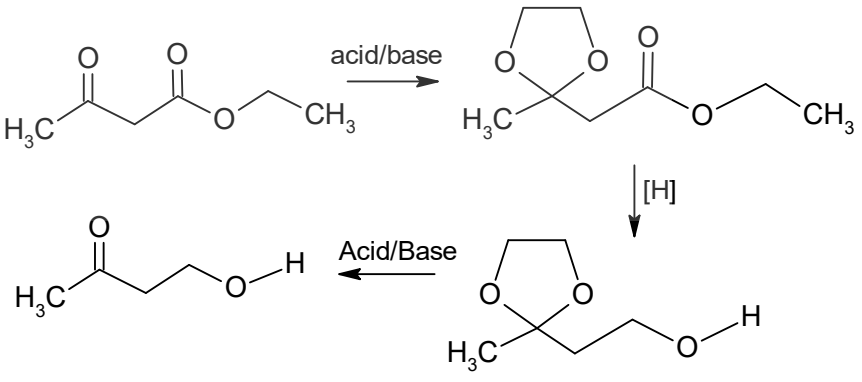
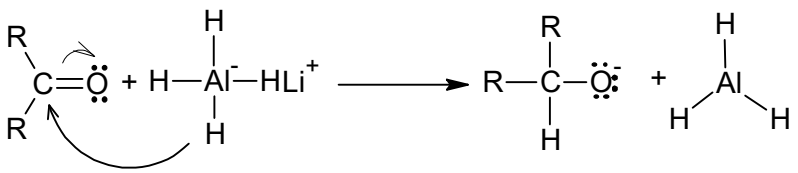


Step 4

12. First we have to protect ketone group by forming cyclic acetal, than acetal is hydrogenated to convert easter group to alcohol. Final it is treated with either base or acid back to ketone.



13. Step 1



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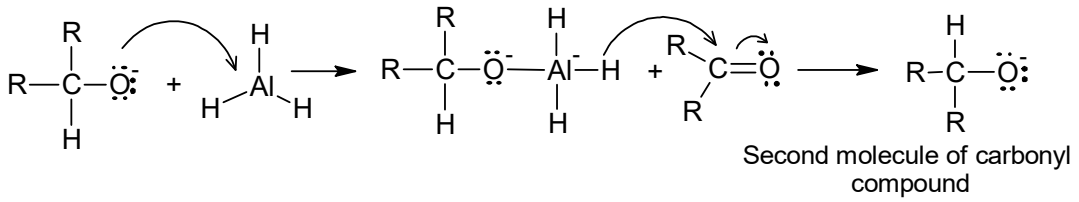
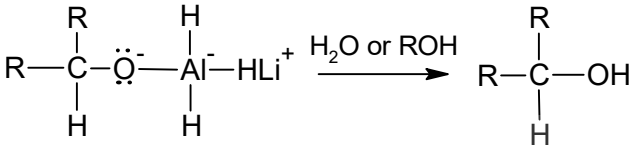


Step 3



14. c; as it is not having α-hydrogens.

15. a) Ethanal reduces both Tollen's reagent and Fehling's solution. Benzaldehyde can reduce Tollen's reagent but it does not reduce Fehling's solution. Ethanal also gives iodoform test.

    b) Ethanal reduces both Tollen's reagent and Fehling solution propanone does not.

Terminal Questions

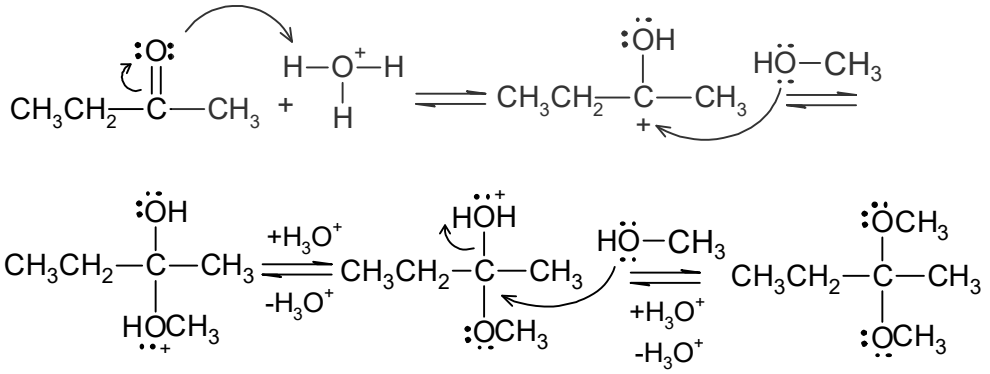
1. a) $RCH_2OH \xrightarrow[\text{Pyridine}]{CrO_3} H_3C-C(=O)-H$

   b) $HC\equiv CH \xrightarrow[Hg^{2+}]{H_3O^+} RCH_2-C(=O)-R$

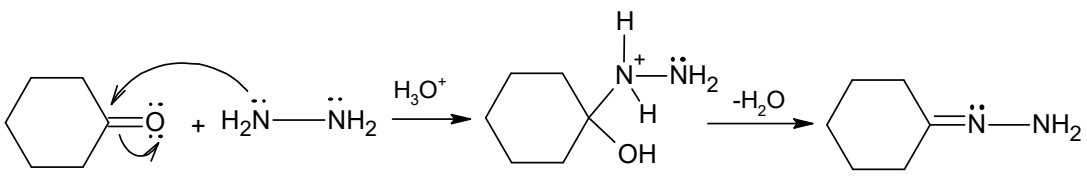
   c) $H_3C-C(=O)-Cl \xrightarrow{H_2/Pd(BaSO_4)} R-C(=O)-H$

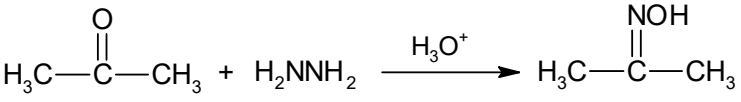
   d) $H_3C-C\equiv N \xrightarrow[2.\ H_2O]{1.\ SnCl_2/HCl} R-C(=O)-H$

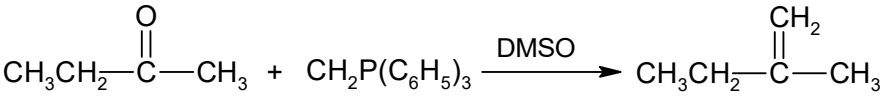
2. a)

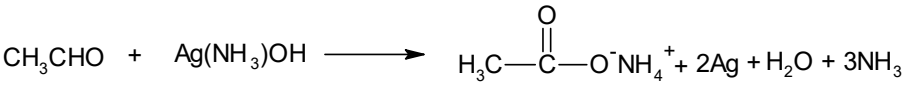


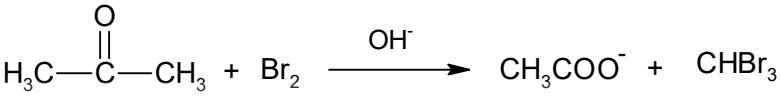
   b)

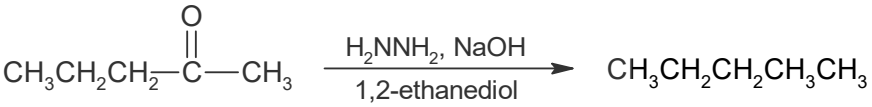


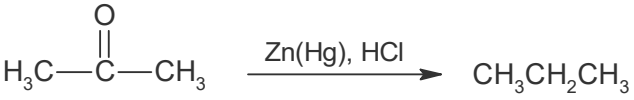
3. a) 

b) 

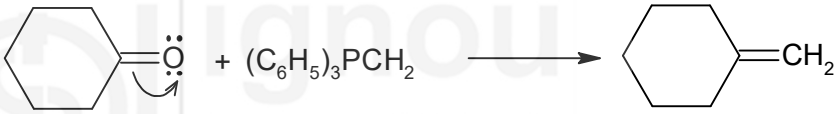
c) 

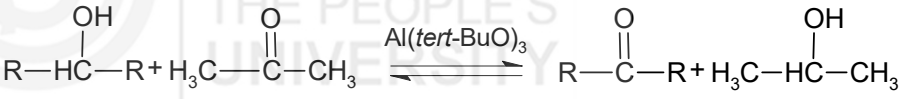
d) 

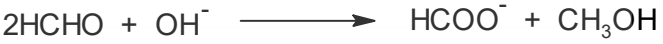
e) 

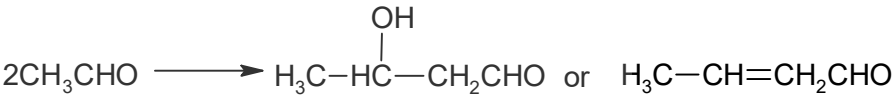
f) 

4. a) 

b) 

5. a) 

b) 

c) 

d) 

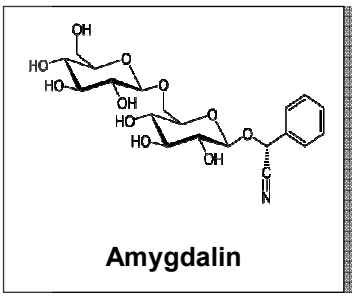
UNIT 19

AROMATIC ALDEHYDES AND KETONS

Structure

19.1 INTRODUCTION

In the previous unit, we have already discussed the chemistry of aliphatic aldehydes and ketones. Aromatic aldehydes and ketones also show the usual reactions associated with carbonyl group but they display some unique reactions arising from the influence of the aromatic group. Benzaldehyde and phenylethanone (acetophenone) are the simplest example of aromatic aldehydes and ketones, respectively. Benzaldehyde is present in bitter almonds in the form of its glucoside, **amygdalin** ($C_{20}H_{27}O_{11}N$). When amygdalin is boiled with dilute acids, it hydrolyses and converts into benzaldehyde, HCN and glucose. Phenylethanone, which is known by its preferred name acetophenone, is naturally found in several fruits. It has distinct organic scent. Thus, it is often used in scenting lotions and flavoring foods. Acetophenone has also been used in medicine as hypnotic under the trade name hypnone. In this unit, we will take up preparations and reactions of benzaldehyde and acetophenone in detail.



Amygdalin

Expected Learning Outcomes

After studying this unit, you should be able to:

- explain how aromatic aldehydes and ketones can be prepared; and
- describe the reactions due to both carbonyl group and aromatic ring of aromatic aldehydes and ketones.

19.2 PREPARATION OF BEZALDEHYDE AND ACETOPHENONE

Benzaldehyde can be obtained by the following methods.

i) By Hydrolysis of (dichloromethyl)benzene (benzal chloride)

Benzaldehyde is prepared by the hydrolysis of (dichloromethyl)benzene (benzal chloride) in either aqueous acid or aqueous alkali.

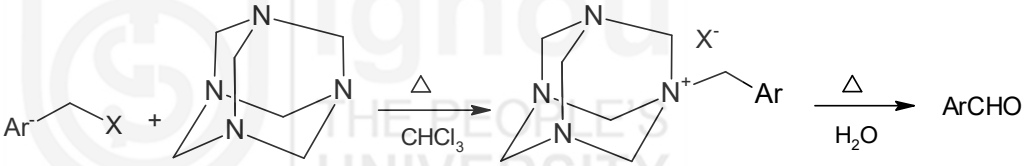
$$C_6H_5CHCl_2 + OH^- \text{ or } H_3O^+ \longrightarrow C_6H_5CHO$$

ii) By oxidation of (chloromethyl)benzene

Mild oxidising agents like copper or lead nitrate convert (chloromethyl)benzene (benzyl chloride) into benzaldehyde while reagents like HNO_3 convert it into benzoic acid.

$$2\,C_6H_5CH_2Cl \xrightarrow{\text{aq. } PbNO_3} 2C_6H_5CHO + PbCl_2 + 2HNO_3$$

(Chloromethyl)benzene can also be converted to benzaldeyde by the **Sommelet reaction**. This reaction involves refluxing (chloromethyl)benzene in aqueous solution with hexamethylenetetramine followed by hydrolysis.



iii) Oxidation of methylbenzene (toluene)/phenylmethanol (benzyl alcohol)

Methylbenzene (toluene) can be oxidised with chromium trioxide and ethanoic anhydride (acetic anhydride) or with chromyl chloride (Etard' reaction) to gives benzaldehyde:

$$C_6H_5CH_3 \xrightarrow[\text{or } CrOCl_2]{CrO_3/(CH_3CO)_2O} C_6H_5CH(OAc)_2 \xrightarrow{H_3O^+} C_6H_5CHO$$

In this preparation, acetic anhydride prevents further oxidation of benzaldehyde by converting it into diacetate. Subsequent hydrolysis generates the aldehyde group. Phenylmethanol (benzyl alcohol) can also be oxidised to benzadehyde using chromium trioxide in acetic acid.

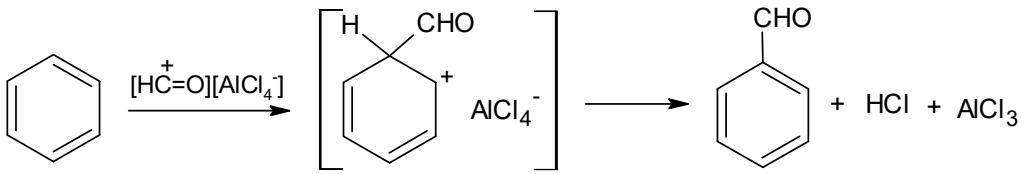
$$C_6H_5CH_2OH \xrightarrow{CrO_3,\ AcOH} C_6H_5CHO$$

iv) By direct formylation of benzene

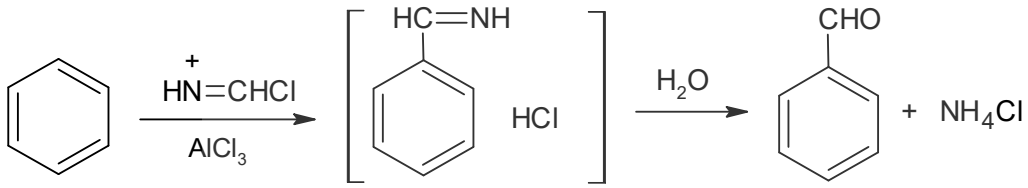
There are several methods for the introduction of the formyl group (–CHO) into aromatic ring. You have already studied Gattermann-Koch formylation and Gattermann synthesis in the previous unit. In Gattermann-Koch reaction carbon monoxide and hydrogen chloride are

passed through a solution containing benzene and aluminium chloride.

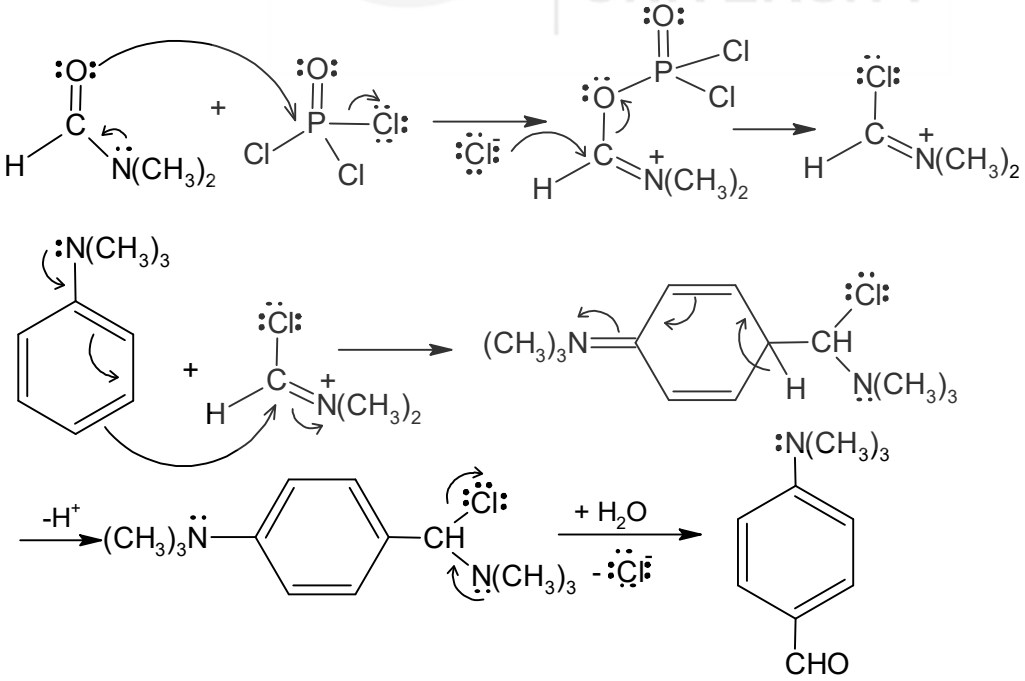
Formyl cation ($H\overset{+}{C}=O$) formed during reaction undergoes electrophilic substitution with benzene.



In a related reaction, Gattermann synthesis, the carbon monoxide is replaced by hydrogen cyanide. This reaction precedes *via* aryl imine followed by treatment with water.



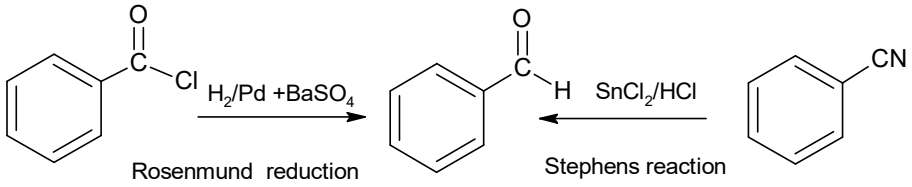
There is another interesting example of formylation reaction called Vilsmeier-Haack reaction. Activated aromatic compounds such as phenols, aryl ethers and aryl amines can be formylated by a mixture of *N,N*-dimethylformamide [$HCON(CH_3)_2$] and phosphorus oxychloride ($POCl_3$). The reaction involves electrophilic attack of a intermediate, chloroiminium ion [$(CH_3)_2N{=}CHCl$], which is formed by the reaction of *N,N*-dimethylformamide and phosphorus oxychloride. Hydrolysis of dimethyl imine gives final product.



v) By Rosenmund reduction and Stephens reaction

The Rosenmund reduction is controlled hydrogenation of acid halides in presence of a catalyst poison, $BaSO_4$ or quinoline/sulphur, which prevents over reduction to alcohols. In the Stephens reaction, a nitrile

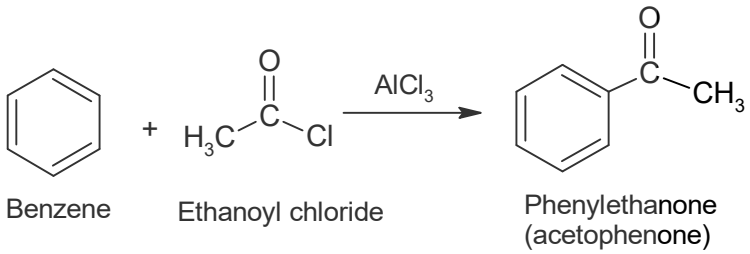
group is reduced by tin(II) chloride and HCl to imine salt which is hydrolysed to give benzaldehyde.



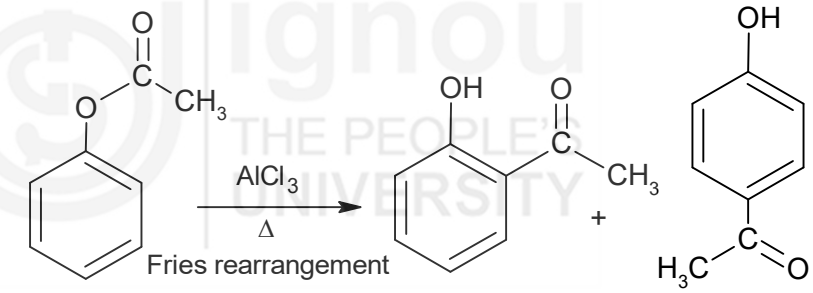
Acetophenone can be obtained by the following methods.

v) By the Friedel-Crafts Acylation Reaction

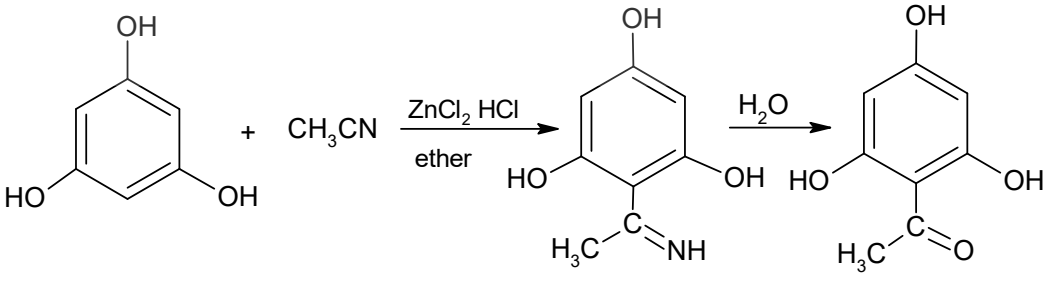
Aryl ketones can be prepared by Friedel-Crafts acylation reaction. For example, acetophenone is prepared as follows:



Phenolic aromatic ketones can be prepared by **Fries rearrangement** and **Hoesch reaction** or **Houben–Hoesch reactions**.



Hoesch reaction or Houben–Hoesch reaction is variation of Gattermann-Koch formylation. In this reaction, activated aromatic compounds such as dihydric and trihydric phenols can be acylated by reaction with acetonitrile in presence of a Lewis acid usually Zinc chloride and HCl. This reaction proceeds *via* formation of an iminium salt, which is isolated and subsequently hyrolysed.

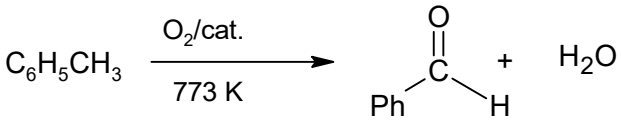


Houben-Hoesch reaction

Commercially benzaldehyde and acetophenone are preapared as follows:

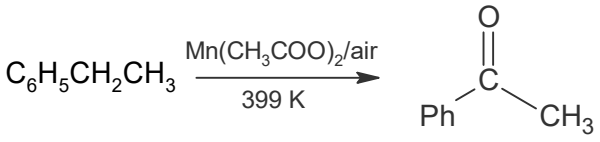
Benzaldhyde is prepared commercially by the oxidation of methylbenzene. This is done either in the vapour phase or in the liquid

phase. In the vapour phase oxidation, methylbenezene (toluene) vapours, mixed with air, are passéd over a catalyst, a mixture of oxides of manganese, molybdenum, ziroconium etc., heated to 773 K:



Liquid phase oxidation uses manganese dioxide and 65% suplhuric acid at 313 K.

Acetophenone is manufactured by the oxidation of ethylbenzene with air in the presence of manganese ethanoate as catalyst at 399 K:



SAQ 1

Benzaldehyde is obtained by the hydrolysis of:

a) methyl benzoate

b) (chloromethyl)benzene

c) (dichloromethyl)benzene

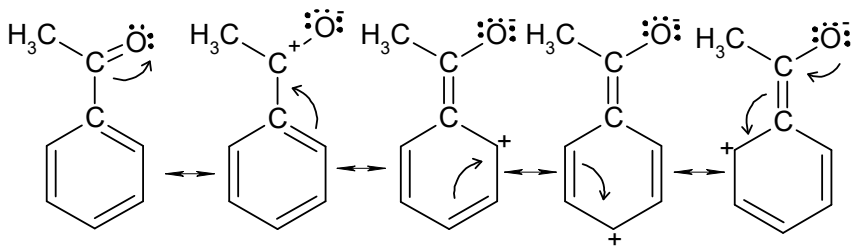
SAQ 2

How will you prepare 2,6-dihydroxyacetophenone from benzene-1,3-diol?

19.3 REACTIONS OF ARYL ALDEHYDES AND KETONES

The major differences between aromatic carbonyl compounds and most aliphatic analogues are that i) the carbonyl group of former reacts with nucleophile at a much slower rate ii) the aromatic ring of former also reacts with electrophile at a slower rate and iii) those reactions depending upon the presence of alpha hydrogen are not observed in the case of benzaldehyde.

The less reactivity of carbonyl group of aromatic aldehydes and ketones towards nucleophilic attack can be attributed to the resonance interaction between carbonyl group and aromatic ring.



Resonating structures of acetophenone

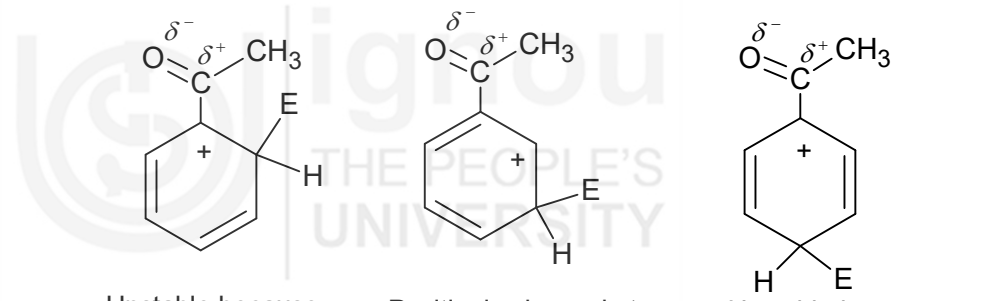
The result of this resonance interaction is

i) a weakening of the positive charge on the carbonyl carbon atom through dispersal of the charge into the ring, and

ii) deactivation of ring.

Because the carbon atom of carbonyl group attached to the ring is positively charged due to the electrongativity of oxygen atom, thus carbonyl group behaves as an electron withdrawing group and so it deactivates the ring towards electrophilic substitution reactions. As illustrated above, *ortho* and *para* positions have positive charges and the electron density at the *meta* position is not much affected by the carbonyl group. Therefore, the electrophiles preferably go to the *meta* position. Thus, both benzldehyde and acetophenone will form major *meta* disubstituted products and attack of electrophile will be slower than attack in benzene.

Formation of the major *meta* product can also be explained on the basis of the stability of the cyclohexadienyl cation intermediates formed on attack of electrophile. The intermediates for *ortho* and *para* substitution are particular unstable because each has a resonance structure in which there is a positive charge on the ring carbon that bears the electron-withdrawing substituent. Such situation is not observed in case of meta attack.



Unstable because of adjacent positively charged atoms

Positively charged atoms not adjacent, most stable intermrdiate

Unstable because of adjacent positively charged atoms

With the above general ideas, it will be easier to understand the reactions of aromatic aldehydes and ketones. Many of the reactions, which aliphatic aldehydes and ketones undergo, are also shown by aromatic aldehydes and ketones. In next sub-section, our focus mainly will be on the reactions, which show exceptional behaviors.

SAQ 3

Why are aromatic aldehydes and ketones less reactive than alphatic aldehydes and ketones for nucleophilic attack?

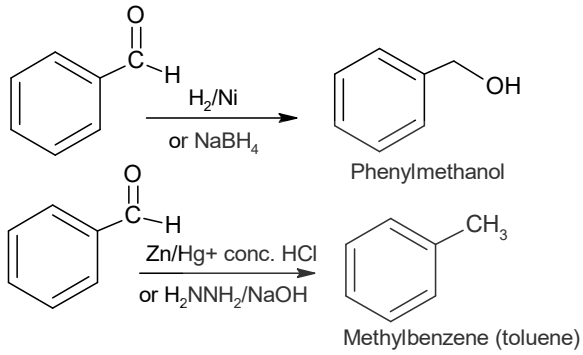
19.3.1 Benzaldehyde

Reactions of Aldehyde Group

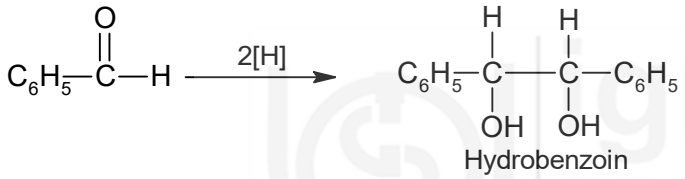
Even though the carbonyl group of benzaldehyde is less reactive than carbonyl group of aliphatic aldehydes, benzaldehyde gives many general reactions of aldehydes as described in previous unit. Benzaldehyde forms

many useful intermediate products with a range of nitrogen nucleophiles. Imines (Schiff bases) are formed with amines, hydrazones with hydrazines, semicarbazones from semicabazide and oximes from hyroxylamine. These products are of value in the synthesis of heterocycles.

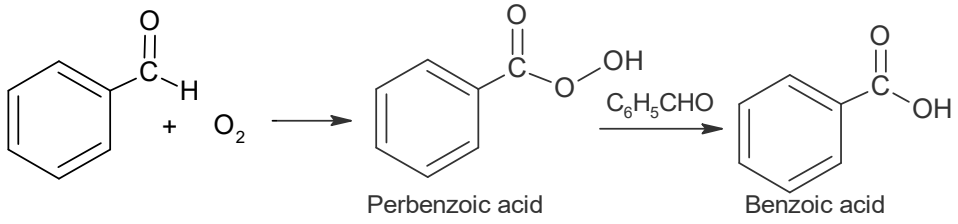
Catalytic hydrogenation and chemical reduction convert benzaldehyde to phenyl methanol (benzyl alcohol). On the other hand, Clemmension and Wolff-Kishnner reduction converts it into methylbenzene (toluene).



Benzaldehyde reacts with zinc and hydrochloric acid or with sodium amalgam and undergoes reductive dimerisation to give 1,2-diphenyl-1,2-ethanediol (hydrobenzoin):

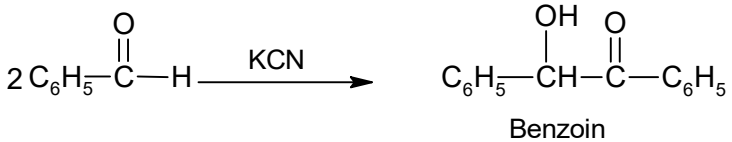


However, it does not reduce Fehling's solution but is easily oxidised by mild oxidising agents such as ammoniacal silver nitrate (Tollens' reagent). These two reactions are used to differentiate benzaldehyde from aliphatic aldehydes and ketones. Even atmospheric oxygen is enough to convert this to benzoic acid. When benzaldehyde is exposed to air, it forms a peroxide, perbenzoic acid, which oxidises another molecule of benzaldehyde as follows:

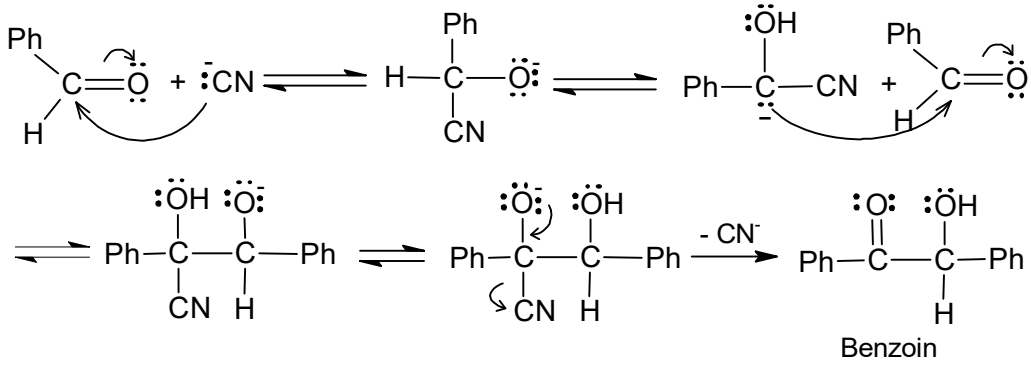


This type of oxidation, known as auto-oxidation, may be prevented by adding small amount of any antioxidant such as hydroquinone.

Formation of cyanohydrin from aromatic aldehydes and ketones with hydrogen cyanide is not a very useful reaction, but benzldehyde undergoes condensation reaction on refluxing with aqueous ethanolic potassium cyanide and forms benzoin. This condensation is known as **benzoin condensation**.



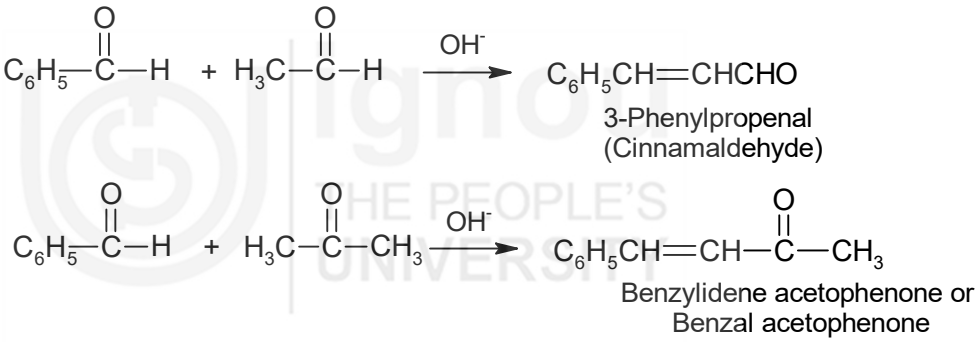
The mechanism of this condensation reaction is as follows:



Benzoin

As mentioned above, benzadehyde does not have an alpha hydrogen. Therefore, it cannot be enolised and therefore, enolate/carbanion cannot be generated from it. However, benzaldehyde can react with enlolates/carbanions generated from other aldehydes, ketones, esters, anhydrides, and so undergoes wide range of condensation reactions.

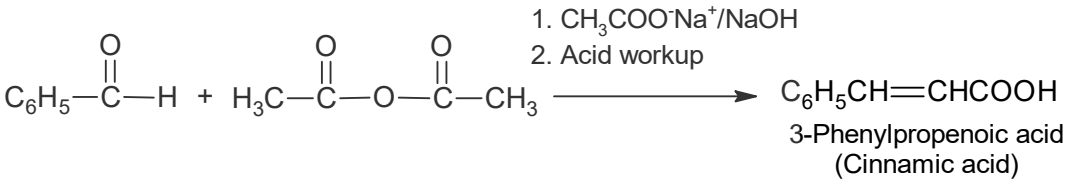
We have seen earlier that benzaldehyde undergoes mixed aldol condensation with aldehydes or ketones having α-hydrogen in the presence of alkali to form α, β-unsaturated carbonyl compounds. This reaction is also known as **Claisen-Schmidt reaction**.



3-Phenylpropenal
(Cinnamaldehyde)

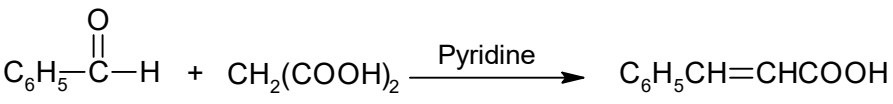
Benzylidene acetophenone or
Benzal acetophenone

On treatment with ethanoic anhydride and sodium ethanoate, benzaldehyde gives 3-phenylpropenoic acid (cinnamic acid). This condensation is known as **Perkin reaction**.



3-Phenylpropenoic acid
(Cinnamic acid)

Benzaldehyde also gives 3-phenylpropenoic acid with propanedioic acid (malonic acid) in the presence of pyridine. This reaction is known as **Knoevenagel condensation**.

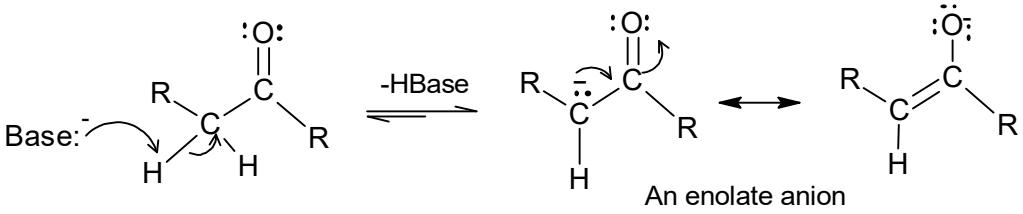


3-Phenylpropenoic acid
(cinnamic acid)

Mechanistically, both the named reactions discussed above proceed by a common pathway involving four steps:

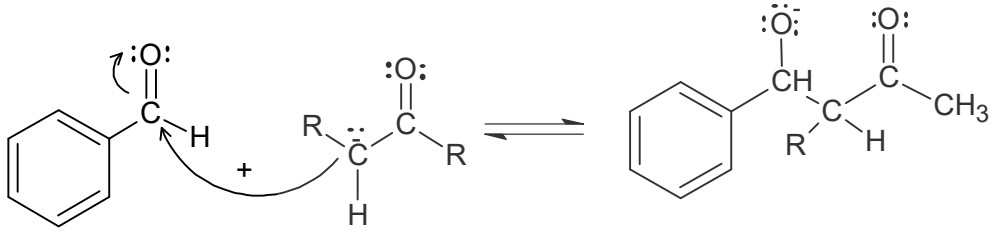
Step 1

Generation of a carbanion: Carbonyl compounds having active α-hydrogen generate the resonance-stabilised enolate anion on reaction with a base.



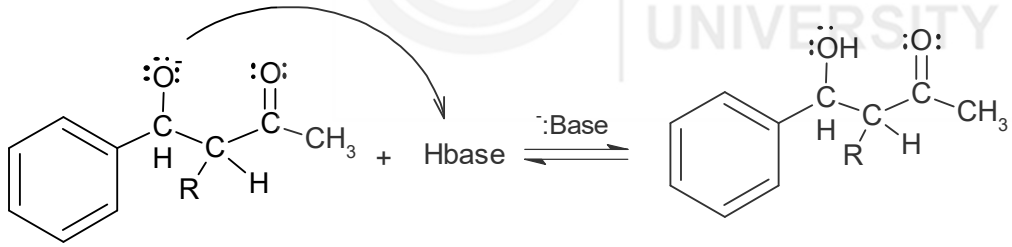
Step 2

Making a new C−C bond between a nucleophile and an electrophile: Nucleophilic addition of the enolate anion to the carbonyl carbon of benzaldehyde gives addition intermediate, oxyanion.



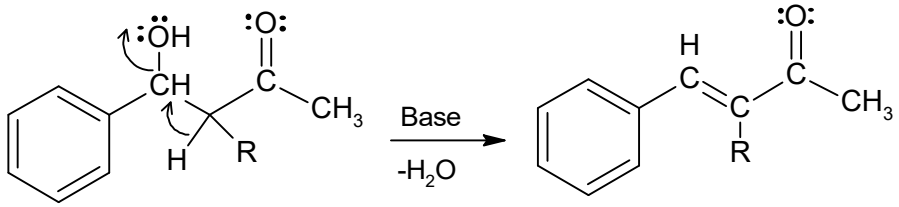
Step 3

Protonation of the oxyanion formed in the previous step: Reaction of the oxyanion intermediate with a proton donor gives the aldol product and generate a new base catalyst.

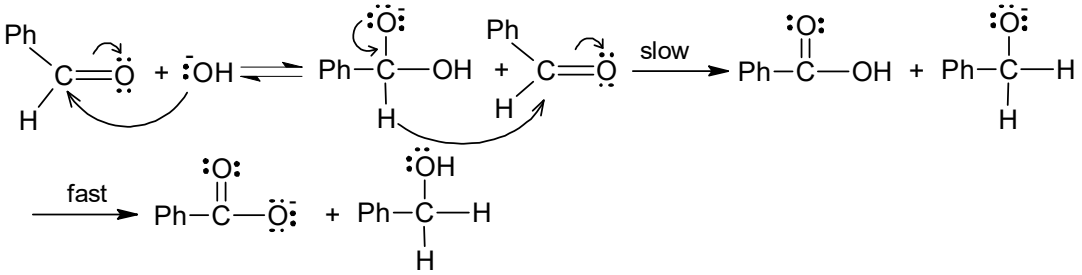


Step 4

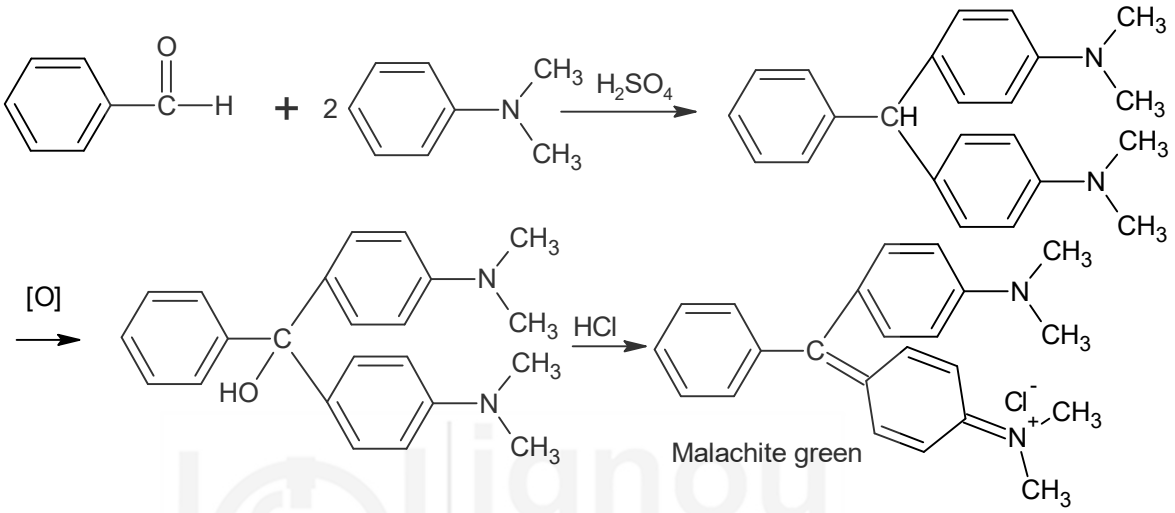
Dehydration of the aldol product: In such aldol condensation reactions, dehydration of the aldol product is rapid, which leads to formation of the more thermodynamically sable *α,β*-unsaturated product and prevent the retroaldol reaction from taking place.



Benzaldehyde undergoes Cannizzaro reaction as discussed with formaldehyde, in which two molecules of benzaldehyde react to produce one molecule of benzoic acid one molecule of benzyl alcohol as per scheme given below:



Condensation of benzaldehyde with phenols or tertiary aromatic amines in the presence of dehydrating agents, H_2SO_4 or $ZnCl_2$, gives triphenyl derivatives. Oxidation with lead dioxide followed by treatment with hydrochloric acid gives a dye, e.g.,



SAQ 4

How the following conversion can be carried out?

a) Benzoic acid from benzaldehyde

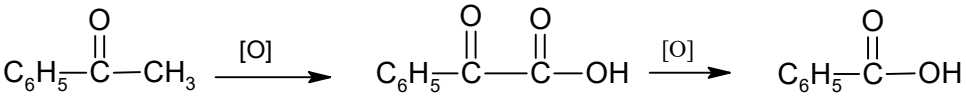
b) Benzyl alcohol from benzadehyde

c) toluene from benzaldehyde

19.3.2 Acetophenone

Acetophenone undergoes typical reactions of ketones, e.g., reduction with sodium and ethanol gives phenylethanol, Clemensen's reduction gives ethyl benzene. It undergoes addition reaction with hydrogen cyanide, hydroxylamine, etc. in the manner expected of a ketone, but because of low reactivity of the carbonyl group, acetophenone does not react with saturated aqueous sodium sulphate.

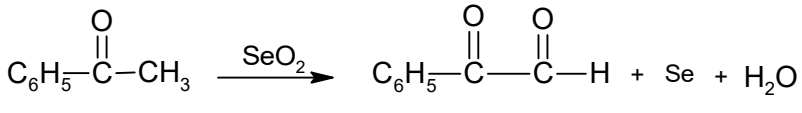
It is oxidised by cold potassium permanganate to give phenyl-2-oxoethanoic acid (phenyl glyoxolic) acid which gets further oxidised to benzoic acid:



Phenyl-2-oxoethanoic acid (Phenyl glyoxalic acid)

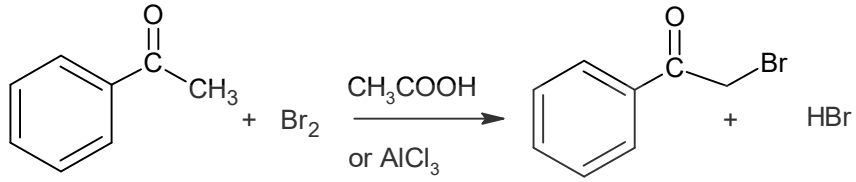
Benzoic acid

Oxidation with selenium dioxide gives phenyl-2-oxoethanal:



Phenyl-2-oxoethanal
(Phenyl glyoxal)

Acetophenone undergoes *α*-halogenation like aliphatic methyl ketones as illustrated by acid catalysed bromination of acetophenone.

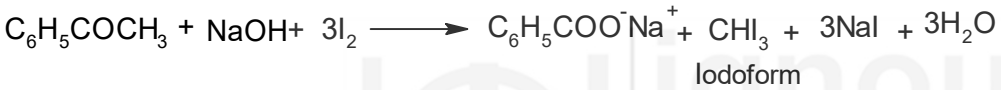


α–Bromoacetophenone
(2-bromo-1-phenylethanone)

On treatment with bromine in ether at 273 K in the presence of aluminium chloride, used as a catalyst, it also gives phenyl-1-bromo-2-ethanone (phenacyl bromide):

2-Chloro-1-phenylethanone is used as riot control agent (tear gas).

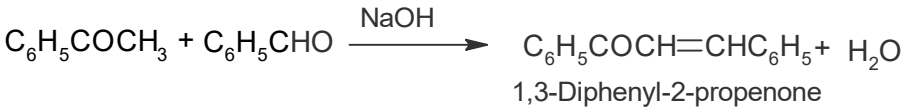
Acetophenone also undergoes iodoform reaction with iodine.



Iodoform

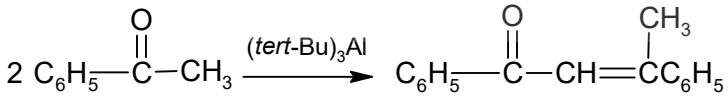
If we use one equivalent of aluminium chloride and bromine is added after the formation of aluminum chloride complex with acetophenone, nuclear bromination is taken place and major product will be 3'-bromoacetophenone.

The methyl group in acetophenone is adjacent to a carbonyl group. Therefore it can form stable carbanion/enolate and takes part as nucleophile in addition reaction and condensation reactions similar to aliphatic ketones.



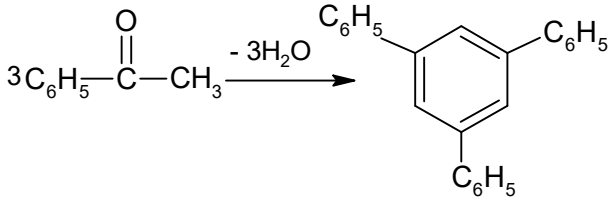
1,3-Diphenyl-2-propenone
(Chalcone)

Two molecules of acetophenone can also condense together in the presence of aluminium *tert* -butoxide to give 1,3 diphenyl-2-buten-1-one(dypnone):

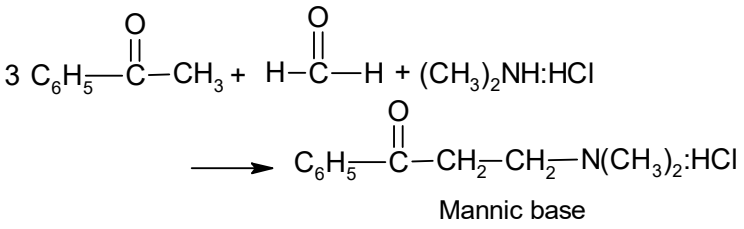


1,3-Diphenyl-2-buten-1-one
(Dypnone)

Condensation in the presence of hydrochloric acid forms 1,3,5-triphenylbenzene:



Acetophenone reacts with methanal (formaldehyde) and ammonia or a primary or secondary amine (as hydrochloride) to give ketoamines called Mannich bases. This reaction is called the **Mannich reaction**, e.g.,

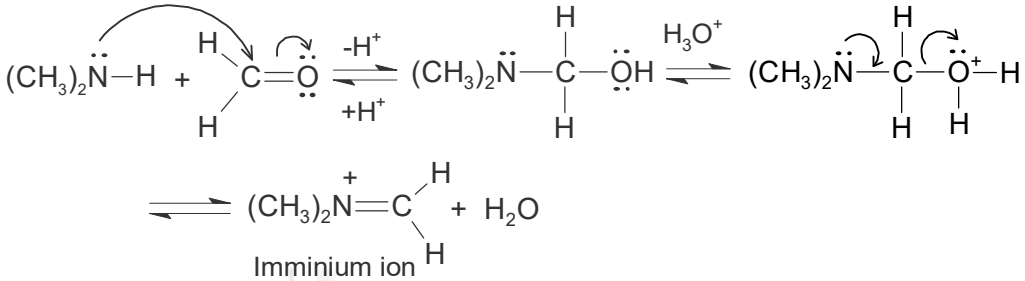


Mannic base

Mechanism of Mannich reaction:

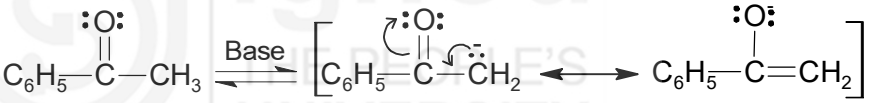
Three steps are involved in the Mannich reaction: Step 1: formation of Imminium ion, Step 2: formation of carbanion and Step 3: attack by carbanion.

Step 1: Formation of imminium ion

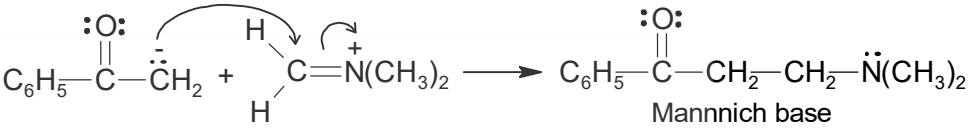


Imminium ion

Step 2: Formation of carbanion

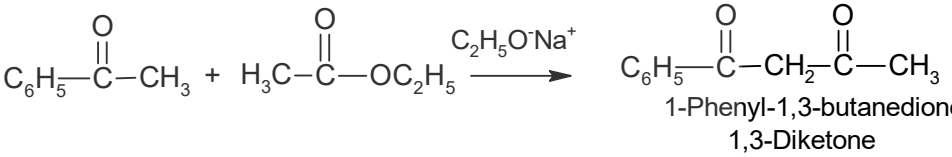


Step 3: Attack by carbanion



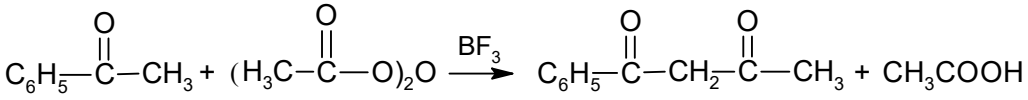
Mannnich base

1, 3-Diketones are formed from acetophenone by condensation either with ethyl ethanoate in the presence of sodium ethoxide or with ethanoic anhydride in the presence of boron trifluoride:



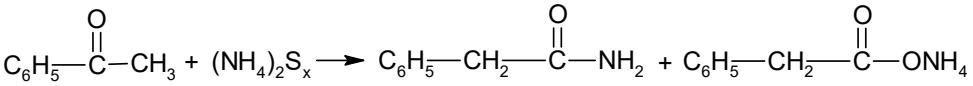
1-Phenyl-1,3-butanedione

1,3-Diketone



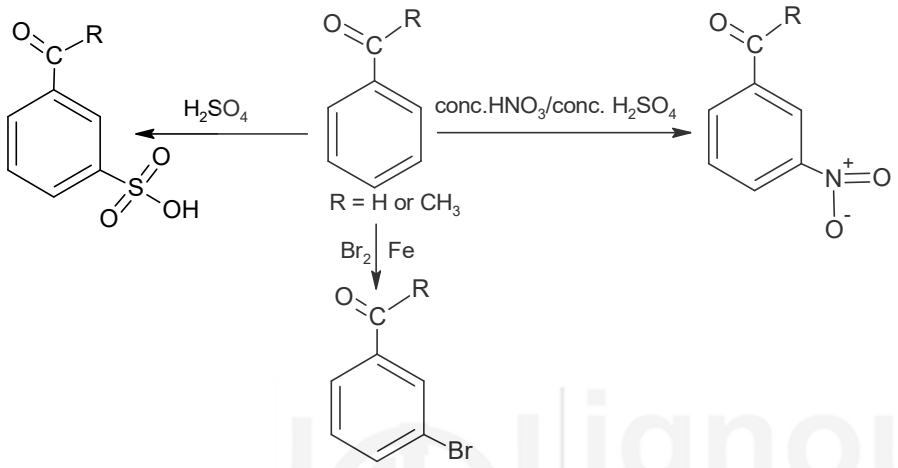
1,3-Diketone

By heating acetophenone with aqueous yellow ammonium polysuplhide, phenylethanamide and ammonium phenylethanoate are obtained (**Willgerodt reaction**):



19.3.3 Reactions due to the Benzene Ring

As we mentioned earlier, the carbonyl group is a deactivated in electrophilic aromatic substitution reactions and directs substitution to the *meta* positions. Therefore, benzaldeyde and phenylethanone are less reactive towards electrophilic substitution reactions than the benzene. Nitration and sulphonation are possible, but care must be taken to avoid interaction with the carbonyl group. Dilute nitric acid brings about oxidation of the –CHO group of benzaldehyde. Strong concentrated nitric and sulphuric acids are normally used in nitration reactions. As discussed above, ring halogenations depend on the reaction condition used. Both benzadehyde and acetophenone do not undergo Friedel-Craft reaction.



SAQ 5

Complete the following reactions:

a) $C_6H_5COCH_3 + C_6H_5CHO \xrightarrow{NaOH}$

b) $C_6H_5CHO + KCN$

c) $C_6H_5COCH_3 + CH_3COOC_2H_5 \xrightarrow{C_2H_5ONa}$

d) $C_6H_5COCH_3 + HCl \longrightarrow$

19.4 SUMMARY

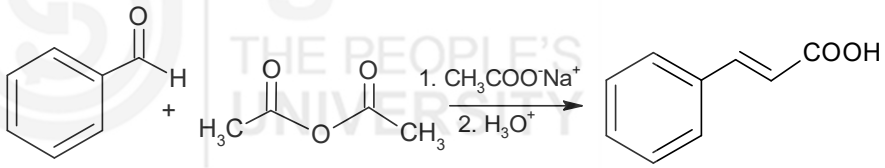
In this unit we have described the chemistry of aromatic aldeydes and ketones. We are summarising below what we have studied:

- Benzaldehyde can be prepared by the hydrolysis of (dichloromethyl) benzene and by the oxidation of toluene with chromium trioxide in acetic anhydride. It can also be prepared by direct formylation of benzene usimg several methos such as Gattermann-Koch reaction, Gattermann synthesis, Vilsmeier-Haack reaction, etc. Benzaldehyde can also be obtained from benzoic acid using Stephens reaction and from benzoyl chloride using Rosenmund reduction.
- Acetophenone can be prepared by the Friedel-Crafts acylation, Fries rearrangement and Hoesch reaction.

- Because of the resonance effect necleophilic reactions of the carbonyl group of benzaldehyde and acetophenone take place at a slower rate. Carbonyl group being an electron withdrawing group, it deactivate the benzene ring and the electrophile will preferably attack on *meta* positions of the ring.
- Benzaldehyde undergoes several types of condensation reactions and forms many useful synthetic intermediates, for example: Benzoin condensation, Claisen-Schmidt reaction, Perkin reaction, and Knoevenagel reaction.
- Acid catalysed bromination of acetophenone, brominates side chain. With methanal (formaldehyde) and ammonia or a primary or secondary amine (as hydrochloride), acetophenone undergoes Mannich reaction and forms Mannich base.

19.5 TERMINAL QUESTIONS

1. Write the steps involved in Sommelet reaction.
2. Draw resonating structures for the resonance-stabilised cation intermediates formed by attack of a nucleophile on *ortho, para* and *meta* position to carbonyl group of benzaldehyde.
3. Explain why is carbonyl group is meta directing?
4. Propose a reasonable mechanism for the following conversion.

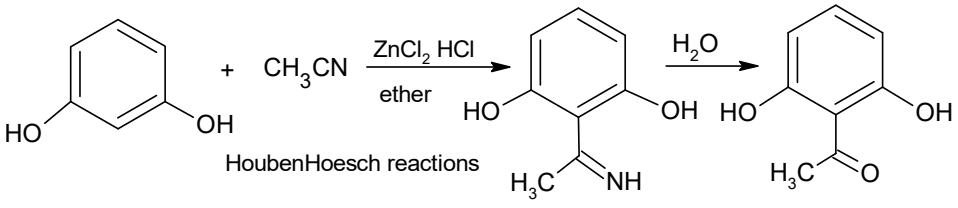


5. How will you bring about following conversions?
   a) Benzaldehyde to cinnamaldehyde
   b) Benzaldehyde to cinnamic acid
   c) Acetophenone to dypnone
   d) Acetophenone to 1,2,3-triphenylbenzene
   e) Acetophenone to 1-Phenyl-1,3-butanedione

19.6 ANSWERS

Self-Assessment Questions

1. c)
2.



3. A weakening of the positive charge on the carbonyl carbon atom through dispersal of the charge into the ring through resonance effect is mainly responsible for the lesser reactivity of aromatic aldehydes and ketones than alphatic aldehydes and ketones for nucleophilic attack.

4. a) By oxidation methods. Benzaldehyde can easily be converted to acid even with mild oxidizing agents.

   b) By the catalytical hydrogenation or chemical reduction using Lithium aluminium hydride or sodium borohydride.

   c) By Clemmension reduction or Wolff-Kishner reduction method.

5. a) $C_6H_5COCH_3 + C_6H_5CHO \longrightarrow C_6H_5COCH_2{=}CHC_6H_5$

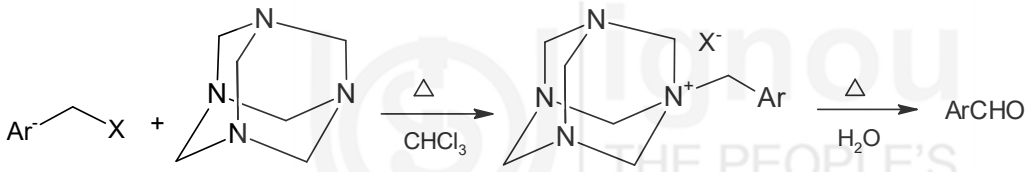
   b) $C_6H_5CHO + KCN \longrightarrow C_6H_5\underset{\displaystyle OH}{\underset{|}{C}}HCOC_6H_5$

   c) $C_6H_5COCH_3 + CH_3COOC_2H_5 \xrightarrow{C_2H_5ONa} C_6H_5COCH_2COCH_3$

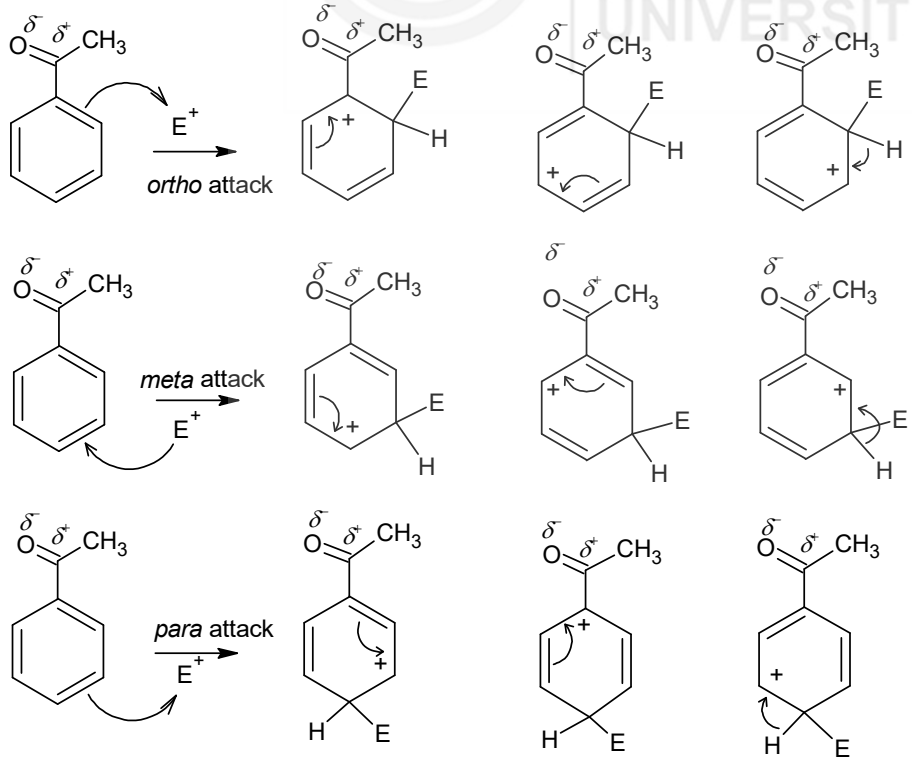
   d) $C_6H_5COCH_3 + HCl \longrightarrow$ 1,3,5-triphenylbenzene

Terminal Questions

1.



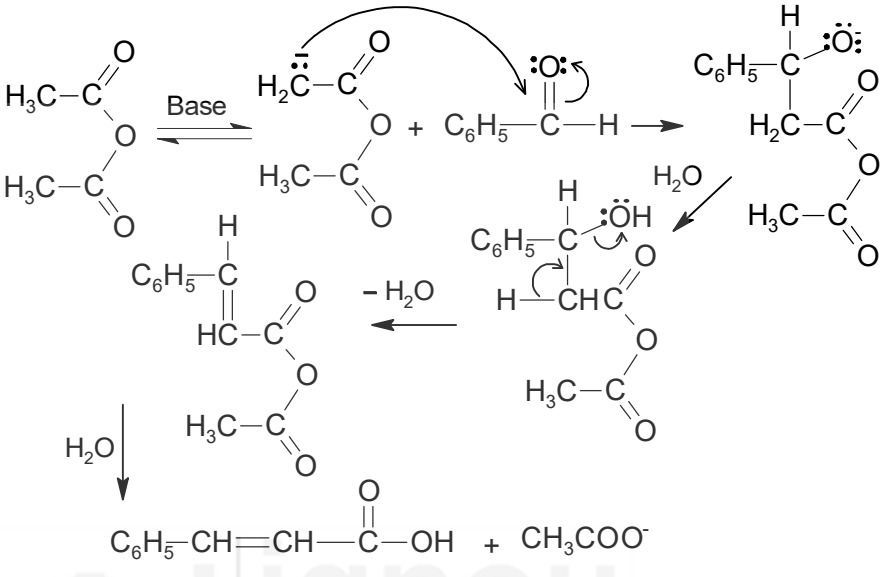
2.



3. The resonace structures drawn for the intermediates formed on ortho , para and meta attack of electophile, clearly indicate that the intermediates for ortho and para substitutions are particular unstable

because each has a resonance structure in which there is a positive charge on the carbon that bears the electron-withdrawing substituent. Such situation is not observed in case of meta attack.

4. Five steps are involved in this reaction: Step 1: Formation of carbanion Step 2: Attack by carbanion on the aromatic carbonyl compound to form alkoxide, Step 3: protonation of the alkoxide ion to form an aldol type compound. Step 4: dehydration, the hydroxyl group and neighbouring hydrogen are removed as water and Step 5: hydration



5. a) $C_6H_5CHO + CH_3CHO \xrightarrow{OH^-} C_6H_5CH{=}CHCHO$

3-Phenylpropenal
(cinnamaldehyde)

b) $C_6H_5CHO + (CH_3CO)_2O \longrightarrow C_6H_5CH{=}CHCOOH$

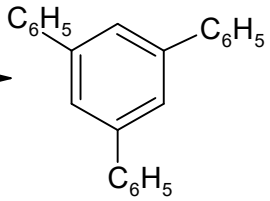
3-Phenylpropenoic acid
(cinnamic acid)

$C_6H_5CHO + CH_2(COOH)_2 \xrightarrow{\text{Pyridine}} C_6H_5CH{=}CHCOOH$

3-Phenylpropenoic acid
(cinnamic acid)

c) $2\ C_6H_5COCH_3 \xrightarrow{(tert\text{-}Bu)_3Al} C_6H_5COCH{=}CC_6H_5$

Dypnone

d) $3\ C_6H_5COCH_3 \xrightarrow{-3H_2O}$ 

e) $C_6H_5COCH_3 + H_3CCOOC_2H_5 \xrightarrow{C_2H_5O^-Na^+} C_6H_5COCH_2COCH_3$

1-Phenyl-1,3-butanedione
1,3-Diketone

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Notes

MPDD/IGNOU/P.O. 16.5K/December, 2019

BCHCT-133 CHEMICAL ENERGETICS, EQUILIBRIA AND FUNCTIONAL ORGANIC CHEMISTRY-I Vol. 2

ISBN : 978-93-89668-67-4