→ Phenols :→

– Introduction:→

– Phenol are compounds containing hydroxyl group (–OH) directly attached to an aromatic ring.

– The term phenol is commonly used in the context of hydroxybenzene.

– Phenol is also known as carbolic acid in pharmacy.

– Phenol is a liquid at room temperature when contaminated with a little water.

– It was the first chemical to be used as an antiseptic in 1857 (Joseph Lister).

– It is also used as raw material in the manufacture of synthetic polymers.

– A number of phenols and phenolic ethers occur in nature –

(i) Salicylic acid occurs in willow tree.

(ii) Methyl salicylate or oil of wintergreen occurs in liminents.

(iii) Acetylsalicyclic acid (Aspirin) is a analgesic and antipyretic drug.

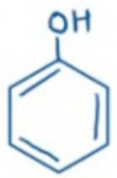
(iv) Thymol is found in thyme and is widely used in mouthwash because of its flavour and antiseptic property.

(v) Clove oil contain, eugenol which is used as an antiseptic.

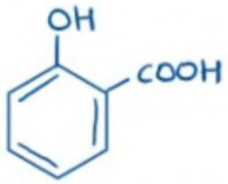
– Certain phenolic compounds are known for their specific physiological actions.

(i) poison ivy (irritants) are 1,2- dihydroxy benzene derivative.

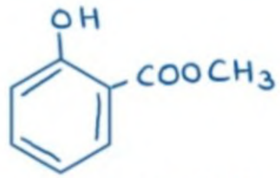
(ii) Tetrahydrocannabinol is found in intoxicant marijuana.



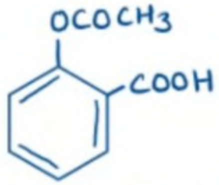
Phenol
(carbolic acid)



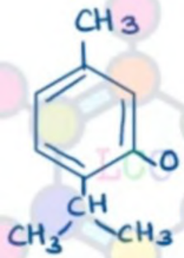
Salicyclic acid



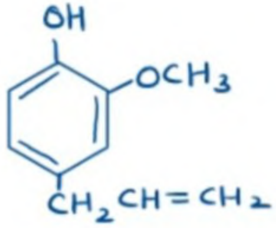
Methyl salicylate



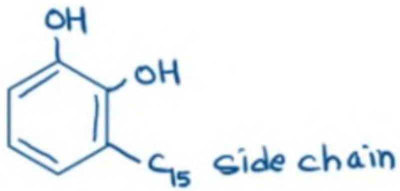
Acetylsalicylic acid
(Aspirin)



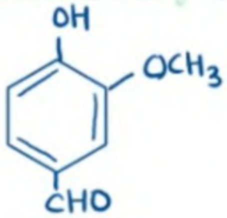
Eugenol



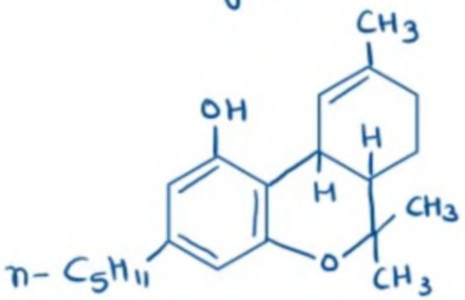
Thymol



Poison ivy irritants



Vanilin



(−) − Tetrahydrocannabinol

→ Phenols:-

- Nomenclature:-

- Phenols are hydroxy derivatives of aromatic (benenoid) compounds.
- General formula is Ar-OH.
- Depending upon the number of hydroxy groups, phenols are classified as-

  Monohydric phenols → one -OH group
  Dihydric phenols → two -OH groups
  Trihydric phenols → three -OH groups
  Polyhydric phenols → more than three -OH groups

- Following two systems are used for nomenclature of phenols-

(i) Common system:-

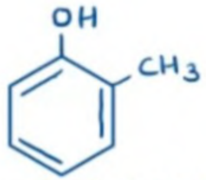
- A number of phenols are assigned special name, while others are named as derivatives of these substances.

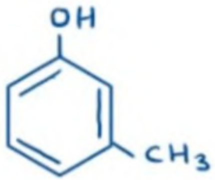
(ii) IUPAC system:-

- In this system the simplest phenol is called benzenol but all substituted phenols are named as derivatives of phenol.
- The numbering started from carbon atom bearing -OH group and substituents are numbered in such a way that they get lowest numbers.

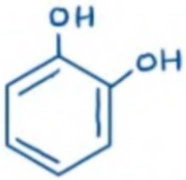
- Dihydric, trihydric and polyhydric phenols are named as benzenediols, benzenetriols and benzenepolyols respectively. These names are also written as hydroxy derivatives of benzene. However they are better known by their trivial names (In parenthese).

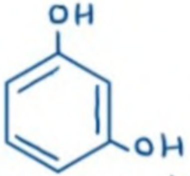

Benzenol
(Phenol)

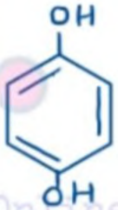

2-Methylphenol
(o-Cresol)

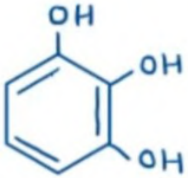

3-Methylphenol
(m-Cresol)

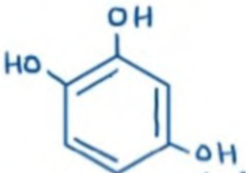

4-Methylphenol
(p-Cresol)

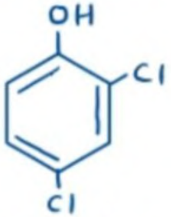

1,2-Benzenediol
or 1,2-dihydroxybenzene
(Catechol)

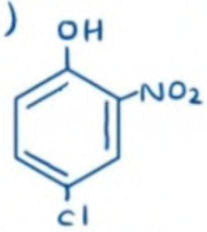

1,3-Benzenediol
or 1,3-dihydroxybenzene
(Resorcinol)

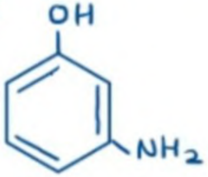

1,4-Benzenediol
or 1,4-dihydroxybenzene
(Phloroglucinol)


1,2,3-Benzenetriol
or 1,2,3-trihydroxybenzene
(Pyrogllol)

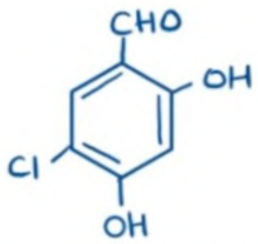

1,2,4-Benzenetriol
or 1,2,4-trihydroxybenzene
(Hydroxyquinol)


2,4-dichlorophenol

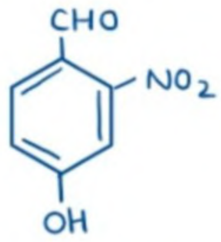

4-chloro-2-nitrophenol


3-Aminophenol
(m-Aminophenol)

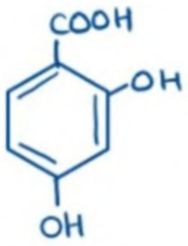
- If functional groups such as carboxylic acid, ester or carbonyl group is present in addition to phenolic group, the phenols are named as hydroxy derivatives of these compounds. The common names of these compounds are retained as root names.



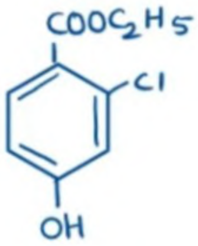
5-chloro-2,4-dihydroxybenzaldehyde



4-Hydroxy-2-nitrobenzaldehyde



2,4-dihydroxybenzoic acid
(β- Resorcylic acid)



Ethyl-2-chloro-4-hydroxybenzoate

→ Phenols :→

- Structure and bonding :-

- In phenols, the C–O bond is formed by the overlap of sp^2- orbital of carbon of benzene ring with a sp^3- orbital of oxygen atom.
- The O–H bond is formed by the overlap of second sp^3- orbital of oxygen with 1s orbital of hydrogen. The remaining two non-bonding sp^3- orbitals of oxygen atom contain lone-pairs of electrons

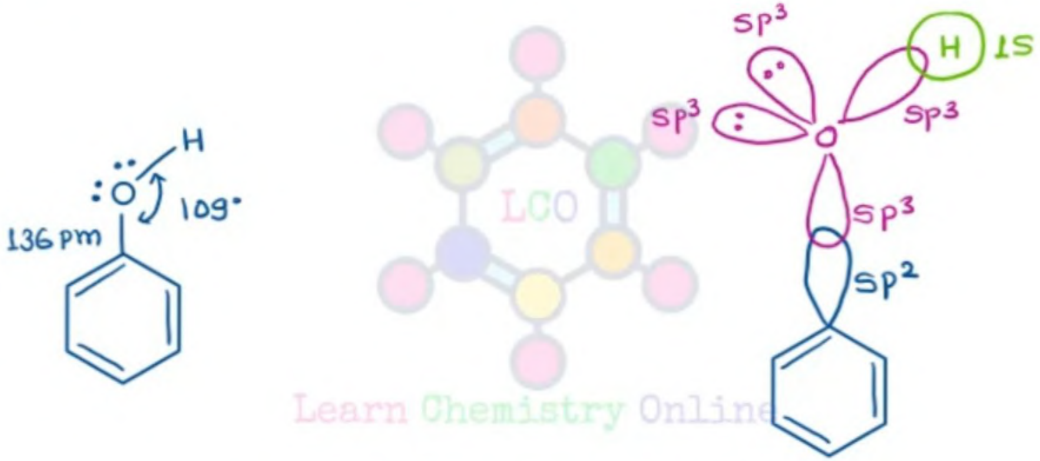
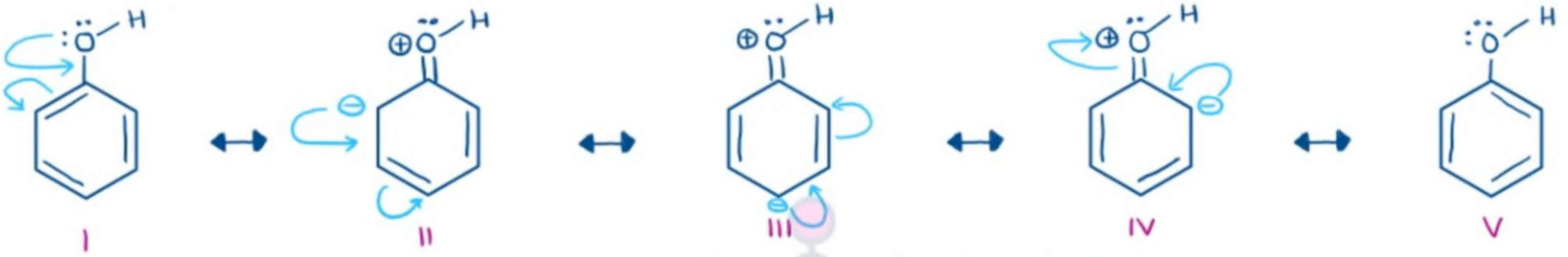


fig:- structure of phenol

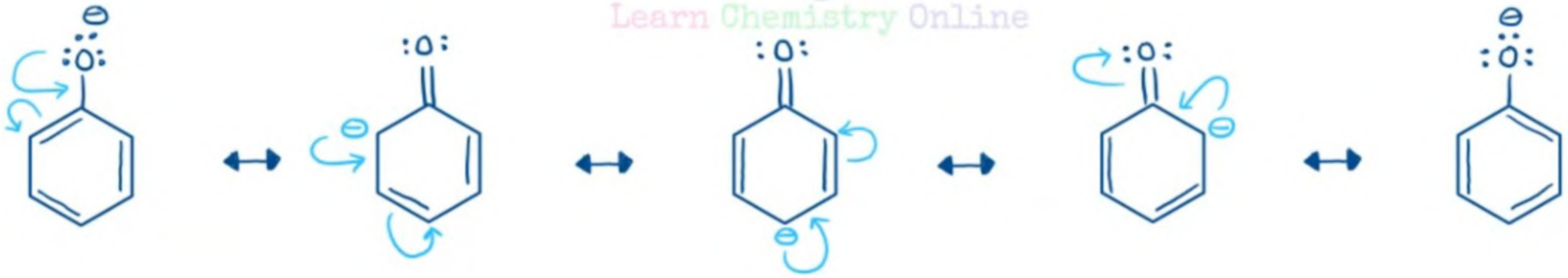
- Due to higher electronegativity of oxygen atom, phenol molecule is dipolar in nature with the oxygen carrying partial negative charge. Due to this dipolar nature, phenols form H-bonds.
- Dipole moment of phenol (1.54 D) is less than that of methanol (1.71 D). because C–O bond in phenol is less polar due to electron withdrawing effect of the benzene ring while in methanol, C–O bond is more polar due to electron donating effect of methyl group.

- The phenol molecule can not be represented by any single valence bond struture. In fact, it is considered as hybrid of the following contributing forms-



Resonating structures of phenol

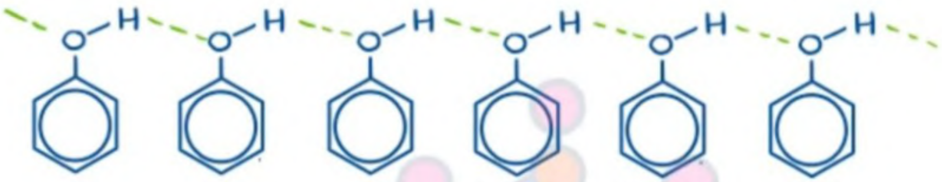
- A study of the contributing forms II, III and IV clearly shows that the oxygen atom aquire positive charge due to resonance. This polarility facilitates release of proton and formation of phenoxide ion which is also stabilised by resonance.



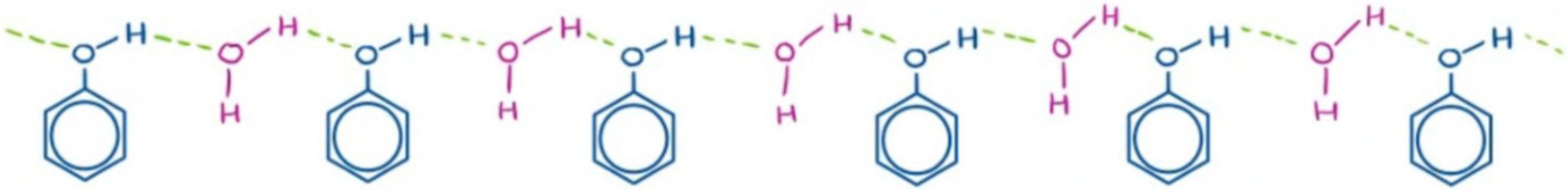
→ Hydrogen bonding in phenols:-

(i) Intermolecular hydrogen bonding:-

- Due to presence of intramolecular hydrogen bonding, phenols exist as polymeric aggregates. This aggregates break up on dilution with non-polar solvents

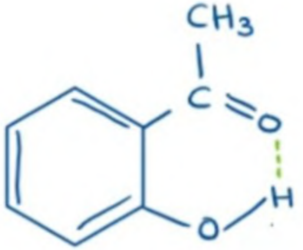


- Boiling point of phenol is higher as compared to toluene (comparable mol. wt.). This is due to intermolecular H-bonding in phenol which causes aggregation of molecule while toluene does not form H-bond.
- Phenol is somewhat soluble in water because it forms cross intermolecular hydrogen bonding with water.

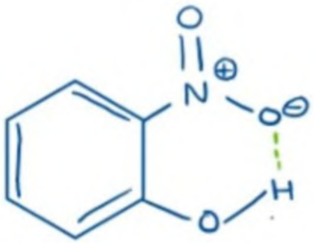


(ii) Intramolecular hydrogen bonding:-

- Phenol containing, carbonyl or nitro group at ortho position forms this type of hydrogen bonding.



o-hydroxyacetophenone



o-nitrophenol

- This type of bonding also alters the physical and chemical properties of these molecules.

→ Phenols:→

→ Methods of formation:→

1. From coal tar:→

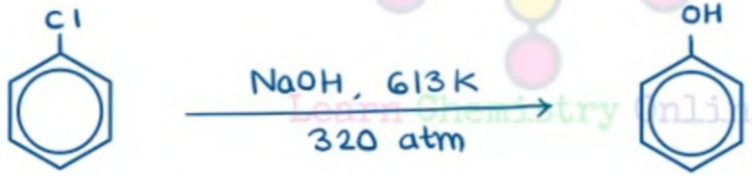
- Phenol is obtained from middle oil fraction (443 - 513K) of coal-tar consists of phenol and cresol in addition to other compounds.

Middle oil $\xrightarrow{\text{Alkali}}$ Alkaline layer separated $\xrightarrow[\text{bubbled}]{CO_2 \text{ is}}$ Phenolic mixture → Fractional distillation

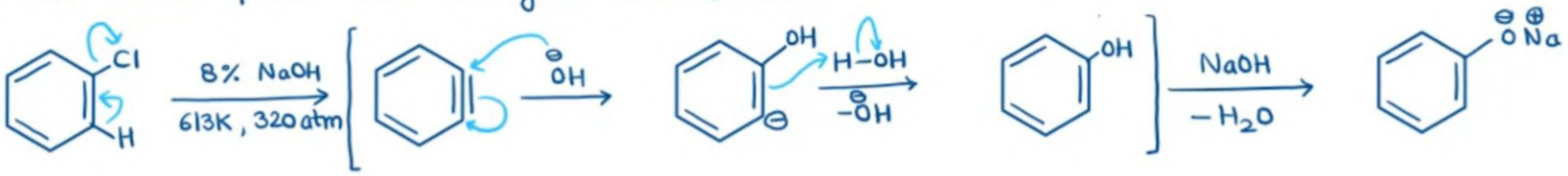
pure phenol ←┘

2. From halobenzene : Dow process :-

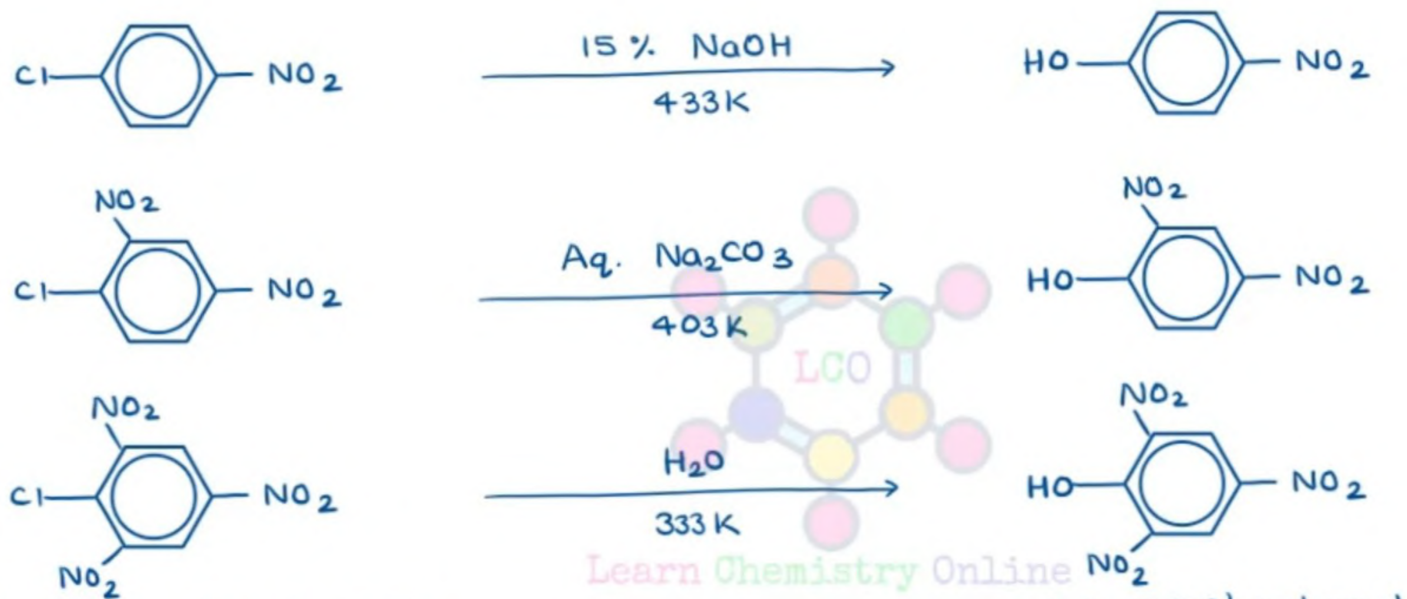
- This method is used for commercial production of phenol and was first developed by Dow Chemicals, USA in 1928.



- This reaction takes place via benzyne mechanism.



- If halobenzene has a strong electron-withdrawing substituent at ortho- or para- position, the hydrolysis of these compounds becomes easier. Thus the reaction requires milder conditions.

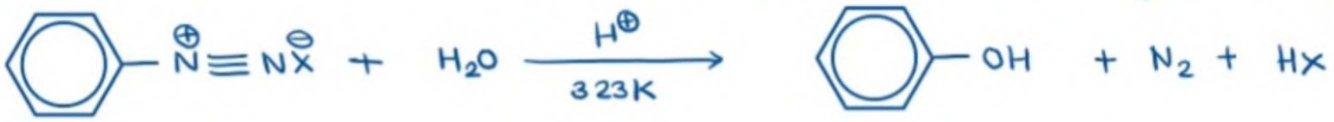


2,4,6 - Trinitrochlorobenzene
(Picryl chloride)

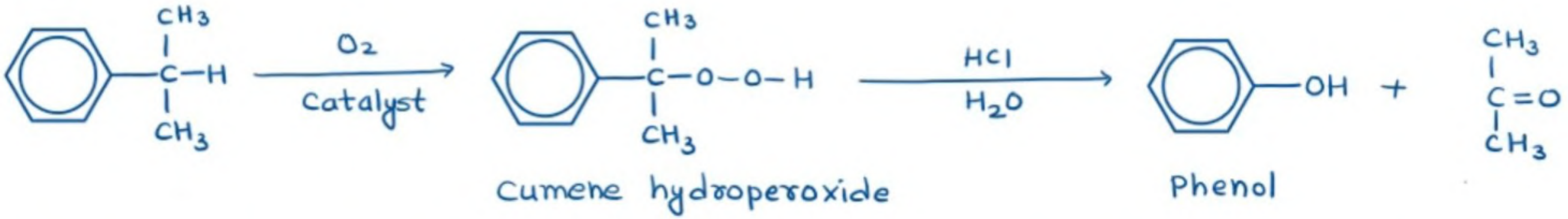
2,4,6 - Trinitrophenol
(picric acid)

3. From diazonium salt :-

- Reaction of diazonium salt with warm 50%. H_2SO_4 at 323 K gives phenol



4. From isopropylbenzene (cumene):→



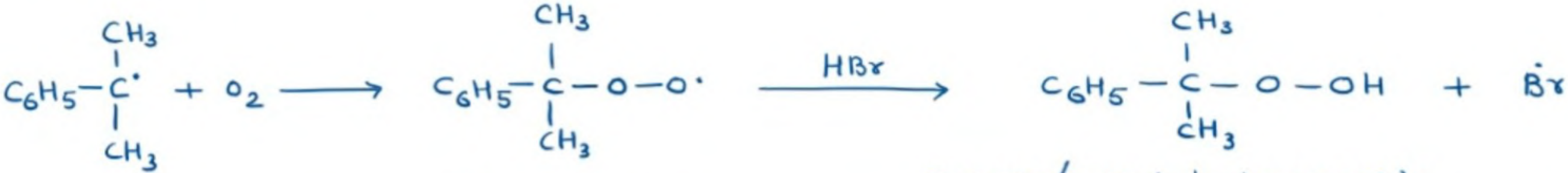
- This reaction is an example of autooxidation and carried out at 423K in the presence of hydrogen bromide as catalyst.
- This reaction takes place by a free radical mechanism.
- Initiation :-

$H-Br + O_2 \longrightarrow \dot{Br} + HOO^{\cdot}$

Hydroperoxide radical ,

$C_6H_5-C(CH_3)_2-H + \dot{Br} \longrightarrow C_6H_5-\dot{C}(CH_3)_2 + HBr$

- Propagation:-

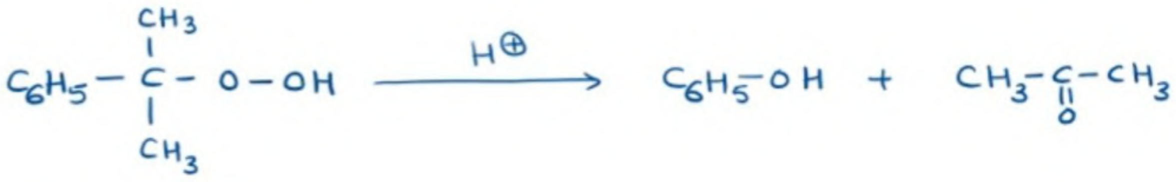


$C_6H_5-\dot{C}(CH_3)_2 + O_2 \longrightarrow C_6H_5-C(CH_3)_2-O-O^{\cdot} \xrightarrow{HBr} C_6H_5-C(CH_3)_2-O-OH + \dot{Br}$

Peroxy radical

cumene/cumyl hydroperoxide

- The cumyl hydroperoxide so obtained is treated with acid to form phenol. This reaction is called cumyl hydroperoxide rearrangement.



$$C_6H_5-\underset{CH_3}{\overset{CH_3}{C}}-O-OH \xrightarrow{H^\oplus} C_6H_5-OH + CH_3-\underset{O}{\overset{}{C}}-CH_3$$

5. From sulphonic acids:-

- Alkali metal salts of sulphonic acid react with NaOH or KOH to give phenol.

$$\underset{\text{Benzene sodium Sulphonate}}{ArSO_3^{\ominus}Na^{\oplus}} + NaOH \xrightarrow[-Na_2SO_3]{573K\,(fuse)} \underset{\text{phenoxide ion}}{Ar-O^{\ominus}} \xrightarrow{H^+} \underset{\text{phenol}}{Ar-OH}$$

→ Phenols :→

→ Physical properties:→

1. Physical state:-

- Most of the simpler monohydric phenols are either liquids or low melting solids.
- Pure phenols are colourless but they usually turn reddish brown due to atmospheric oxidation.

2. Melting and boiling points:-

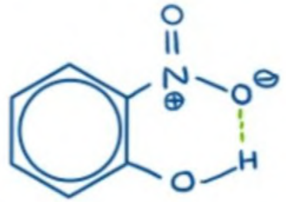
- Phenols, nitrophenols and aminophenols having more than one hydroxyl group have relatively higher melting and boiling points. This is probably due to the increased polar character resulting in higher degree of association involving intermolecular hydrogen bonding.
- In general phenols are more polar than cycloalkanols having similar carbon skeletons. Due to this phenols have higher m.p and b.p. than cycloalkanols.

	Phenol	Cyclohexanol
m.p.	316 K	298 K
b.p.	454 K	434 K

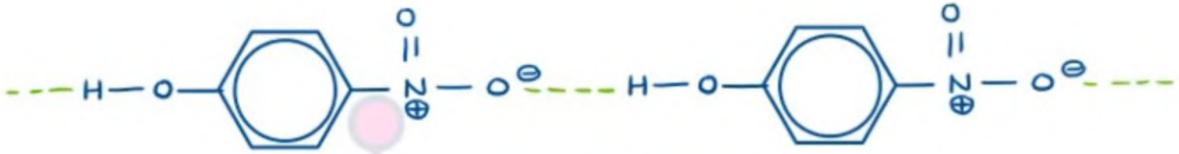
3. Solubility:-

- The solubility of phenol is more than that of the cyclohexanol. This difference can be attribute to the fact that the phenolic –OH is more polarised than alcoholic –OH group because of the resonance involving benzene ring in the case of the phenol.

- In case of isomeric fluoro- and nitrophenols, the ortho- isomers have lower melting points, boiling points and water solubilities and are weaker acids than the corresponding meta- and para- isomers. This is due to intramolecular hydrogen bonding in case of ortho- isomers and inter molecular hydrogen bonding in case of meta- and para- isomers.



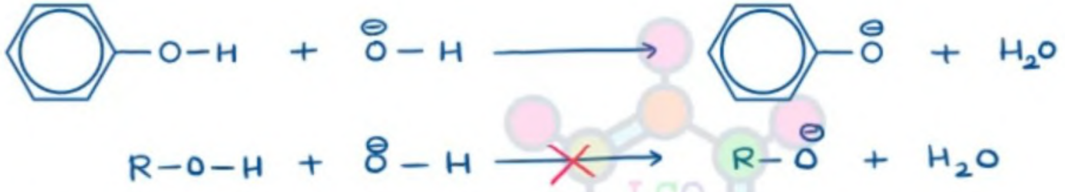
o-nitrophenol
(Intramolecular H-bond)



p-nitrophenol
(Intermolecular H - bond)

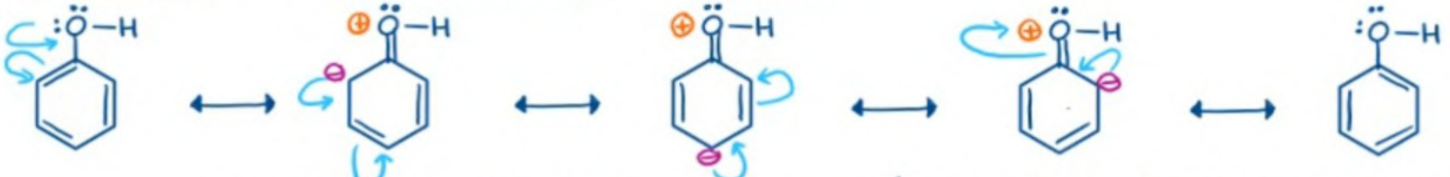
→ Acidic characters of Phenol :→

- Both phenols and alcohols contain an -OH group and due to difference in electronegativities of oxygen and hydrogen, both types of compounds show acidic characters.
- Phenols are more acidic than alcohols. The difference in acidic character can be idedified on the basis of reaction with alkali. Phenol forms phenoxide salt when reacts with alkali whereas alcohols do not react under these conditions.



- Explanation for greater acid strength of phenols than alcohols:-
- Alcohols neither react with NaOH nor turns blue litmus red. This can be explained on the basis of fact that phenols and phenoxides are more stable than alcohols and alkoxides due to resonance in benzene ring.

- Further the phenoxide ions are much more stable than alkoxide ions due to dispersal of negative charege in the former. whereas the difference in stability of phenols (involving separation of charge) and alcohols is not much pronounced.

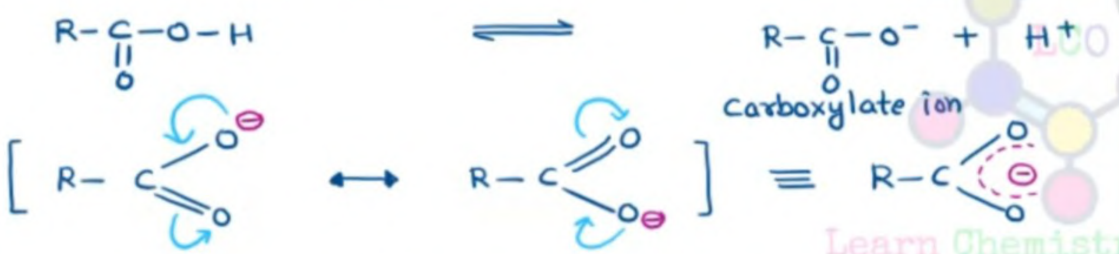


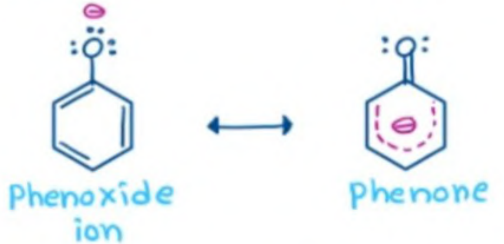
Resonance stabilisation of phenol (separation of charge, less stable)

Resonance stabilisation of phenoxide ion (dispersal of charge, more stable)

- Thus acid strength of phenol becomes evident from the fact that phenoxide ion is resonance stabilised to a larger extent due to dispersal of charge, as compared to phenol where resonance involves separation of charge.

- comparasion of acid character of phenols and carboxylic acids:-





⭑ −ve charge only on oxygen atom

⭑ −ve charge both on oxygen and carbon

- Oxygen is more electronegative than carbon therefore carboxylate ion is more stable than phenoxide ion. Hence phenols are less acidic than carboxylic acids.

- Effect of substituents :-

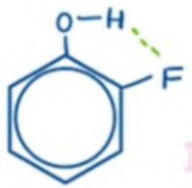
+ $\overrightarrow{\text{EWG}}$ (-I Effect)

- EWG will decrease the e- density in benzene ring and hence increases acidic character

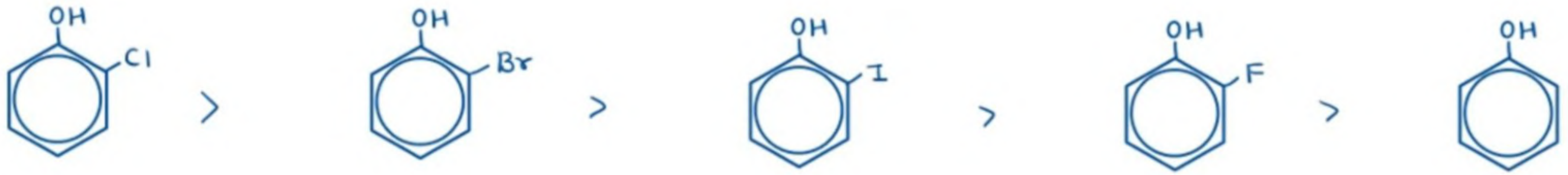
+ $\overleftarrow{\text{EDG}}$ (+I Effect)

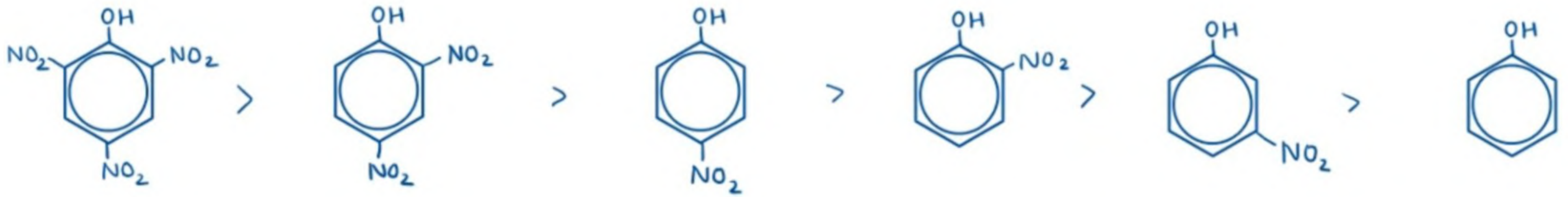
- EDG will increase the e- density in benzene ring. so does not support formation of phenoxide ion and hence decreases acidic character

- o- fluorophenol is less acidic than o- chlorophenol because F form H-bond. so decreases acidic character. (releasing of proton becomes difficult)

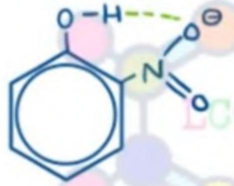


Intramolecular H-bond in O-fluorophenol





- o-nitrophenol is less acidic than p-nitrophenol due to intramolecular hydrogen bond



- m-nitrophenol is less acidic than o- and p-nitrophenols because o- and p-nitrophenoxides are stabilised by five resonating structures while m-nitrophenoxide is stabilised by four resonating structures. In other words o-nitrophenoxide ion and p-nitrophenoxide ion are more stable than m-nitrophenoxide ion.

- m-cresol is more acidic than o- and p-. because when -ve charge comes at o- and p-, it is pushed back by CH_3 group (+I). so, destabilising the phenoxide ion.

→ Phenols:→

→ Chemical reactions:→

1. Acylation - Ester formation:-

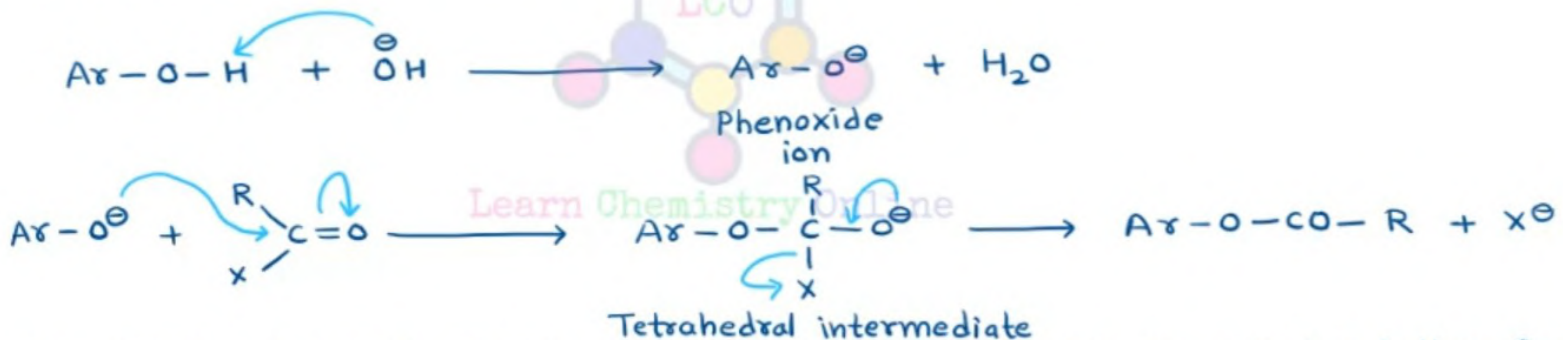
- Phenols are converted into the corresponding esters by the action of acid chorides or acid anhydrides in presence of acidic or basic medium.

$$Ar-OH + CH_3-CO-X \xrightarrow[\text{or conc. } H_2SO_4]{\text{aq. NaOH or Pyridine}} \underset{\text{Ester}}{Ar-O-CO-CH_3} + HX$$

$(X = Cl, -OCOCH_3)$

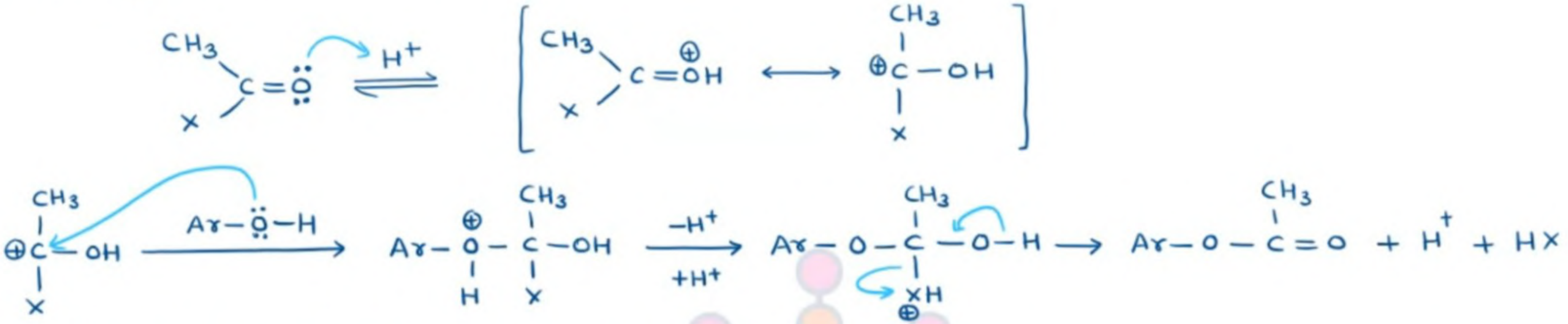
- Mechanism:-

(i) Base catalysed esterification:



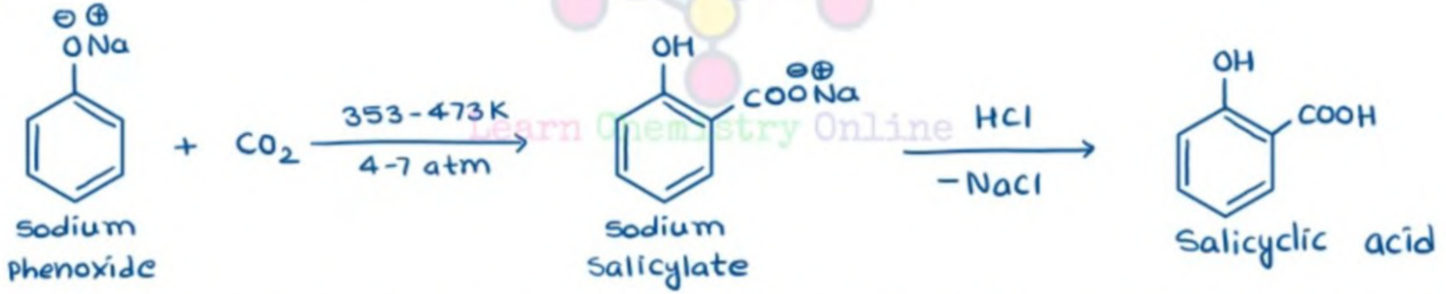
- The reaction of phenol with benzoyl chloride in the presence of NaOH is called Schotten-Baumann reaction

(ii) Acid catalysed esterification:-



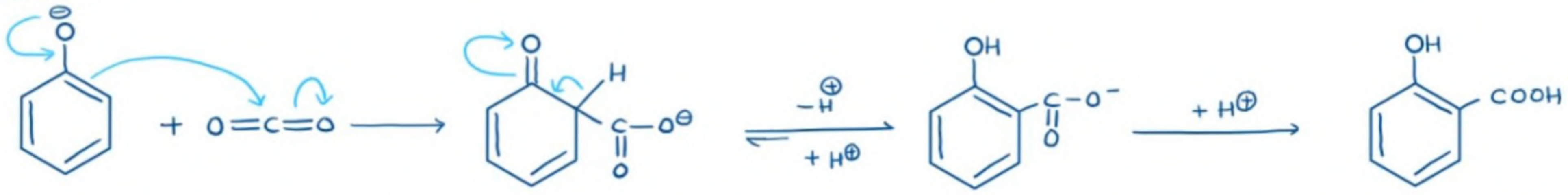
2. Carboxylation – Kolbe reaction or Kolbe-Schmidt reaction:-

- This reaction is an example of electrophilic aromatic substitution reaction involving very weak electrophile - CO_2.



At lower temperature the ortho isomer predominates whereas para isomer is obtained in excess at higher temp. since in this reaction a –COOH group is directly introduced in the ring. It is also known as carboxylation.

- Mechanism:-



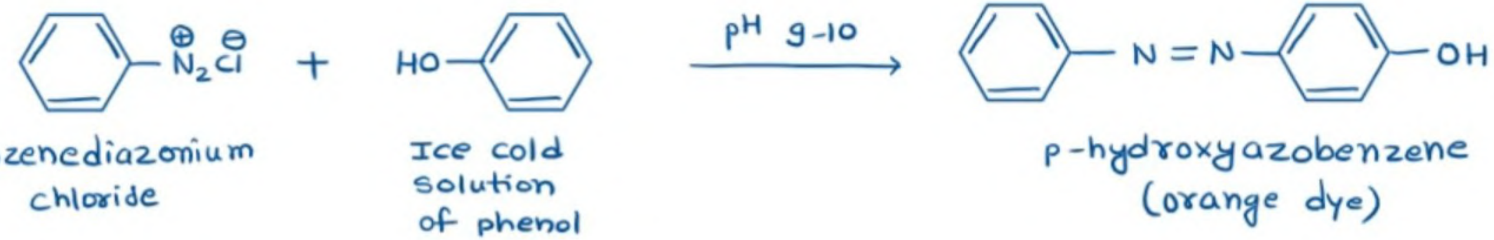
– Under these conditions only half of phenol is carboxylated whereas at lower temp. (393-413K) and under high pressure (5-7 atm), phenol is converted into the product. This modification is known as Kolbe-Schmidt reaction.

3. Williamson's synthesis: Ether formation:-

$$Ar-O-Na + R-X \xrightarrow[\Delta]{S_N2} \underset{\text{Alkyl phenyl ether}}{Ar-O-R} + NaX$$

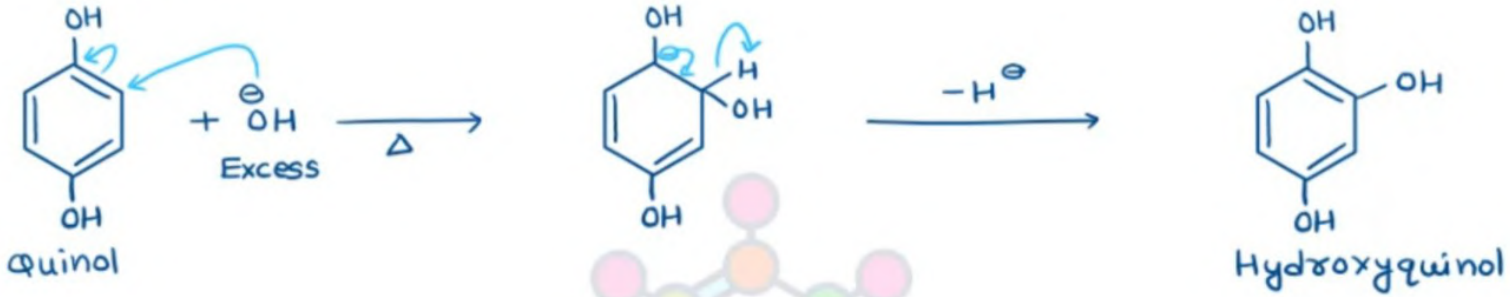
$$Ar-O-Na + \underset{\text{dialkyl sulphate}}{R-O-SO_2-OR} \longrightarrow \underset{\text{Alkyl phenyl ether}}{Ar-O-R} + NaOSO_2OR$$

4. Coupling reaction:-



5. Hydroxylation:-

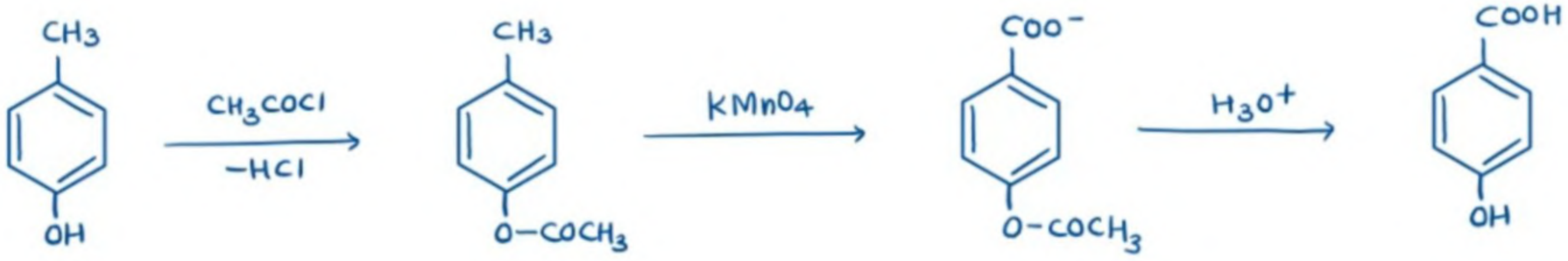
- Polyhydric phenols, upon fusion with alkali form products having more hydroxyl groups attached to the aromatic ring.



6. Oxidation:-

(i) with alkaline $KMnO_4$

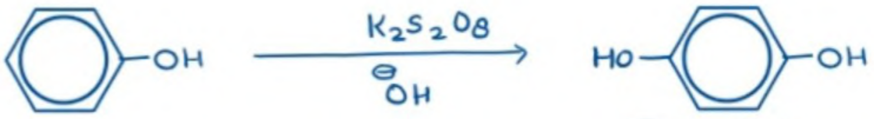
- Oxidation of phenols with alkaline $KMnO_4$ leads to cleavage of aromatic ring. However, if the −OH group is protected by acylation or alkylation, the alkyl side chain can be oxidised to give corresponding hydroxy acids.



(ii) with weaker oxidising agent such as $FeCl_3$ →

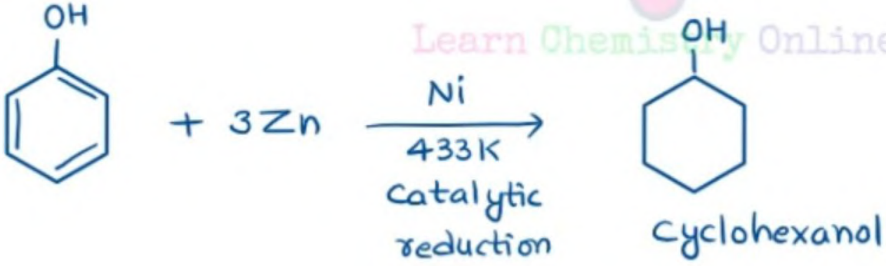
- Phenol gives phenoxyl radical when react with $FeCl_3$. This phenoxyl radical undergo coupling reaction at ortho-ortho, ortho-para and para-para positions

(iii) Oxidation with alkaline potassium persulphate. (Elbs persulphate oxidation)



Quinol

7. Reduction:-

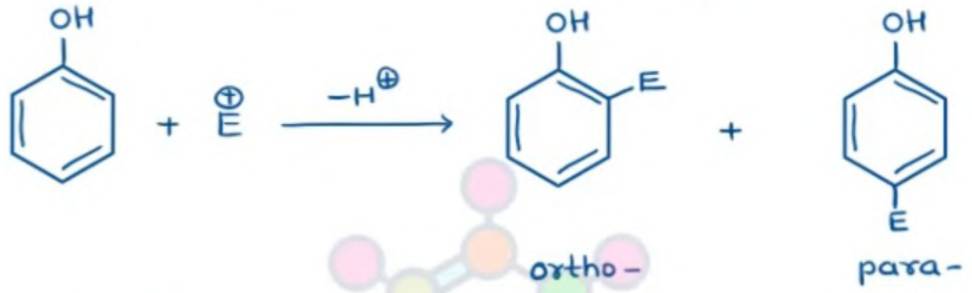


Cyclohexanol

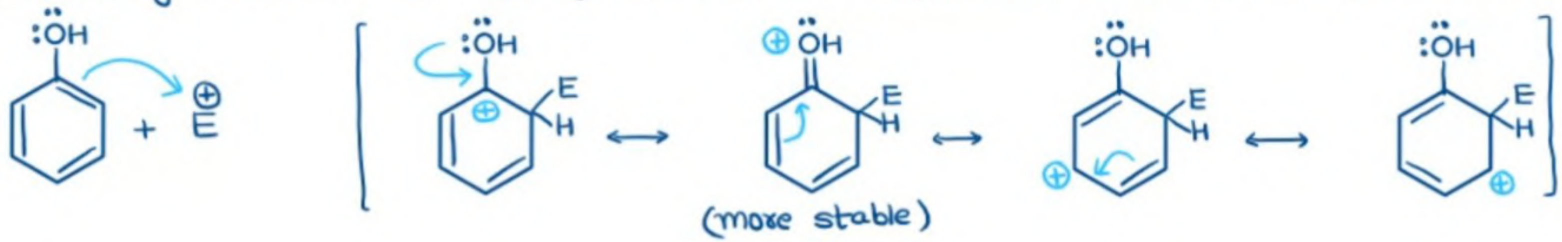
→ Phenols:-

→ Electrophilic aromatic substitution:→

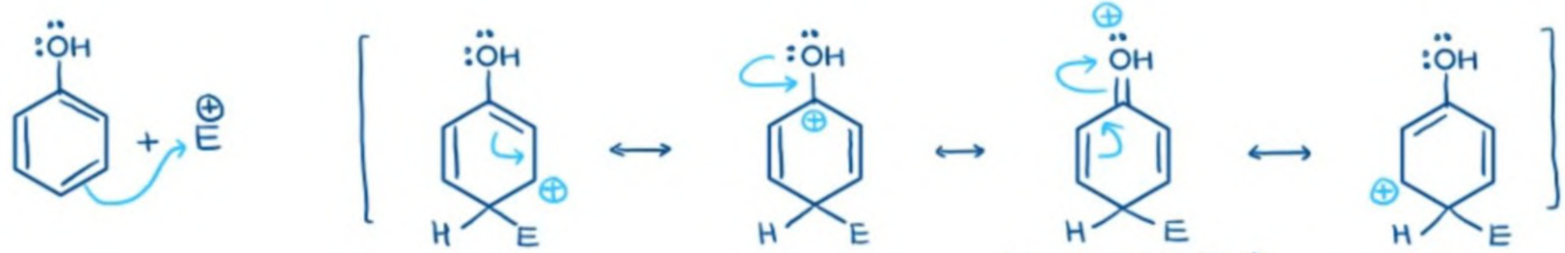
- The −OH group attached to the benzene ring activates it towards electrophilic substitution. Also it directs the incoming group to ortho− and para- positions in the ring.



- Explanation for ortho, para directing and activating influence of −OH group.
- one of the lone pairs of electrons of oxygen of −OH group interacts with the π-electrons of the benzene ring due to which the electron density gets increased at all the carbon atoms of the ring. This increase in electron density activates the ring for electrophilic substitution. Further, the increase in electron density is higher at ortho− and para− positions relative to meta− position. Therefore, electrophilic substitution is preferred at o− and p− positions in comparision to m− position.
- This o,p− directing influence of OH group can be explained in term of relative stability of carbocation.
- O-attack

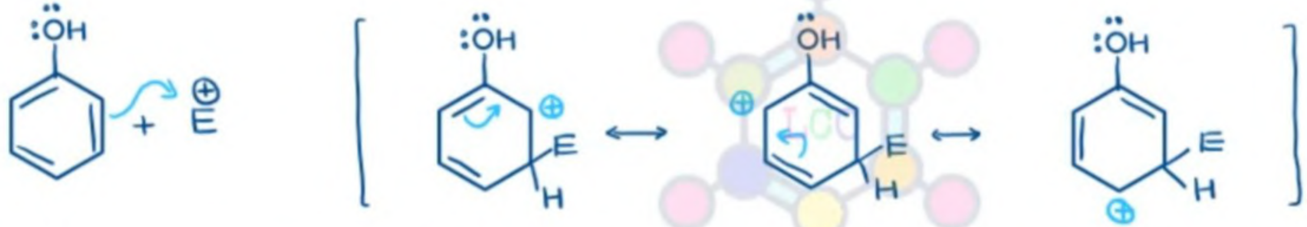


- p-attack



(more stable)

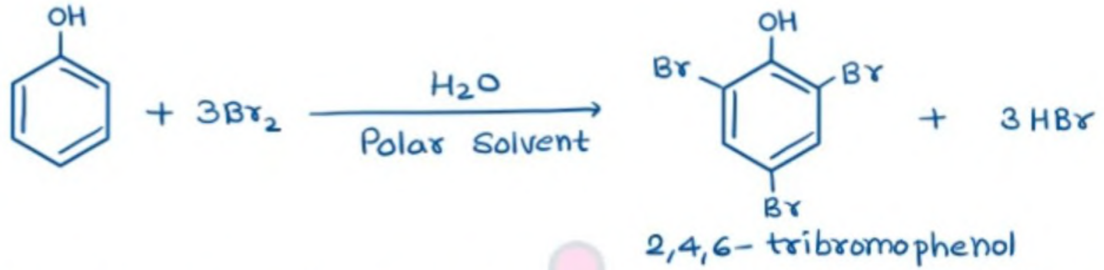
- m-attack



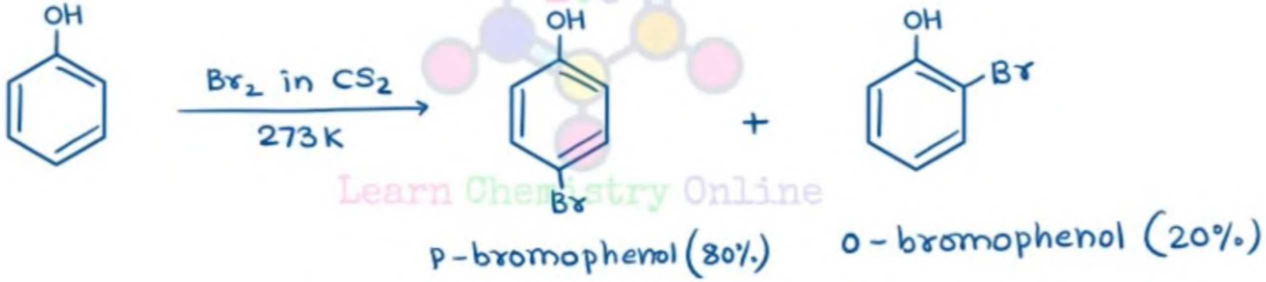
- A look at the carbocations formed by the attack of electrophile on the ring show that the carbocation formed during o- and p-attack are resonance hybrid of four contributing forms out of which one is highly stable because in this each atom (except H) has a complete octet of electrons. But in case of m-attack the resulting carbocation has no such contributing forms. This indicates that the carbocations formed during o- and p-attack are more stable than those formed by m-attack. Therefore, electrophilic substitutions in phenols occur at o- and p-positions preferentially.

- Some important electrophilic substitution reactions are

(a) Halogenation:-

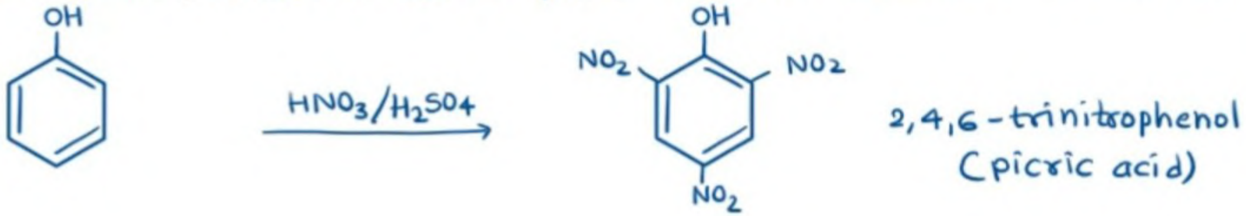


- However, halogenation can be stopped at monohalogenation state, if the reaction is carried out in presence of non-polar or less polar solvent at low temp.

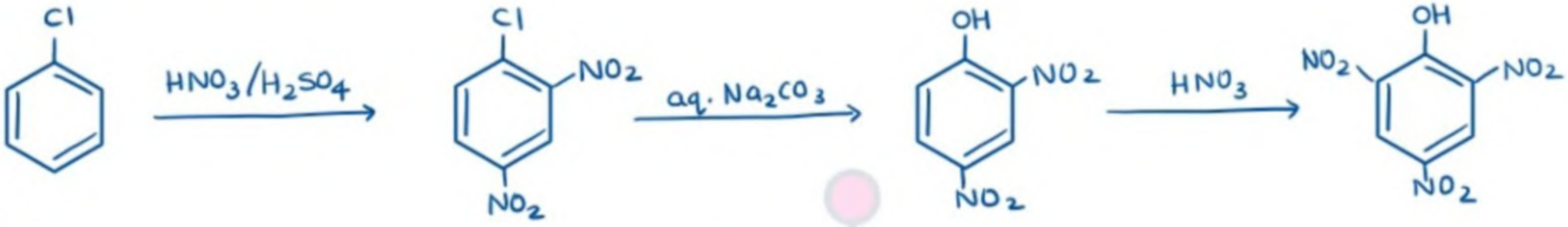


(b) Nitration:-

- Due to high reactivity of phenol, nitration takes place at all available ortho and para positions.

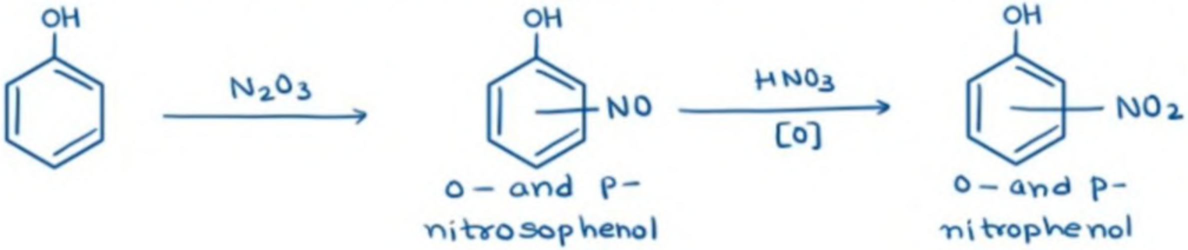


- This reaction gives very low yield of picric acid because most of phenol is oxidised by nitric acid. Therefore, following alternative methods are used for synthesis of picric acid-
- From chlorobenzene



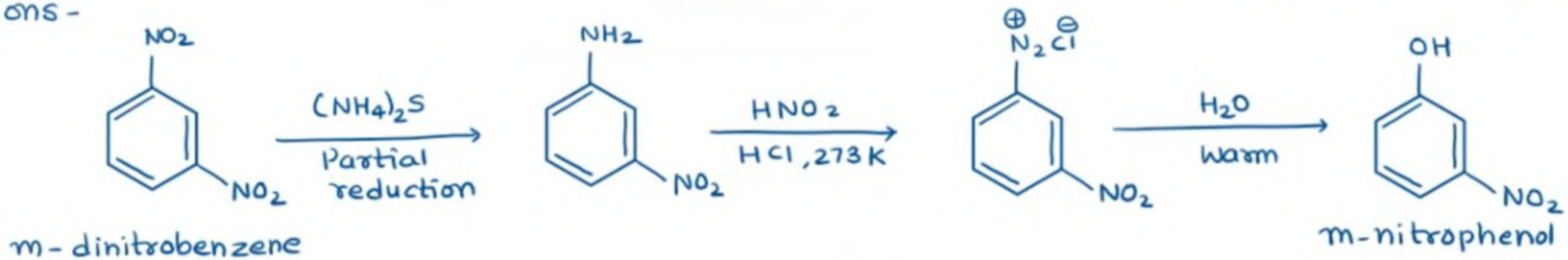
- From phenol

- Picric acid is very strong acid (stronger than carboxylic acids) due to presence of three $-NO_2$ groups.
- Picric acid is used as disinfectant and laboratory reagents.
- o- and p-nitrophenols can be prepared by reaction of phenol with dilute HNO_3.

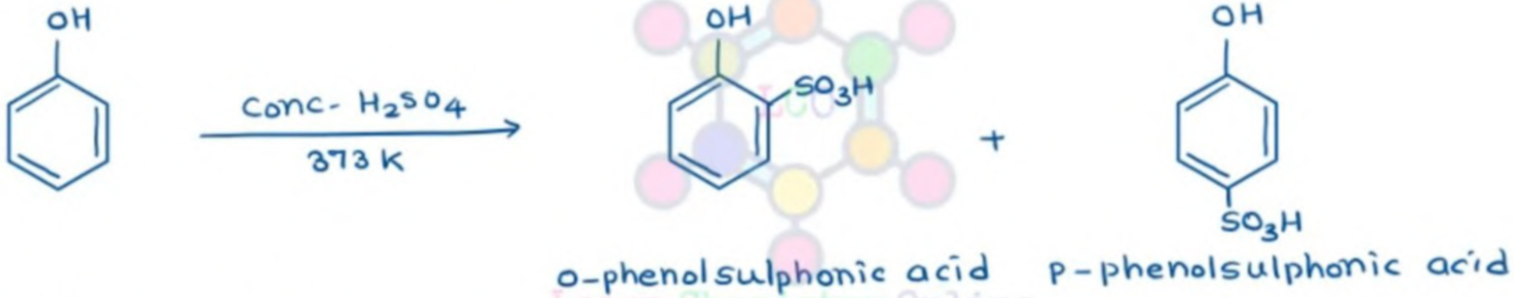


✲ N_2O_3 is produced from nitric acid *in situ*.

- m-nitrophenol cannot be prepared by direct nitration of phenol. But can be prepared by following reactions -



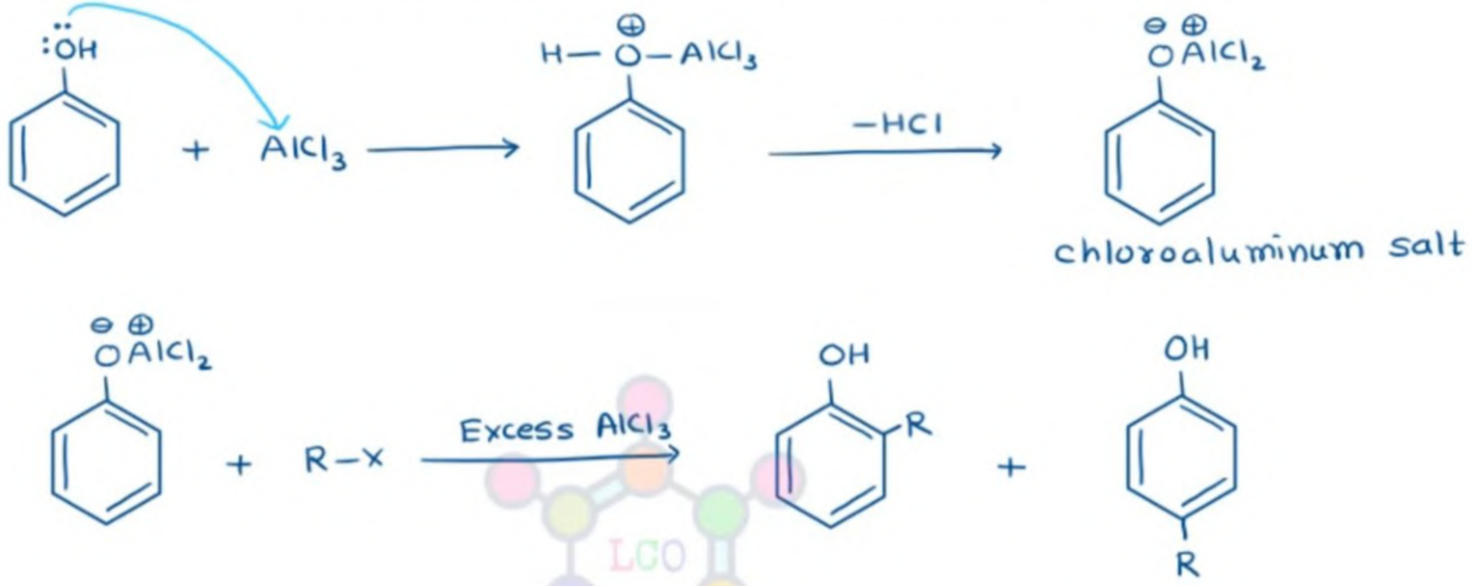
(c) Sulphonation:→



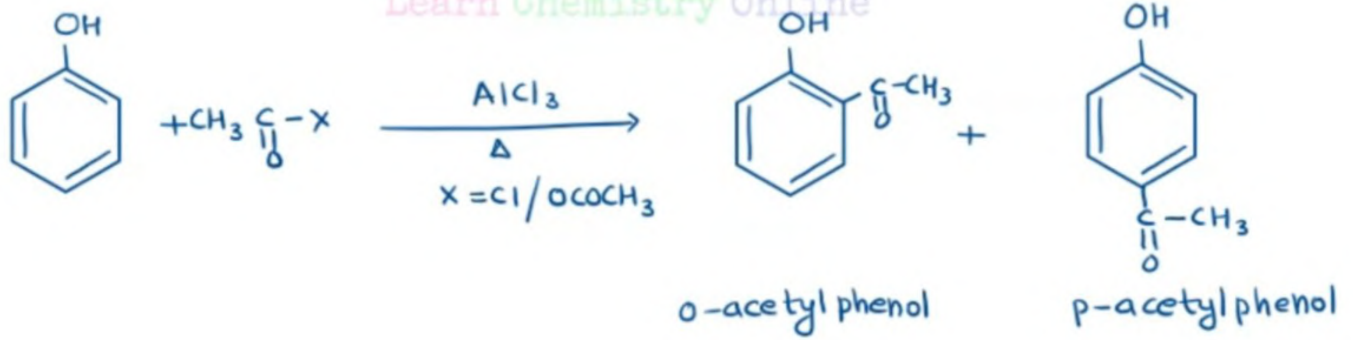
- At low temp (293K) o - isomer predominates but at high temp. (373K) p - isomer is the major product. Further, when o - isomer heated to 373 K it gives thermodynamically more stable p-isomer.

(d) Friedel- Crafts alkylation:→

- Phenols upon treatment with alkyl halides, in presence of anhy. $AlCl_3$ produce ortho and para alkyl phenols.
- $AlCl_3$ is used in excess because phenol reacts with aluminium chloride to form chloroaluminum salt which is more reactive than phenol.

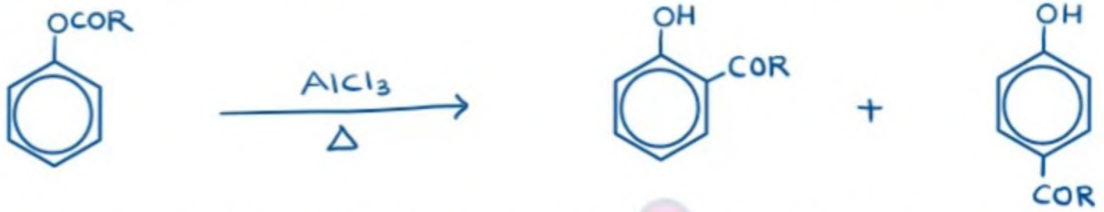


(e) Fridel-Crafts acylation:-

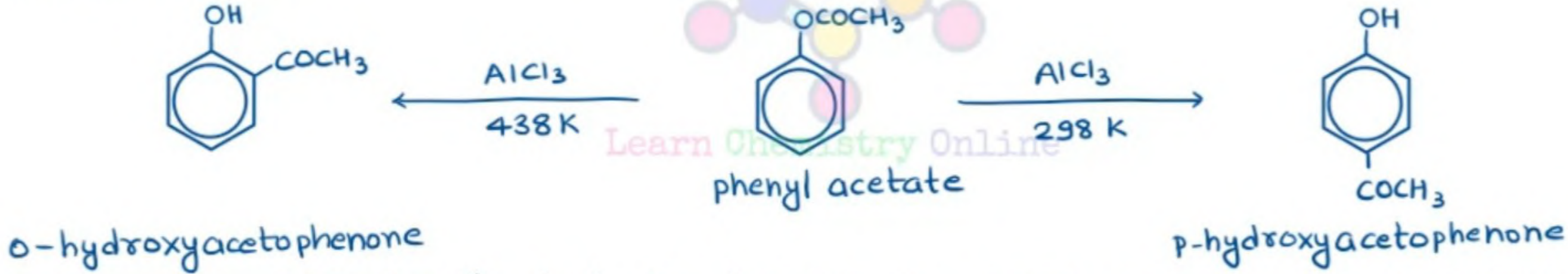


→ Fries rearrangement :→

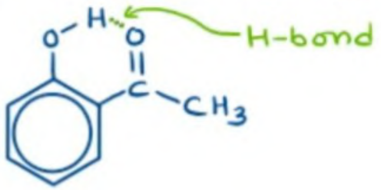
- The phenolic esters, upon heating with anhydrous aluminium chloride, are converted into the isomeric o- and p-hydroxy ketones or more often, into a mixture of both.



- This reaction is called Fries migration and Fries rearrangement.
- p-isomer predominates at lower temp whereas o-isomer is obtained in larger amounts at higher temp. (due to steric effect). p-produt can be converted into o-isomer on further heating with aluminium chloride.

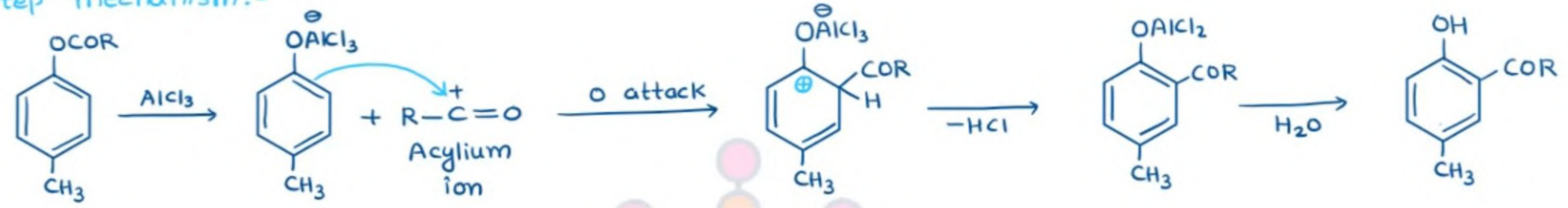


- Aluthough p-isomer is obtained easily but o- isomer is more stable due to intramolecular hydrogen bonding.

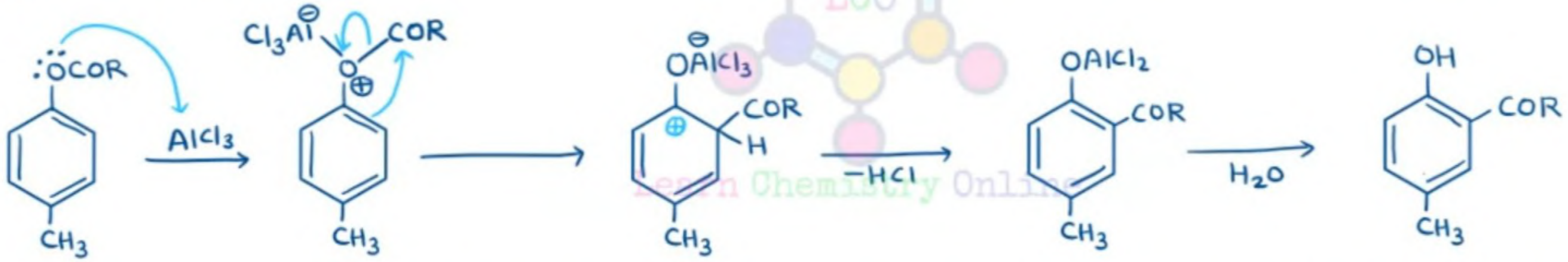


→ Mechanism:→

- The reaction can take place by two alternate mechanistic patways, i.e. by one step or two step mechanism.
- Two step mechanism:-



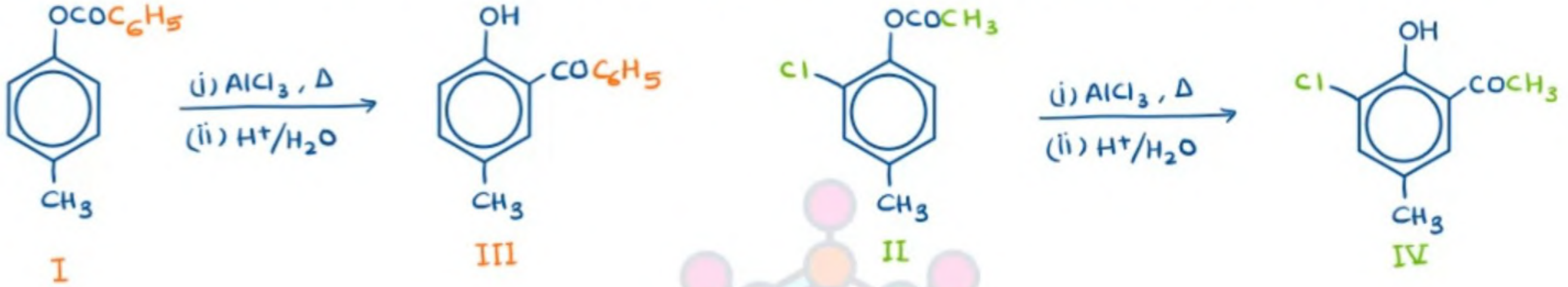
- One step mechanism:-

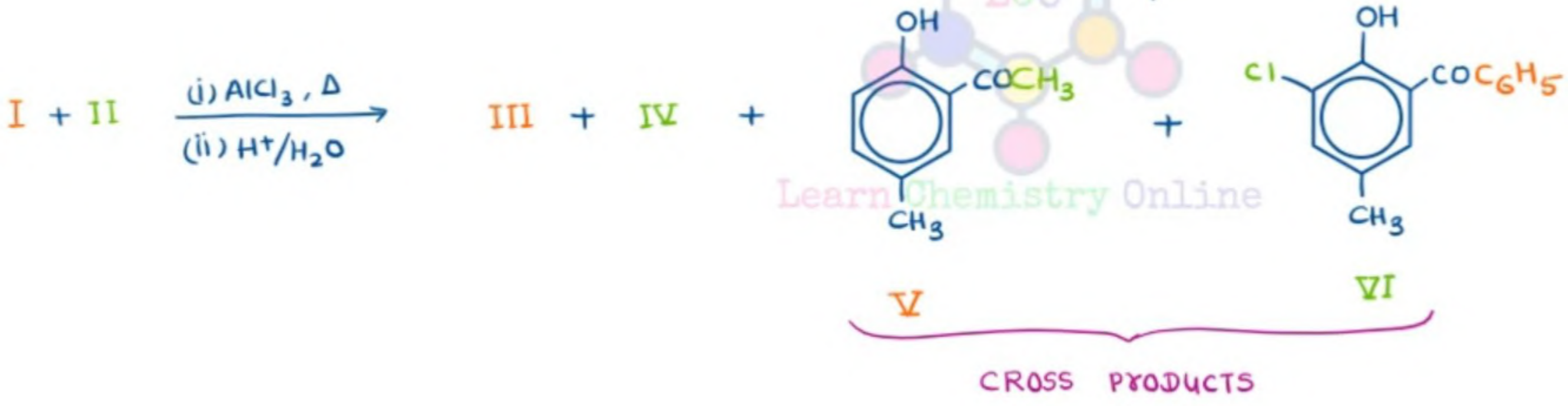


- In most of cases the reaction takes place through two step mechanism. This is proven by isolation of cross products when a mixture of two identical but differently substituted substrates is treated under conditions of reaction.

- Example:-

- Esters I and II gives the ketones III and IV respectively. When a mixture of I and II is heated with $AlCl_3$ apart from III and IV cross products V and VI are also obtained.





→ Claisen rearrangement :→

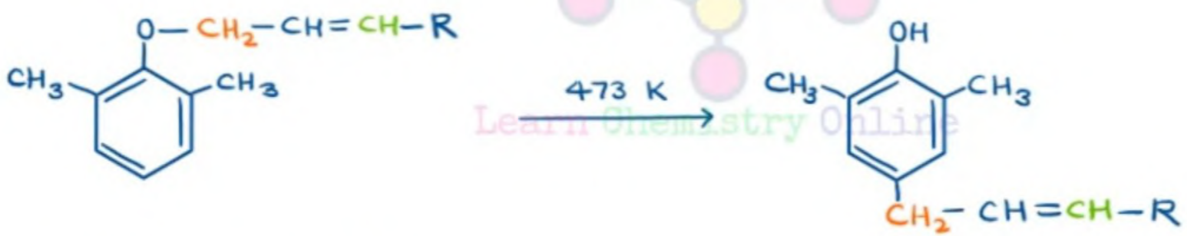
- When allyl aryl ethers heated at 473 K, allyl group from ether oxygen migrates to ring carbon at ortho position and when both the ortho positions are blocked, the allyl group migrates to para position. However, in no case does it go to meta position.
- Ortho rearrangement

- Para rearrangement

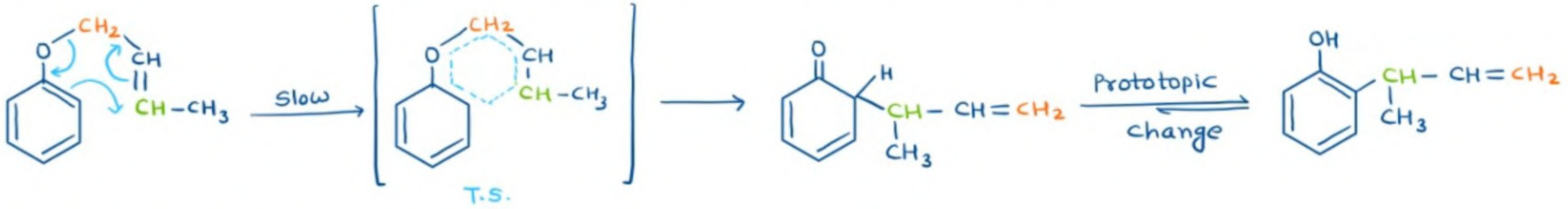
- Mechanism:→
- The reaction does not require any catalyst and shows first order kinetics with respect to the allyl aryl ether.
- The claisen rearrangement is an example of pericyclic reactions and is known as Sigmatropic rearrangement.
- The reaction is proceed in concerted manner as evidenced by heating a mixture of ethers having two different allyl groups, whereby cross-products are not obtained.

- An interesting feature of the rearrangement is that when migration takes place to the ortho-position, the γ-carbon of the allyl group attaches itself to the ring carbon.
- In other words, ortho migration involves an inversion in the position of substituents with respect to that of the starting compounds. However, no such inversion takes place in the case of para migration.
- Ortho rearrangement

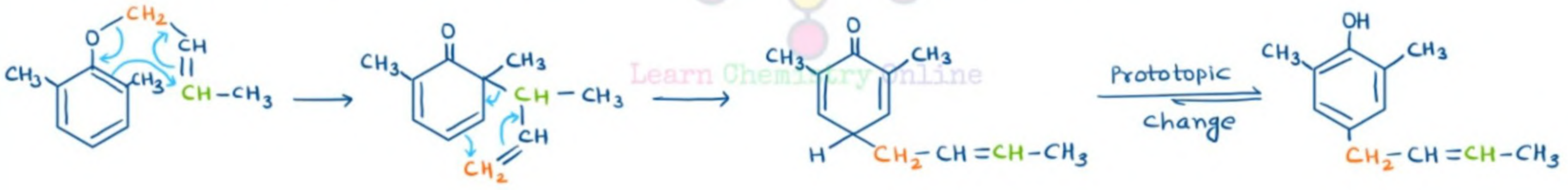
- Para rearrangement



- Mechanism of ortho-rearrangement:-
- This reaction proceeds through six membered cyclic transition state. (cyclohexadiene intermediat
- The cleavage of allyl-oxygen bond and formation of allyl-carbon bond at ortho position takes place simultaneously.
- The intermediate converts into product through prototopic change.

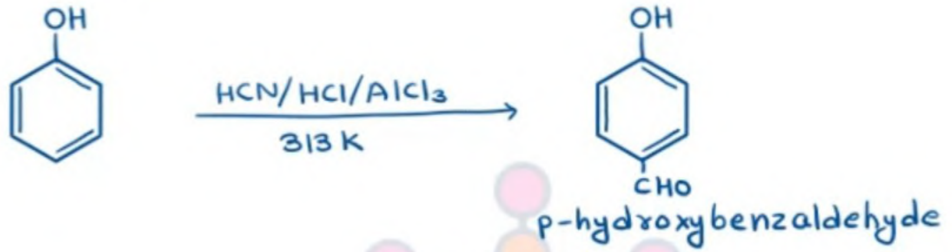


- Mechanism of para-rearrangement:-
- When ortho positions are blocked, then allyl group migrates at para-position.
- This migration takes place at two stages. In the first stage migration takes place ortho position and in the second stage migration takes place at para position. Thus, in para rearrangement one inversion is followed by another and overall there is no inversion. The driving force for the para migration is regaining of aromatic character after allylic migration



→ Gatterman Synthesis: Gatterman formylation:→

- It is an important synthetic procedure for preparing phenolic aldehydes.
- It involves treatment of phenol with a mixture of hydrogen cyanide and hydrogen chloride in presence of anhydrous aluminium chloride.

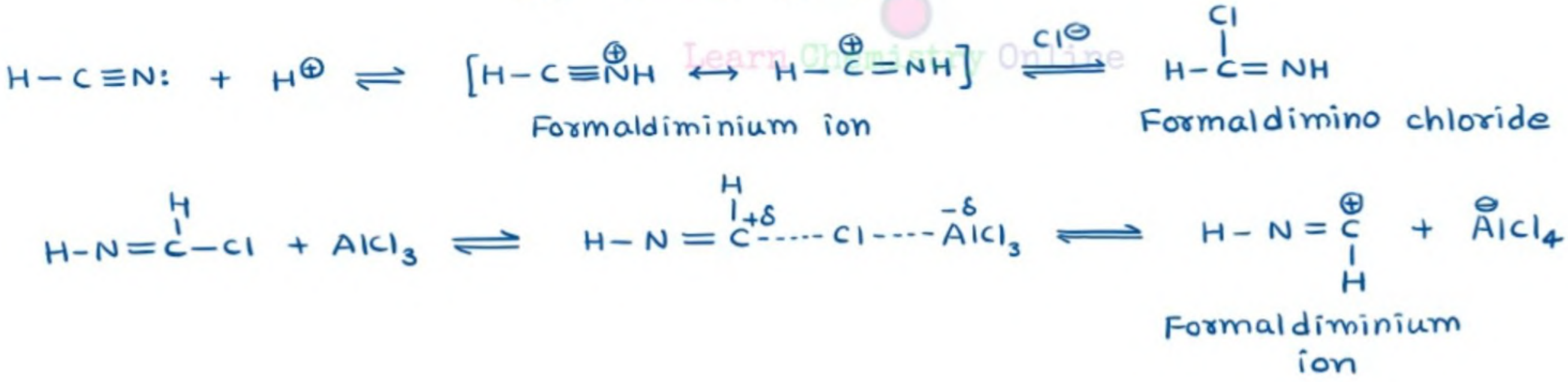


p-hydroxybenzaldehyde

– Mechanism:→

- It is an electrophilic substitution reaction
- Formaldiminium ion (electrophile) is formed by reaction of HCl and HCN.

$$HCl \rightleftharpoons H^{\oplus} + Cl^{\ominus}$$



$$H-C\equiv N: + H^{\oplus} \rightleftharpoons [H-C\equiv \overset{\oplus}{N}H \longleftrightarrow H-\overset{\oplus}{C}=NH] \xrightleftharpoons{Cl^{\ominus}} H-\overset{Cl}{\overset{|}{C}}=NH$$

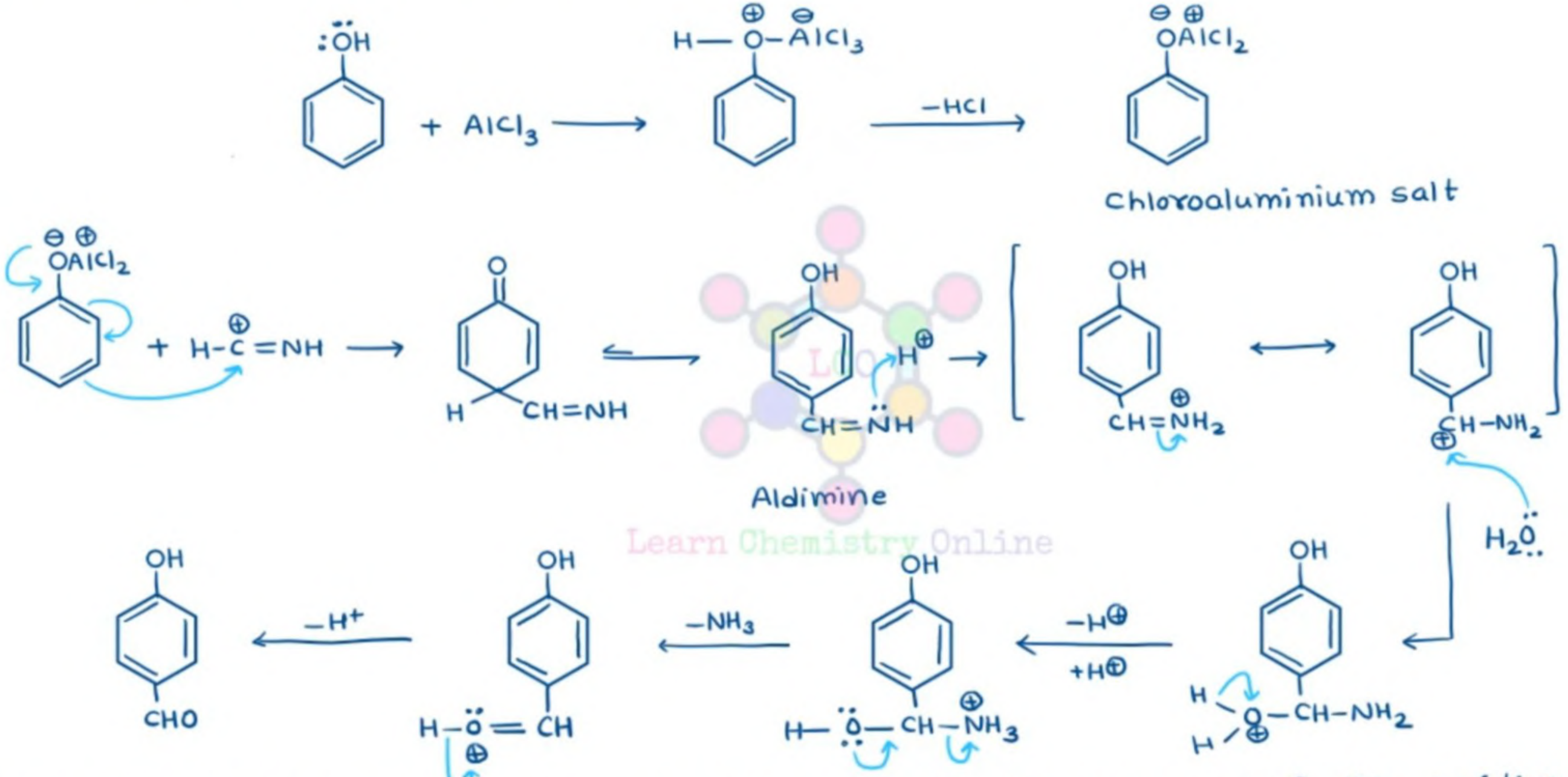
Formaldiminium ion

Formaldimino chloride

$$H-N=\overset{H}{\overset{|}{C}}-Cl + AlCl_3 \rightleftharpoons H-N=\overset{H}{\overset{|}{C}}{}^{+\delta}\cdots Cl\cdots \overset{-\delta}{AlCl_3} \rightleftharpoons H-N=\underset{H}{\underset{|}{\overset{\oplus}{C}}} + \overset{\ominus}{AlCl_4}$$

Formaldiminium ion

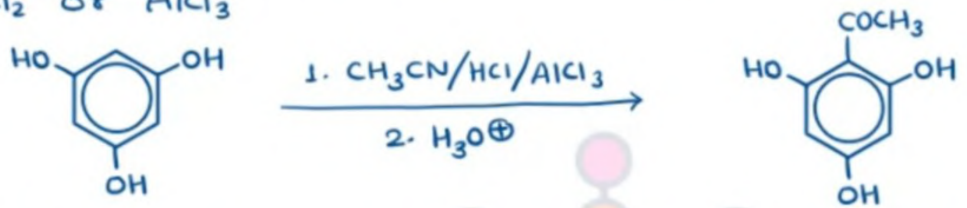
- Formaldiminium ion attaks on aromatic ring to form aldimine, which on hydrolysis with mineral acids to give formyl derivative of phenol.



- The formyl group goes to para-position with respect to phenolic group and if this position is blocked then it goes to ortho-position.

→ Hauben - Hoesch reaction:→

- It is an extension of Gatterman reaction and involves acylation of highly reactive polyhydric phenols having hydroxyl group in the meta-position with respect to each other.
- The reaction is carried out by treating these phenols with alkyl cyanide and hydrogen chloride in presence of $ZnCl_2$ or $AlCl_3$



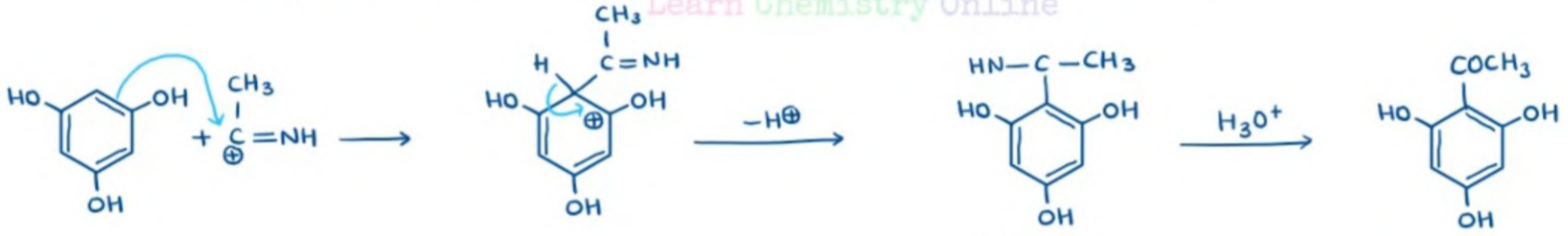
Phloroglucinol

Phloroacetophenone
(2,4,6- Trihydroxyacetophenone)

- Mechanism:-

- Similar to Gattermann reaction.

$$CH_3-C\equiv N: + H^+ \xrightarrow{AlCl_3} [CH_3-C\equiv \overset{\oplus}{N}H \longleftrightarrow CH_3-\overset{\oplus}{C}=NH]$$

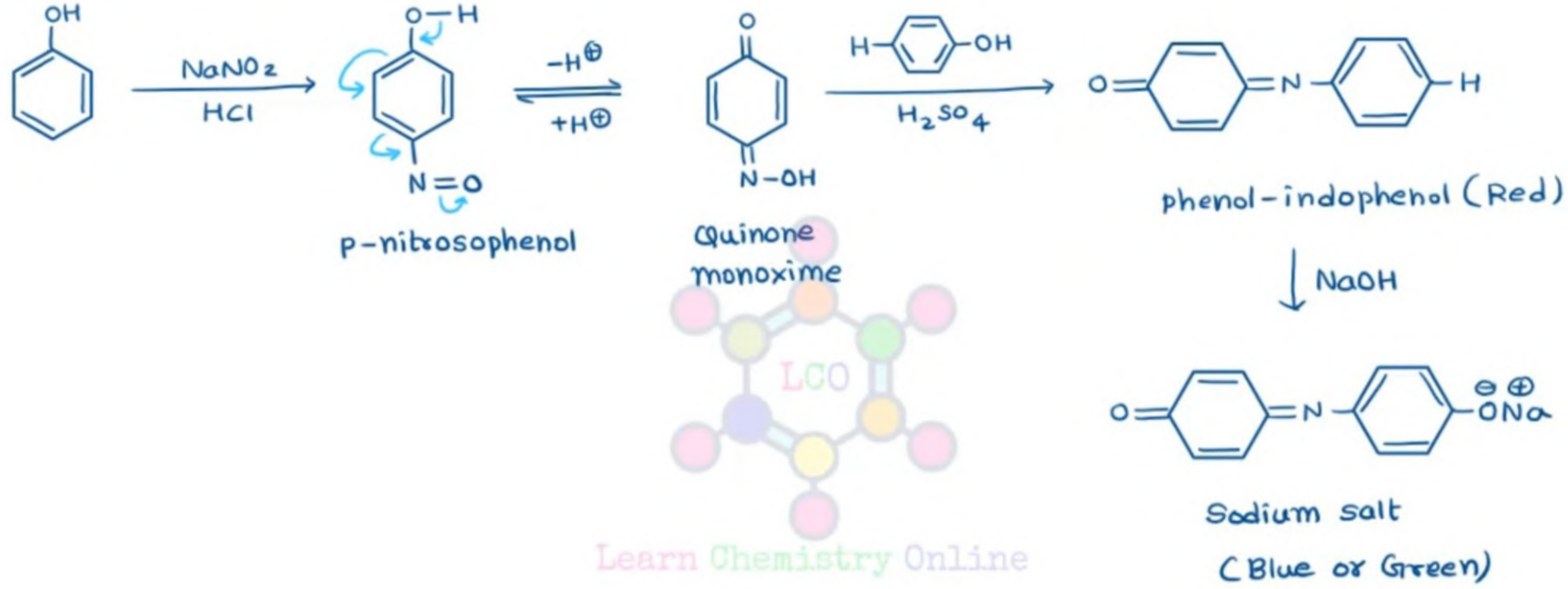


Ketimine

Phloroacetophenone

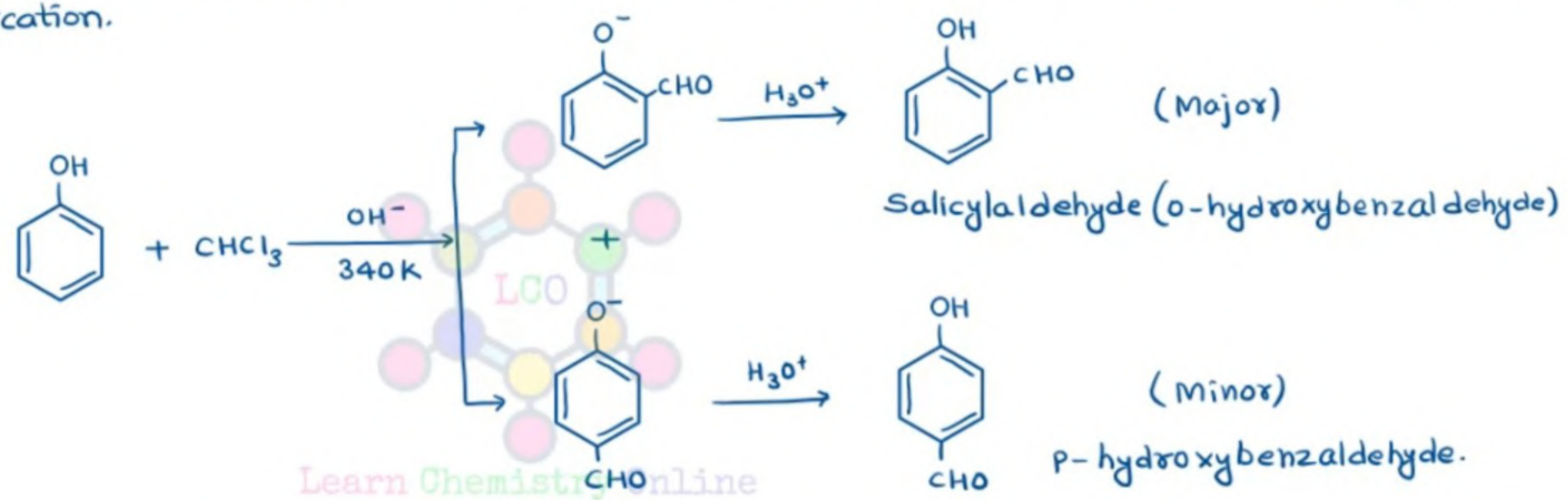
→ Liebermann's nitroso reaction:→

- This reaction used as a test for the detection of phenol.



→ Reimer – Tiemann reaction :→

- The most sucessful method for the formylation of aromatic ring of phenols.
- In this reaction phenol is treated with chloroform in alkaline solution at temperature lower than boiling point of chloroform.
- Ortho - isomer formed as a major product which can separated from the para - isomer by steam distillation after acidification.



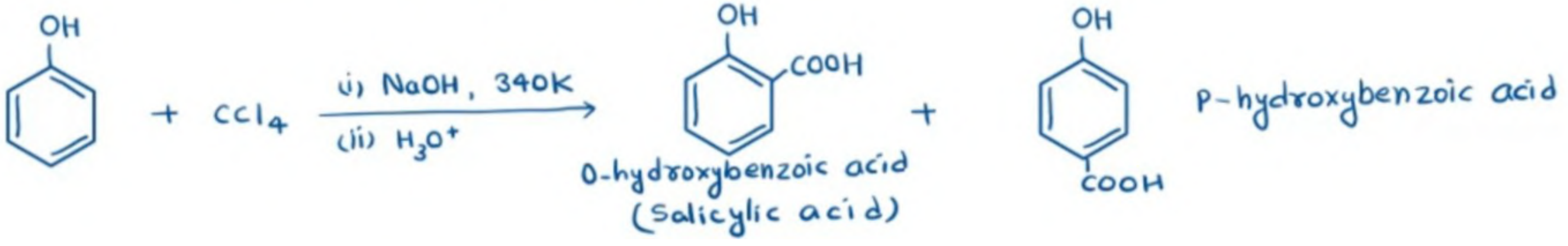
(Major)

Salicylaldehyde (o-hydroxybenzaldehyde)

(Minor)

p- hydroxybenzaldehyde.

- If Carbon tetrachloride is used instead of chloroform, salicyclic acid is obtained as major product along with small amount of p-hydroxybenzoic acid.



0-hydroxybenzoic acid
(Salicylic acid)

p-hydroxybenzoic acid

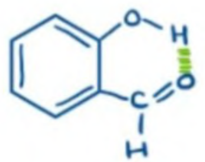
→ Mechanism:→

- Formation of dichlorocarbene (E1cB reaction)

$$\overset{\ominus}{O}H + H-CCl_3 \underset{}{\overset{Fast}{\rightleftharpoons}} H_2O + :\overset{\ominus}{C}Cl_3 \quad ; \quad Cl_2\overset{\ominus}{C}:-Cl \xrightarrow{slow} \underset{\text{dichlorocarbene}}{:CCl_2} + \overset{\ominus}{Cl}$$

- Attack of dichlorocarbene as electrophile on phenoxide ion (Electrophilic substitution reaction)

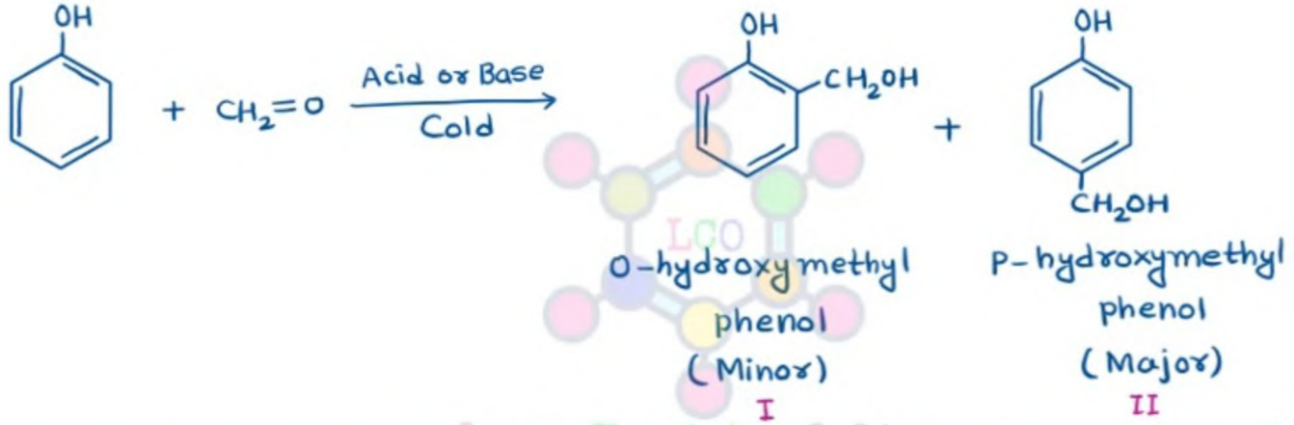
- The predominance of ortho-isomer may be due to its greater stability resulting from intra molecular hydrogen bonding (chelation). Further due to intramolecular hydrogen bonding, ortho-isomer having lower boiling point than para-isomer. Therefore ortho- and para- isomers can be separated by steam distillation.



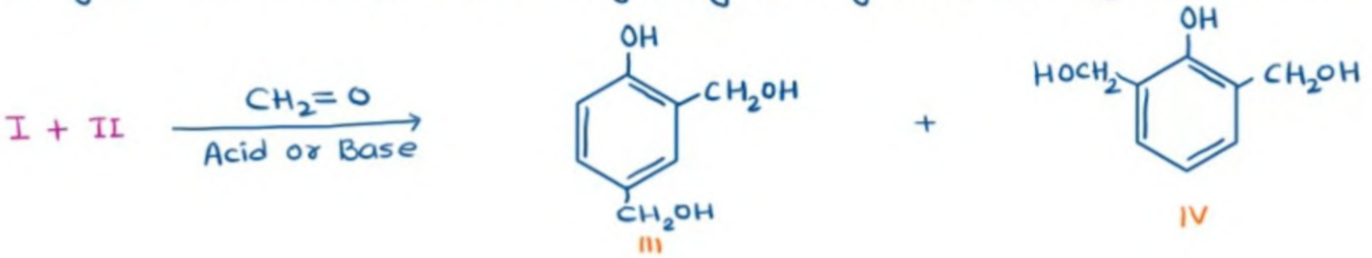
← Intramolecular hydrogen bond in ortho-isomer

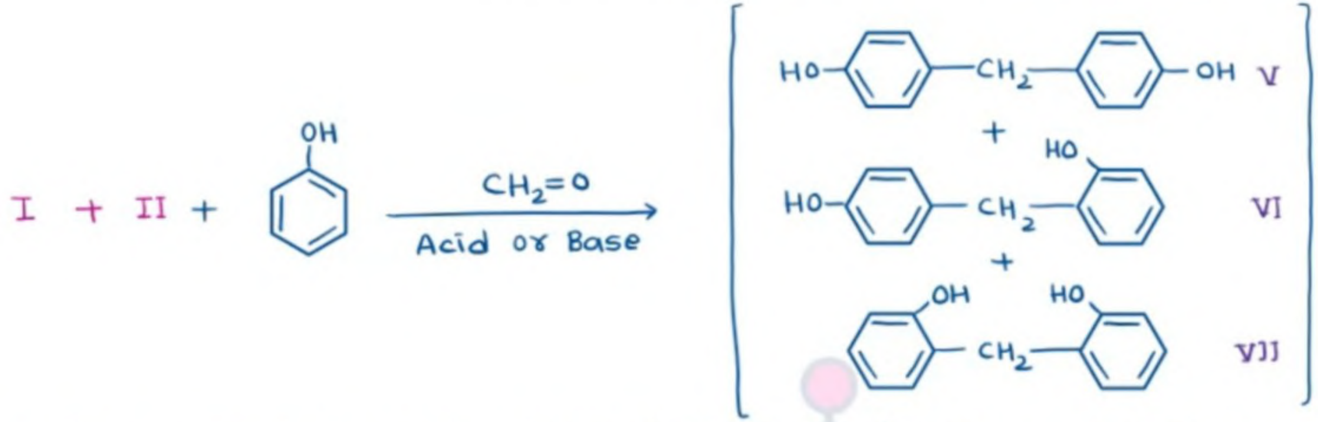
→ Lederer - Manasse reaction :→

- In this reaction phenol is condensed with aliphatic and aromatic aldehydes in presence of either an acid or a base as a catalyst.
- If phenol is treated with formaldehyde in presence of acid or alkali, o- and p-hydroxybenzyl alcohols are formed which are important starting materials for manufacture of Bakelite (Phenol-formaldehyde resin).

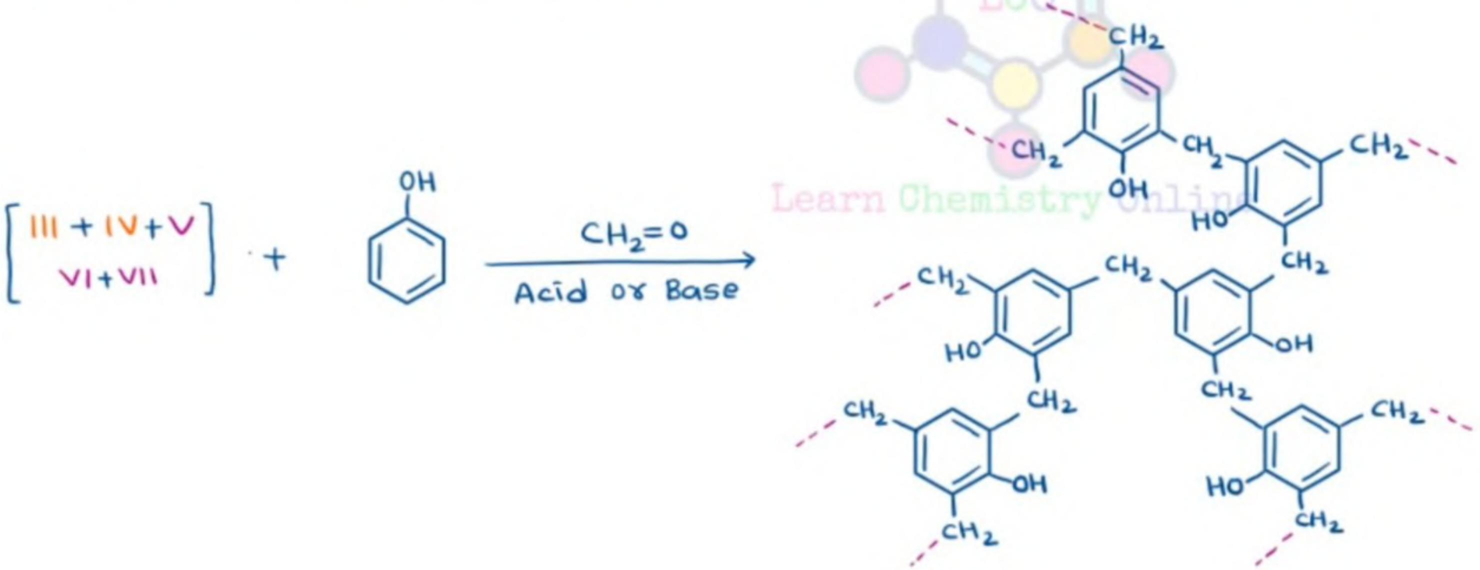


- But the reaction does stop at this stage and the phenolic alcohols (I & II) condense with further amount of formaldehyde to form bishydroxymethyl phenol (III & IV) or with further amount of phenol to give all the possible dihydroxydiphenylmethanes (V, VI & VII)





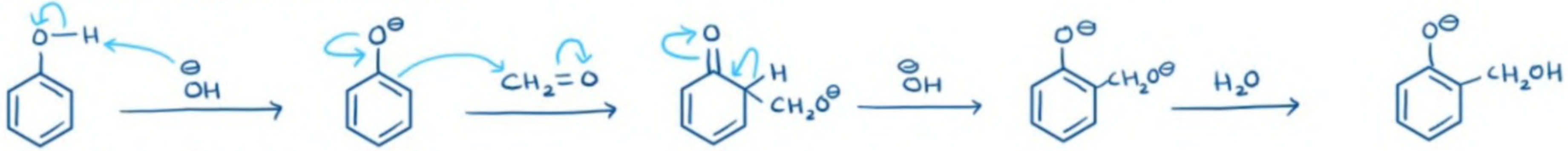
- Such condensations reactions are repeated and finally a Bakelite polymer is obtained.
- Bakellite is a thermosetting plastic and is very hard and rigid.



Phenol - formaldehyde polymer
(Bakelite)

→ Mechanism:-

- Alkaline medium (dilute alkali)



- Acidic medium (dilute acid)