Organic Chemistry Review

Hybridisation

- Hybridisation is a model used to explain the **observed shapes** of molecules about the central atom.

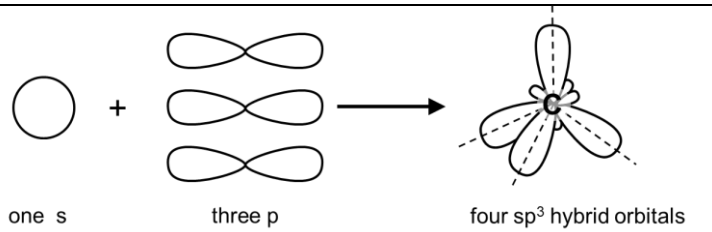
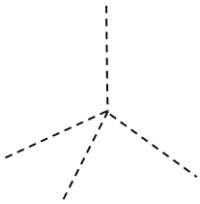
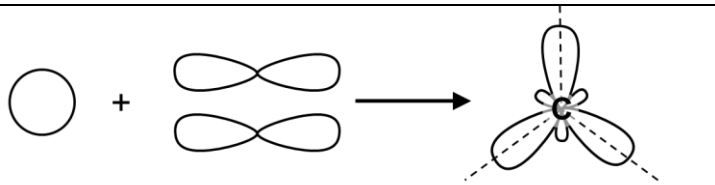
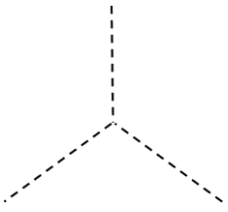
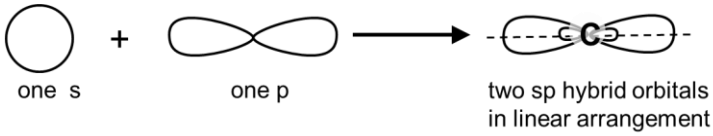
- Hybridisation model shows **mixing of pure atomic orbitals** in an atom to generate **a set of degenerate hybrid orbitals (hybrid orbitals are of same energy level)**.

General shape of sp^3 / sp^2 / sp hybrid orbital

In the formation of covalent bonds, only the front lobe is used to overlap with an orbital of another atom as the front lobe is bigger and results in a more effective overlap.

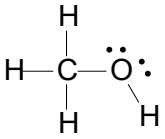
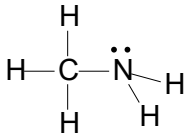
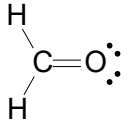
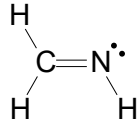
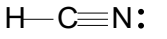
- **No. of atomic orbitals mixed = No. of hybrid orbitals formed**
  Hybrid orbitals take part in sigma (σ) bonding only. Pi bonds (π) are formed by unhybridised p orbitals.

Arrangement of hybrid orbitals around the central atom

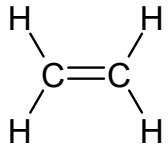
Total no. of electron regions	Hybridisation of central atom	Formation of hybrid orbitals and arrangement of hybrid orbitals around the central atom	Let's practice!
4	**sp^3**		
3	**sp^2**	 **Note: There is one unhybridised p orbital for π bonding**	
2	**sp**	 **Note: There are two unhybridised p orbitals for π bonding**	

Note: For C atom, hybrid of 2s and 2p orbitals produces 2sp / 2sp^2 / 2sp^3 hybrid orbitals where "2" represents the principal quantum number (e.g. 2nd electron shell)

O and N atoms can undergo hybridisation similar to carbon. The type of hybridisation depends on the number of electron regions (bond pair regions + lone pair regions) around the atom.

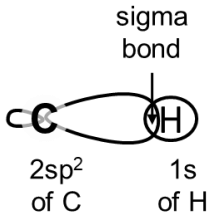
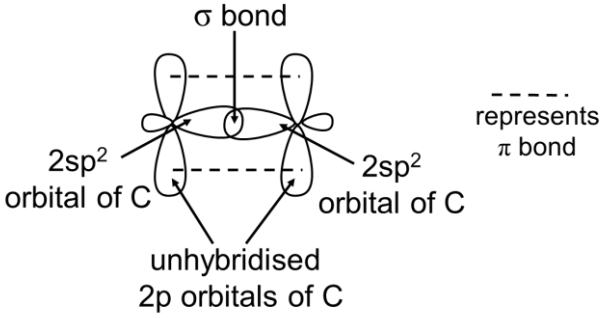
Number of electron regions	Hybridisation	Examples
4	**sp^3**	 sp^3 C and sp^3 O  sp^3 C and sp^3 N
3	**sp^2**	 sp^2 C and sp^2 O  sp^2 C and sp^2 N
2	**sp**	 sp C and sp N

Drawing of orbitals overlap in formation of sigma and pi bond

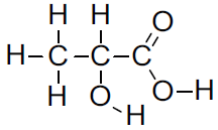
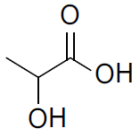


Central atoms

Both C are sp^2 hybridised (3 e^- regions)

Bonds	Orbitals involved	Drawing of overlap of orbitals to form bond
C−H	$2sp^2$ hybrid orbital of C **head-on** overlap with 1s orbital of H	
C=C	**sigma bond :** $2sp^2$ hybrid orbital of C **head-on** overlap with $2sp^2$ hybrid orbital of C **pi bond :** unhybridised 2p orbital of C **side-way** overlap with unhybridised 2p orbital of C	

Various representations of organic compounds

Type of Formulae	Representation	Characteristics
Molecular Formula	$C_3H_6O_3$	• does not show how the various atoms in the organic compound are connected to one another
Condensed Formula	$CH_3CH(OH)CO_2H$	• shows the order of arrangement of atoms • bonds are not displayed
Displayed / Full structural Formula		• shows **ALL** atoms and bonds in the molecule.
Skeletal Formula		• Carbon atoms in a straight chain are drawn in a zigzag manner • each end of a line represents a carbon if other symbol of an atom is **not** written • C–H bonds at each C are **not** shown. • each C forms 4 bonds. Any "missing" bond not drawn out in a skeletal structure would be a C–H bond.

Isomerism

ISOMERISM
(Compounds with same molecular formula)

Constitutional (Structural) isomerism

- same molecular formula,
- different structural formulae atoms are connected differently

chain isomerism
- different arrangements of carbon skeleton

positional isomerism
- different locations of substituents / functional groups on carbon chain

functional group isomerism
- different functional groups

Stereoisomerism

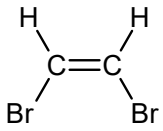
- same molecular and structural formulae
- different spatial (3D) arrangement of atoms

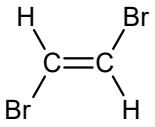
optical isomerism (enantiomerism)
- Presence of chiral centre (4 diff groups attached to C)

***cis-trans* isomerism**
- different structures due to restricted bond rotation

Cis-trans isomerism

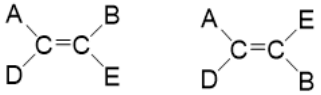
Requirement : **2 different groups attached to each C** in the restricted bond (C=C)
We must show the **trigonal planar arrangement around the C=C** for cis and trans isomers.


cis


trans

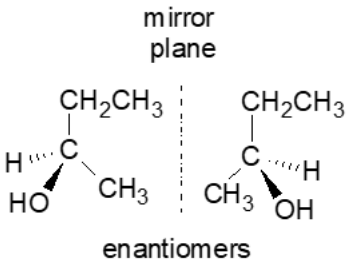
Note: C=C in a ring cannot exhibit cis-trans isomerism

Note : Alkenes with four different substituents across C=C also exhibit cis-trans isomerism.
Another naming convention (E / Z) is used instead.
**E/Z naming is not in H2 syllabus.

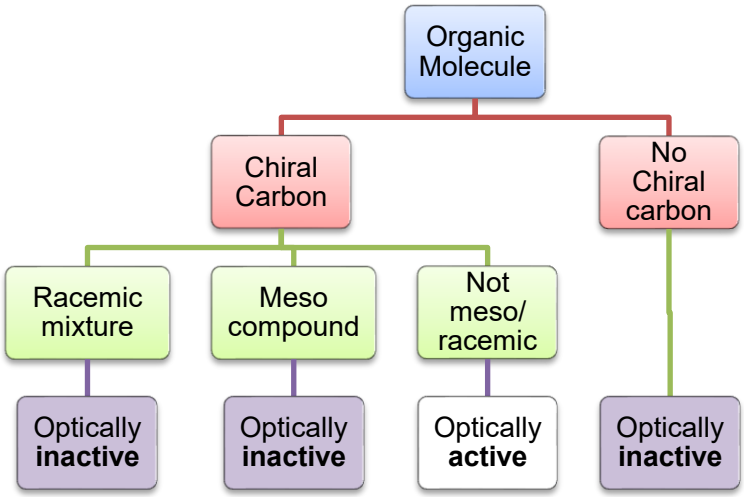


Optical isomerism

Requirement : A chiral carbon (C atom bonded to 4 unique groups)
We must show the **3-D tetrahedral arrangement around the chiral C** for optical isomers.

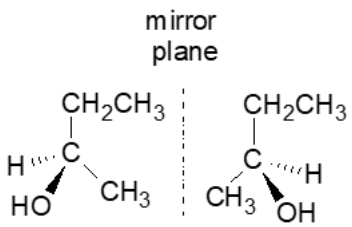


Optical activity of organic molecules



Racemic mixture

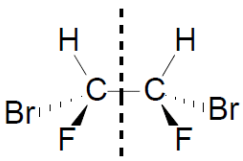
Equal amounts of the 2 enantiomers
-Rotation of plane of plane-polarised light by each enantiomer cancels out completely



50 : 50 ratio

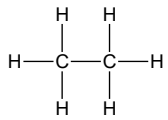
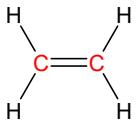
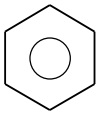
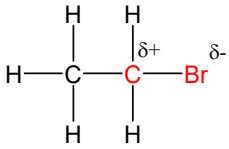
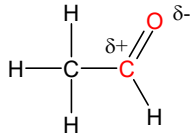
Meso compound

A compound with 2 chiral carbons **AND** internal plane of symmetry
-Rotation of plane of plane-polarised light by each chiral carbon cancels out completely by the other.



Reaction Mechanisms for H2 Chemistry

A chemical equation shows the reactants and products of a chemical reaction in their stoichiometric ratios. A reaction mechanism shows us the detailed reaction process which is not reflected in a chemical equation.

Functional Group	Reactive Site	Species reacting with the C atom	Reaction Type
Alkane 	Non-polar C−H bond	Free Radical	Free Radical Substitution
Alkene 	π electrons in C=C act as source of electrons e^- rich (-ve) C attracts electrophile (+ve)	Electrophile (electron deficient)	Electrophilic Addition (break C=C π bond)
Arene 	Delocalised π electron cloud in ring results in a region of high electron density e^- rich (-ve) C attracts electrophile (+ve)	Electrophile (electron deficient)	Electrophilic Substitution
Halogenoalkanes 	δ+ C in the polar C−Halogen bond e^- deficient (δ+) C attracts nucleophile (-ve)	Nucleophile (electron rich)	Nucleophilic Substitution
Carbonyl Compounds 	δ+ C in the polar C=O bond e^- deficient (δ+) C attracts nucleophile (-ve)	Nucleophile (electron rich)	Nucleophilic Addition (break C=O π bond)

Note:
Benzene rings prefer to undergo substitution rather than addition due to the resonance stabilisation from delocalisation of the π-electron cloud in benzene. Addition reaction would disrupt the aromatic stability and hence it is not favourable.

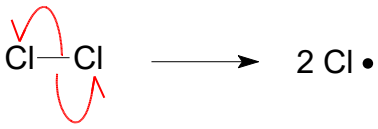
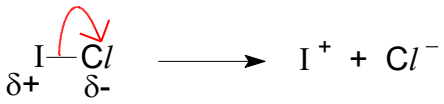
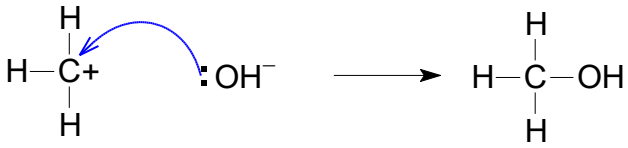
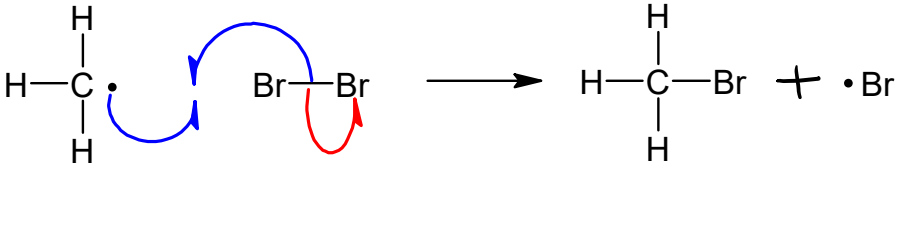
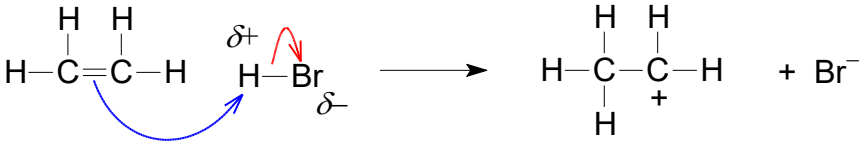
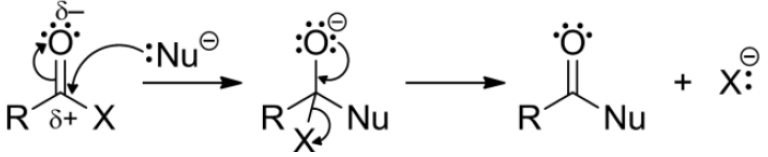
To describe the mechanism of a known organic reaction

(i) Name the type of reaction mechanism undergone.

(ii) Show reaction step-wise using equations – include intermediates or transition states. Indicate the slow step where necessary.

(iii) Indicate δ+ and δ- on the polar bond undergoing reaction (if any).

(iv) Show movement of arrows: Electron flow from electron donor (bond or lone pair electrons) to electron acceptor (atom or existing bond)

<table>
<tr><td rowspan="2">Breaking bonds
(arrow start from the covalent bond)</td><td>Homolytic
(Half arrow to each atom) and produce radicals</td><td>  </td></tr>
<tr><td>Heterolytic
(Full arrow to the more electronegative atom)</td><td>  </td></tr>
<tr><td>Forming bonds
(Arrow start from lone pair electrons to the destination atom)</td><td colspan="2">  </td></tr>
<tr><td>Breaking and forming bonds</td><td colspan="2"> 
 
A π bond is formed when an electron pair moves to an existing sigma bond
 
nucleophilic acyl substitution
FYI</td></tr>
</table>

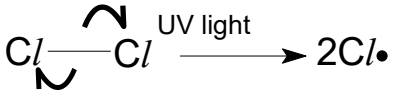
Mechanism: Free Radical Substitution (Alkane)

- Free radicals are atoms or groups of atoms which have a single unpaired electron.
- Free radicals are formed if a bond splits evenly - each atom getting one of the two electrons. (**homolytic fission**)

E.g. Describe the mechanism of free radical substitution between propane, C_3H_8 and Cl_2 (g), UV light to give 2−chloropropane

Free Radical Substitution

Stage 1: Initiation



Important Note:
Initiation stage
- must use half arrows to show homolytic fission
- Indicate "UV" above the reaction arrow

Stage 2: Propagation

$CH_3CH_2CH_3 + Cl\bullet \rightarrow CH_3\dot{C}HCH_3 + HCl$

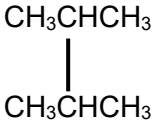
$CH_3\dot{C}HCH_3 + Cl_2 \rightarrow CH_3CHClCH_3 + Cl\bullet$

Propagation stage
- radical reacts with molecule to produce new radical and new molecule
- Use structural formula for alkane to clearly show the C atom that contains the radical. indicate "•" directly next to the C radical.

Stage 3: Termination

$2\ Cl\bullet \rightarrow Cl_2$

$Cl\bullet + CH_3\dot{C}HCH_3 \rightarrow CH_3CHClCH_3$

$CH_3\dot{C}HCH_3 + CH_3\dot{C}HCH_3 \rightarrow$ 

Termination stage
- 2 radicals react to give a compound
- show any 2 equations

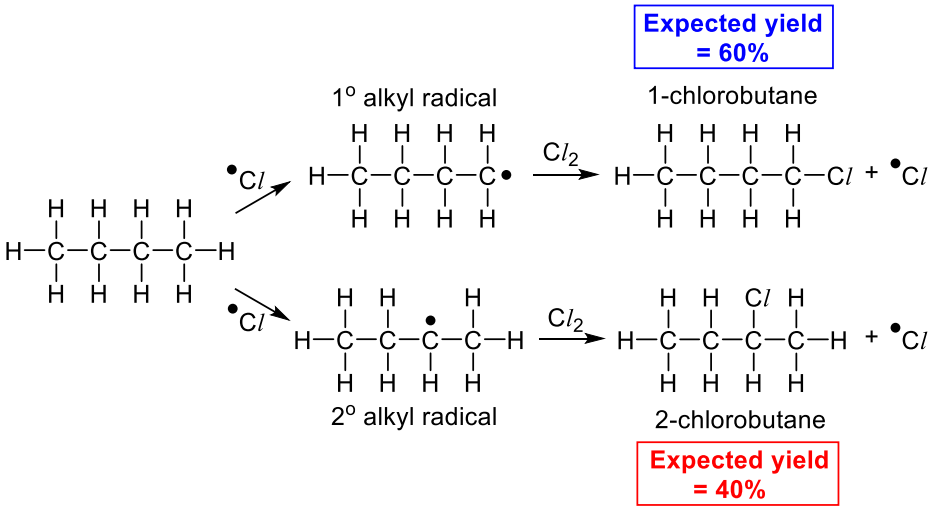
Mechanism: Free Radical Substitution (Alkane)

Things to note for Free Radical Substitution :

(i) Expected yield for monosubstitution of alkane (Based on probability)

In higher members of alkanes, substitution of hydrogen atoms at different carbon atoms leads to different products.

e.g. Butane reacts with chlorine in the presence of UV light to form two mono-substituted products as shown below.



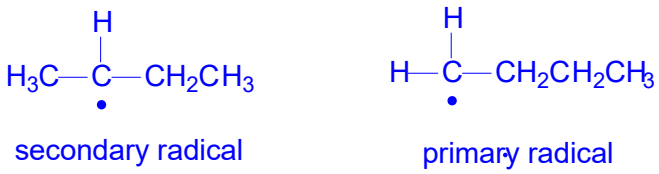
There are a total of 4 H atoms that can be substituted to form 2-chlorobutane while there are a total of 6 H atoms that can be substituted to form 1-chlorobutane

Assuming each H has an equal chance of being substituted by C*l*, thus molar ratio of 1-chlorobutane and 2-chlorobutane formed is 60% : 40%, i.e. 3 : 2.

(ii) Rate of substitution at 1°, 2° & 3° carbon atoms (ONLY discuss using this factor when question state that experimental yield is different from theoretical yield)

Based on the probability consideration, substitution of H atoms of butane would produce 1-chlorobutane and 2-chlorobutane in the expected molar ratio of **60% : 40%**. However, the experimental yields for 1-chlorobutane and 2-chlorobutane are 30% and 70% respectively.

Explain the discrepancy between the expected and experimental ratios of the monochlorinated products?



2-chlorobutane is formed via a secondary (2°) radical whereas 1-chlorobutane is formed via a primary (1°) radical.

Secondary (2°) radical is more stable than primary (1°) radical as there are **more electron-donating alkyl groups** which can **decrease the electron deficiency of the radical**.

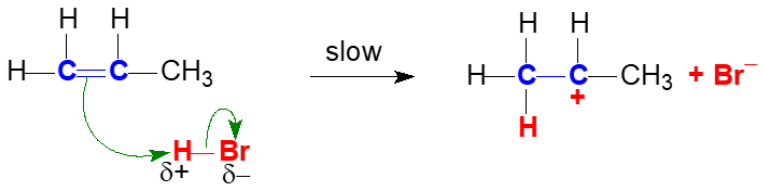
Hence, **secondary (2°) radical is formed preferentially** and yield of 2-chlorobutane is higher than the expected yield of 40%.

Mechanism: Electrophilic Addition (Alkene)

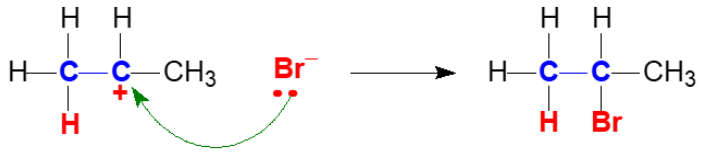
E.g. Describe the mechanism of electrophilic addition between propene, C_3H_6 and HBr (g)

Electrophilic Addition

Step 1: e^- rich C=C reacts with electrophile to give carbocation



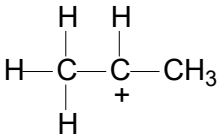
Step 2: carbocation reacts with e^- rich species



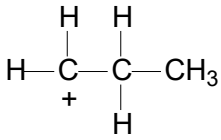
Important Note:
- State the name of mechanism
- Show separation of charges (δ+/δ−) on electrophile and charges on ions
- Between 2 species: Arrows ALWAYS flow from ***electron rich region (π bond of C=C or lone pair of nucleophiles***) to electron deficient region (electrophile or carbocation)
- Bond breaking within a molecule will be from bond pair to δ− atom.
- Indicate the slow step

Explain why 2–bromopropane is the major product?

Electrophile can attack either of the carbon atom in the C=C bond and hence leads to two possible carbocations.



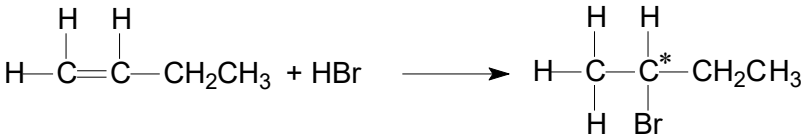
2^o carbocation



1^o carbocation

The C+ in the 2^o carbocation is stabilised to a larger extent due to 2 electron-donating alkyl groups. The more stable 2^o carbocation is formed more abundantly in the rate-determining step, leading to a higher yield of the product.

Explain why the reaction of but-1-ene with HBr (g) produces a racemic mixture?



The **product contains a chiral carbon that is produced in Step 2 of the electrophilic addition mechanism where the Br^- can attack the trigonal planar carbocation from either side with equal probability.** The two enantiomers are produced in equal amounts. The products are a racemic mixture which is optically inactive as the rotation of plane of plane-polarized light by each enantiomer cancels out completely by the other.

Mechanism: Electrophilic Substitution (Benzene)

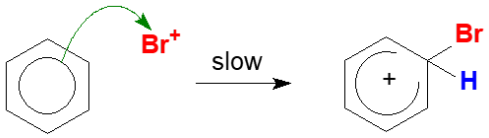
- Benzene resists addition reactions because that would involve breaking the delocalisation of π electron and losing that stability.
- Electrophilic substitutions involves replacing H atom on benzene with
  - (i) Halogen atoms (e.g. –C*l* using Cl_2 and anhydrous A*l*Cl_3 catalyst)
  - (ii) Alkyl group (e.g. $-CH_3$ using CH_3Cl and anhydrous A*l*Cl_3 catalyst)
  - (iii) Ketone group (e.g. $-COCH_3$ using CH_3COCl and anhydrous A*l*Cl_3 catalyst)
  - (iv) Nitro group (e.g. $-NO_2$ using conc HNO_3 and conc H_2SO_4 catalyst)

Describe the mechanism of electrophilic substitution between benzene and Br_2, anhydrous $FeBr_3$

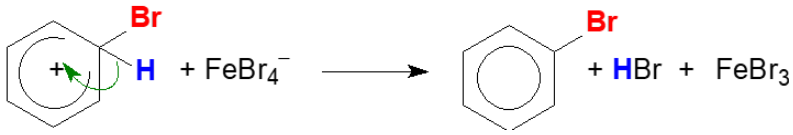
Step 1: reacts with catalyst to generate strong electrophile (+ charge)

$$Br_2 + FeBr_3 \rightarrow FeBr_4^- + \mathbf{Br^+}$$

Step 2: e⁻ rich benzene reacts with electrophile to give Arenium carbocation



Step 3: break C–H bond to restore aromaticity of benzene and regenerate catalyst



Important Note:
(i) State the name of mechanism

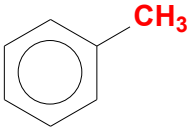
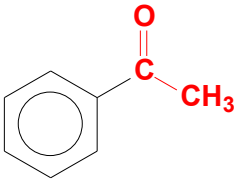
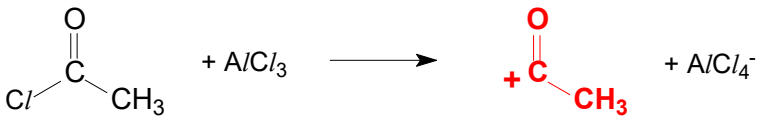
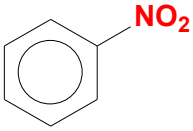
(ii) Show reaction with catalyst to generate strong electrophile

(iii) Arrows ALWAYS flow from ***electron rich region (π electron cloud of benzene or lone pair of nucleophiles***) to electron deficient region (electrophile)

(iv) Indicate the slow step

(v) Show regeneration of catalyst

What about mechanism for the conversion of benzene to

	**Step 1 :** $CH_3Cl + AlCl_3 \rightarrow AlCl_4^- + \mathbf{^+CH_3}$ **Steps 2 & 3 are similar to the example above**
	**Step 1 :**  **Steps 2 & 3 are similar to the example above**
	**Step 1 :** HNO_3 (conc) + H_2SO_4 (conc) → $\mathbf{^+NO_2}$ + HSO_4^- + H_2O **Step 2 similar to the example above** **Step 3 HSO_4^- reacts to regenerate H_2SO_4 catalyst**

Mechanism: Nucleophilic Substitution (Halogenoalkane, R−X)

Nucleophilic substitution involves nucleophiles of:

(i) Hydroxide ions from **aqueous** KOH or NaOH (forms alcohol, R−OH)

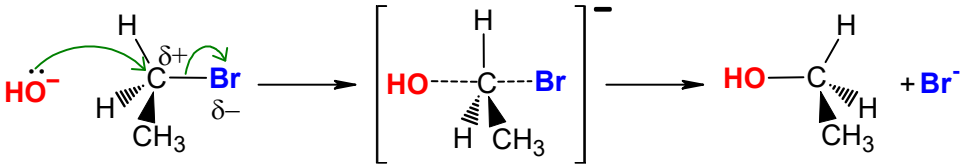
(ii) Cyanide ions (CN^-) from ethanolic KCN or NaCN (forms nitriles, R−C≡N)

(iii) Ethanolic NH_3 (forms amines, R−NH_2)

S_N2 Mechanism (two reactants in SLOW step) – for primary halogenoalkane

E.g. Mechanism of nucleophilic substitution between CH_3CH_2Cl and NaOH (aq), heat

One-step showing nucleophile attacks from opposite side of the leaving group halogen.



Transition State

Inversion of Stereochemistry

Note:
- Based on conservation of charges,
  - the transition state carries a negative charge if the nucleophile is an anion (^-OH)
  - the transition state carries no charge if the nucleophile is NH_3
- Only 1 organic product is formed

Important Note

(i) State the name of the mechanism

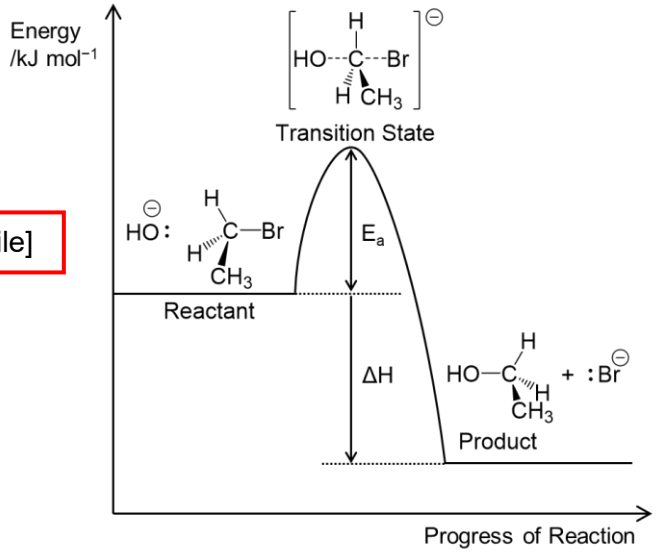
(ii) Show separation of charges (δ+/δ−) on C–X and charges on ions

(iii) Arrows ALWAYS flow from ***lone pairs*** of nucleophiles (electron rich) to electrophiles (electron poor)

(iv) Must show and label the transition state where the nucleophile (OH) is OPPOSITE the halogen atom (Br)

(v) Draw displayed formula to show the inversion of configuration of the organic compounds.

The energy profile or reaction pathway diagram for the S_N2 mechanism is given below.



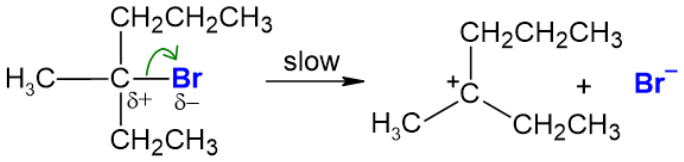
Rate = k[RX][Nucleophile]

Mechanism: Nucleophilic Substitution (Halogenoalkane, R−X)

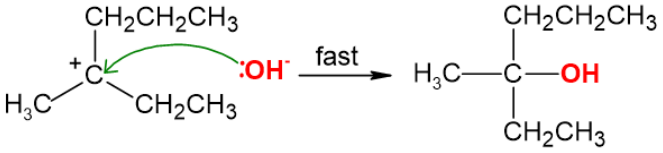
S_N1 Mechanism (one reactant in SLOW step) – for tertiary halogenoalkane

E.g. Mechanism of nucleophilic substitution between tertiary R−X and NaOH (aq), heat

Step 1: breaking C–X bond to generate carbocation



Step 2: Nucleophile reacts with the carbocation



Important Note

(i) State the name of mechanism

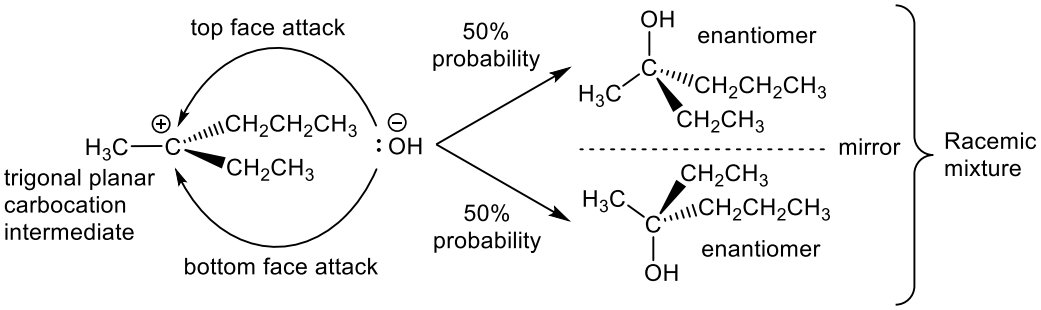
(ii) Show separation of charges (δ+/δ−) on C–X and charges on ions

(iii) Arrows ALWAYS flow from ***lone pairs*** of nucleophiles (electron rich) to electrophiles (electron poor)

(iv) Indicate the slow step

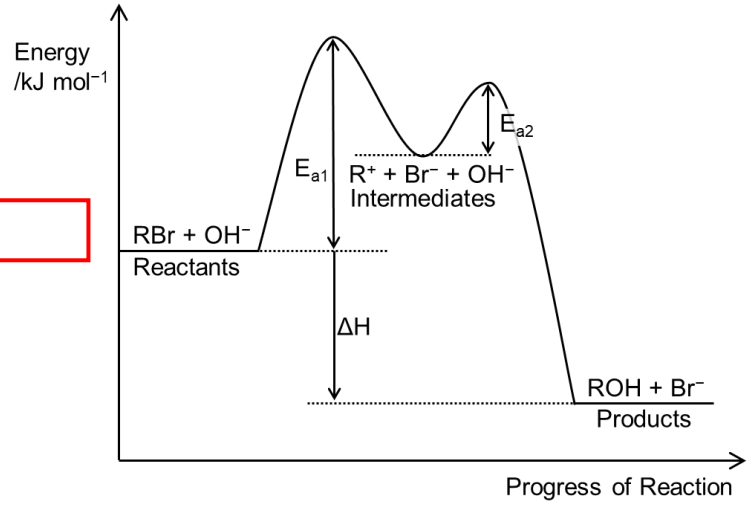
****Explain why the above reaction produces a racemic mixture?***

The product contains a chiral carbon that is produced in Step 2 of the mechanism where the HO^- can attack the trigonal planar carbocation from either side with equal probability. The two enantiomers are produced in equal amounts. The products are a racemic mixture which is optically inactive as the rotation of plane of plane-polarized light by each enantiomer cancels out completely by the other.



The energy profile or reaction pathway diagram for the S_N1 mechanism is given below.

Rate = k[RX]



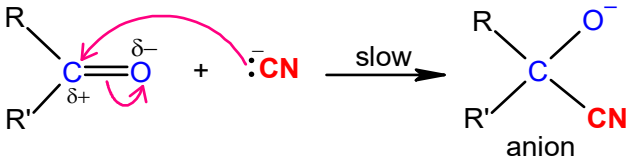
Mechanism: Nucleophilic Addition (Carbonyl compounds)

HCN is added across the C=O bonds.

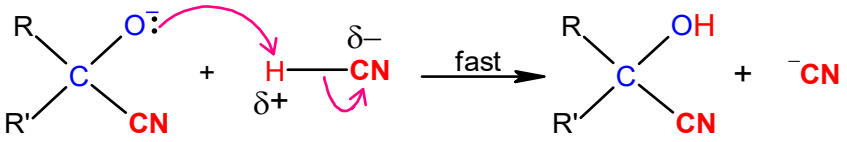
- Reagents used are either
  - Cold HCN with trace amount of NaCN is added OR
  - Cold HCN with trace amount of NaOH is added to produce NaCN
- Hence, a mixture of HCN and free CN^- ions is produced.

E.g. Mechanism of nucleophilic addition between ketone and HCN with NaCN catalyst.

Step 1: Nucleophile ($^-$CN from NaCN) reacts with δ+C of C=O to give anion intermediate



Step 2: HCN reacts with anion intermediate to give cyanohydrin and regenerate $^-$CN



Important Note

(i) State the name of the mechanism

(ii) Show separation of charges (δ+/δ−) on C=O and charge on $^-$CN ions

(iii) Show lone pair electrons on **C of $^-$CN and on O$^-$**

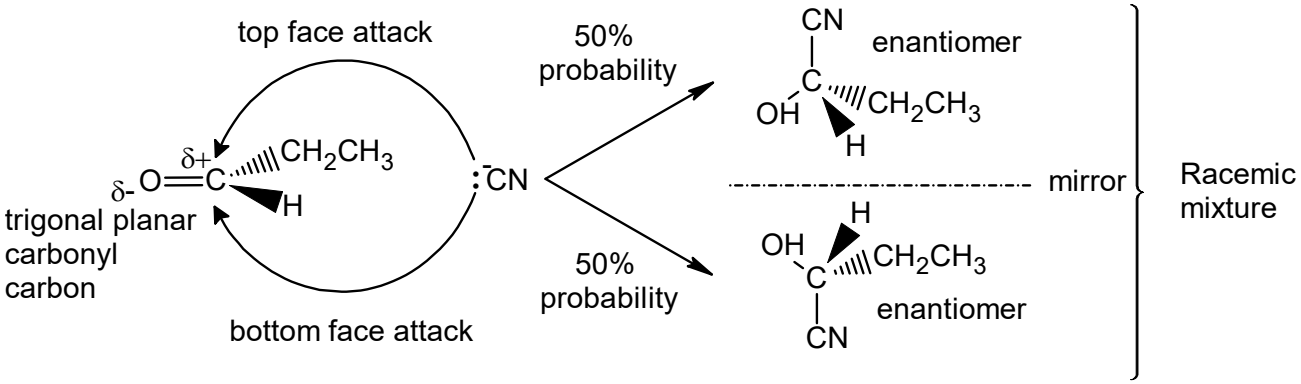
(iv) Curly arrows to show flow of electrons

- Lone pair from C of $^-$CN to δ+ C of C=O
- C=O bond to δ− O
- lone pair on O$^-$ to δ+ H of HCN
- H−CN bond to C

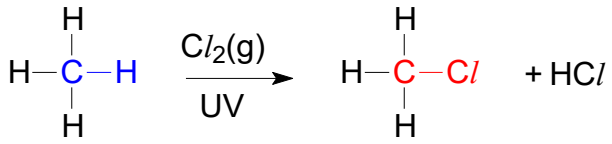
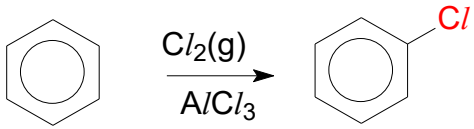
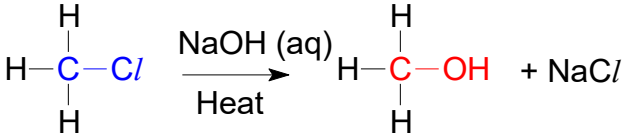
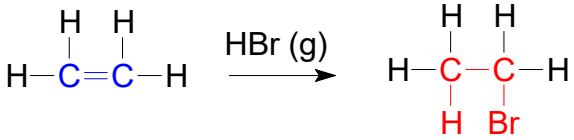
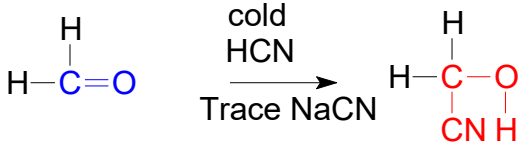
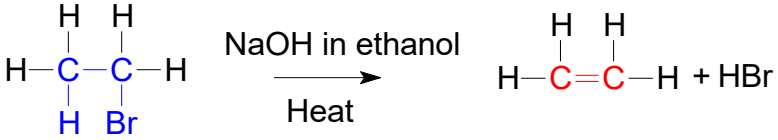
(v) Label step 1 as "slow"

Explain why a racemic mixture is produced from this reaction?

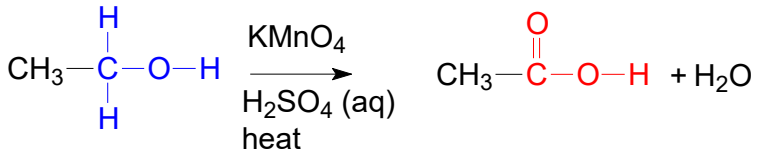
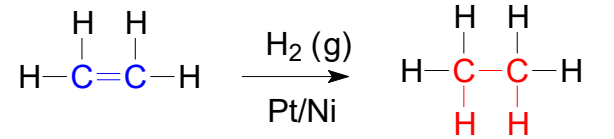
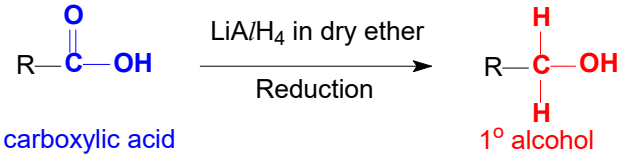
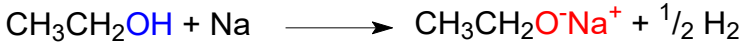
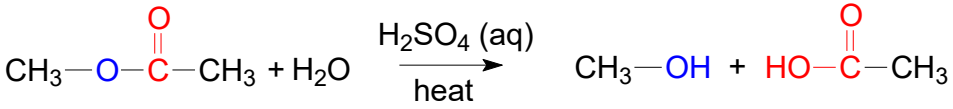
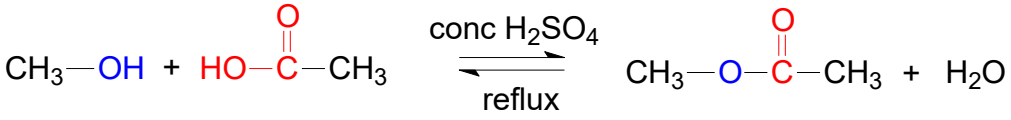
The product contains a chiral carbon that is produced in Step 2 of the mechanism where the $^-$CN can attack the trigonal planar carbon of C=O from either side with equal probability. The two enantiomers are produced in equal amounts. The products are a racemic mixture which is optically inactive as the rotation of plane of plane-polarized light by each enantiomer cancels out completely by the other.



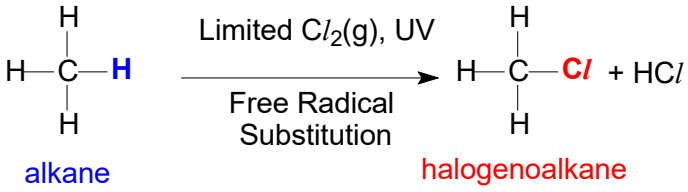
Types of organic reactions (Part 1)

Type of reaction	Examples	Reaction sites
Free radical substitution		Relatively unreactive C atom in alkane Break non-polar C−H bond
Electrophilic substitution		Electron rich C atom in benzene Break non-polar C−H bond
Nucleophilic substitution		Electron deficient C atom in halogenoalkane Break polar C−X bond
Electrophilic addition		Electron rich C atom in alkene Break C=C π bond
Nucleophilic addition		Electron deficient C atom in carbonyl Break C=O π bond
Elimination		Elimination of HX or H_2O from 2 adjacent C atoms Form new π bond

Types of organic reactions (Part 2)

Type of reaction	Examples	Reaction sites
Oxidation		Oxidation of: • alkene • alkyl side chain of benzene • 1° and 2° alcohol • aldehyde • methanoic acid and ethanedioic acid
Reduction	 	Reduction of: • alkene • nitrile • aldehyde & ketone • carboxylic acid • amide
Redox		Reaction of alcohol/phenol/carboxylic acid with Na(s)
Hydrolysis		Hydrolysis of: • nitrile • ester • amide
Condensation		Formation of ester and amide Reaction of carbonyl with 2,4-DNPH
Acid-base reaction/ Neutralisation		Reaction of carboxylic acid/phenol with base. Reaction of amine with acid.

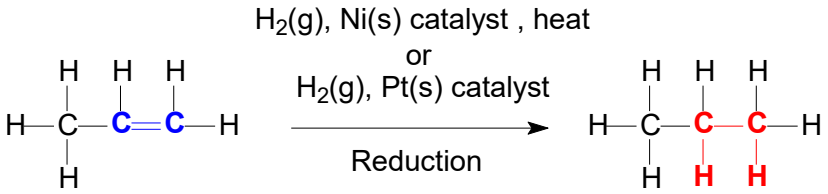
Alkane



alkane → halogenoalkane

*If excess Cl_2 is used, poly-substitution occurs. E.g. producing CH_2Cl_2, $CHCl_3$

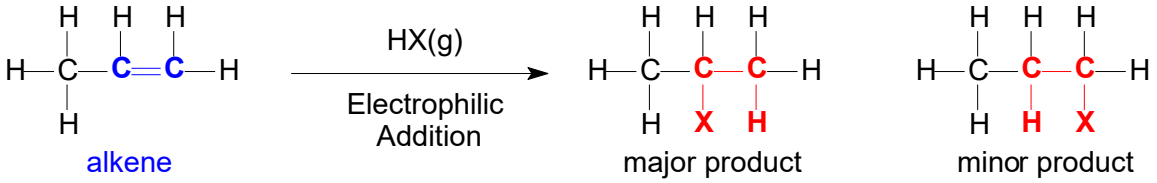
Alkene



alkene → alkane

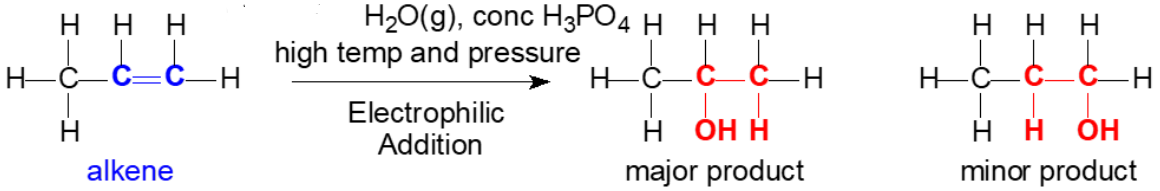
*Alkene cannot be reduced by $LiAlH_4$ (C=C is electron rich, and will repel the H^- ion from $LiAlH_4$)

Alkene



alkene → halogenoalkane

Alkene

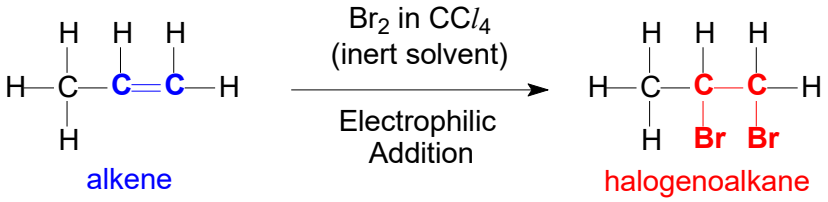


alkene → alcohol

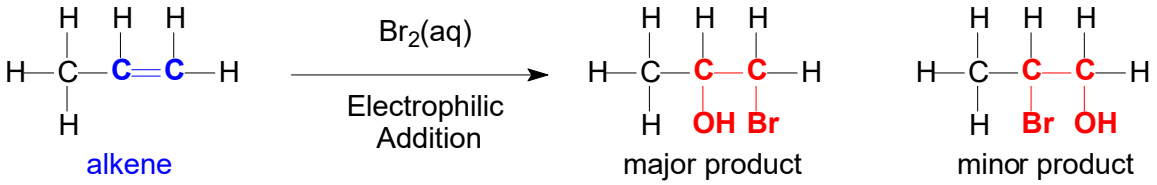
*H^+ from conc H_3PO_4 acts as the electrophile to react with C=C.

*For Electrophilic Addition reactions, electrophile is added first during step 1 of the mechanism, forming a more stable carbocation that leads to the major product.

Alkene



Alkene

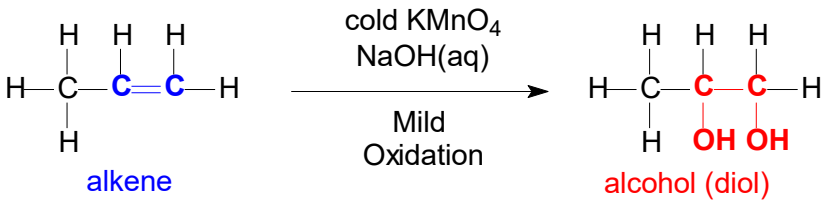


*Br^+ from Br_2 acts as the electrophile to react with C=C. H_2O can react with the carbocation, forming C−OH bond.

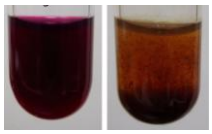
<Distinguishing Test>

Orange Br_2(aq) decolourised

Alkene



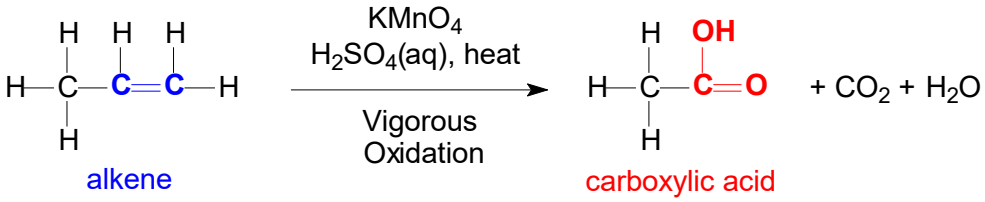
*cold temperature only allows the breaking of the π bond in C=C

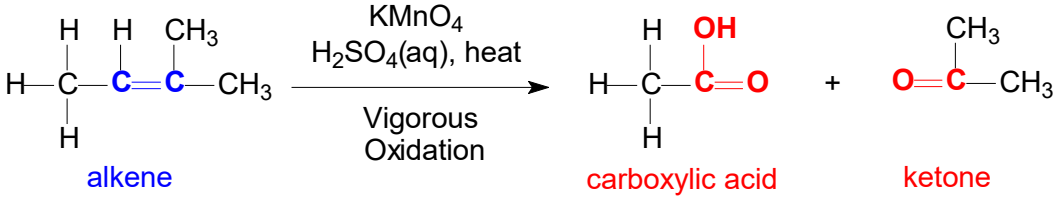


<Distinguishing Test>

In alkaline medium,
purple $KMnO_4$ decolourised and brown solid MnO_2 is formed.

Alkene





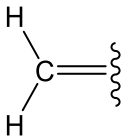
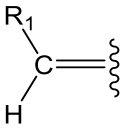
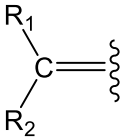
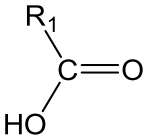
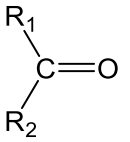
*high temperature allows the breaking of **BOTH** the σ and π bond in C=C bond.

Distinguishing Test

In acidic medium, purple $KMnO_4$ decolourised.
Vigorous oxidation of $C=CH_2$ also produces effervescence of $CO_2(g)$ that forms white ppt with limewater.

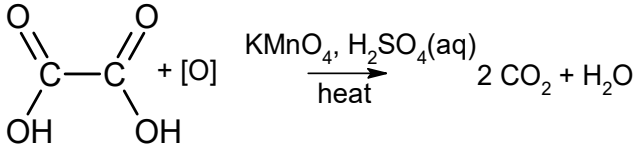
** Alkene cannot be oxidized by acidified $K_2Cr_2O_7$ ($K_2Cr_2O_7$ is a weaker oxidizing agent as compared to $KMnO_4$)

The **types of products** obtained for vigorous oxidation of alkenes depends on the **number of hydrogen atoms** attached to the C atom of the C=C double bond.

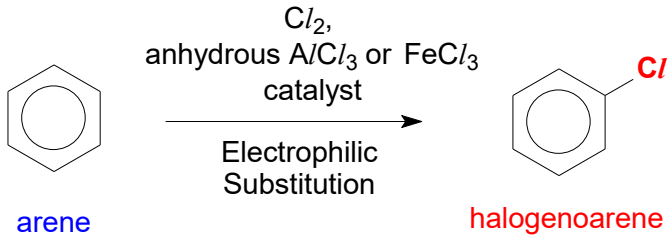
Structure	 terminal alkene		
Products after oxidation with hot acidic $KMnO_4$	CO_2 and H_2O	 Carboxylic acid	 Ketone

NOTE: Oxidative cleavage of large alkene with multiple C=C bonds may produce ethanedioic acid (HOOC-COOH) as a product.

Ethanedioic acid is further oxidised by hot acidified $KMnO_4$ to give CO_2 and H_2O



Arene

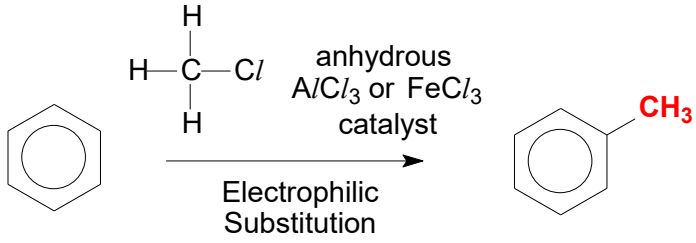


arene — halogenoarene

−H of benzene is substituted by −Cl

*Anhydrous condition is needed such that $AlCl_3$ can act as a Lewis acid (electron pair acceptor) to react with Cl_2 to generate strong electrophile Cl^+.
If H_2O is present, $AlCl_3$ would react with H_2O to give $[Al(H_2O)_6]^{3+}$ (Refer to chapter : The Periodic Table), and loses the ability to react with Cl_2.

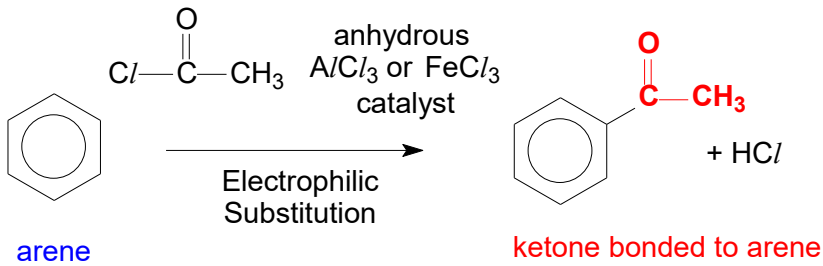
Arene



arene — alkylarene

−H of benzene is substituted by $-CH_3$

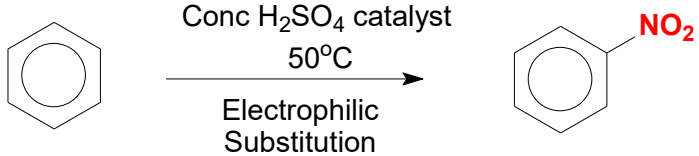
Arene



arene — ketone bonded to arene

−H of benzene is substituted by $-COCH_3$

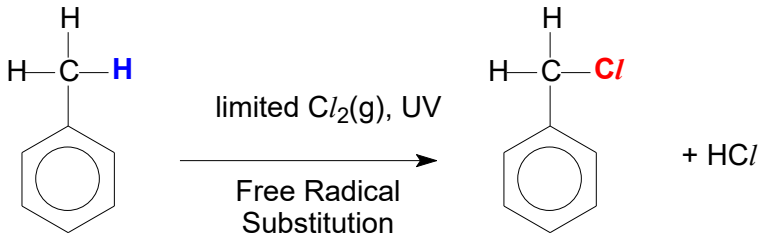
Arene



arene — nitroarene

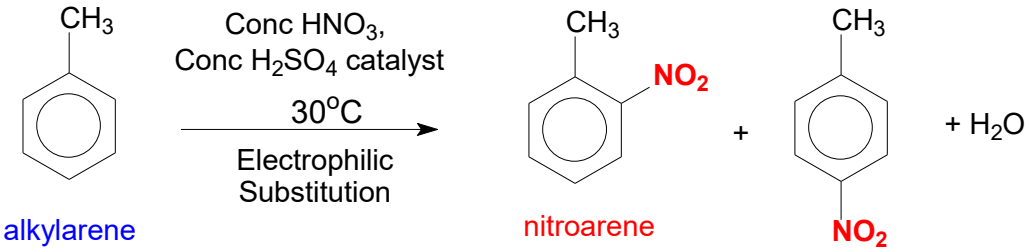
−H of benzene is substituted by $-NO_2$

Alkyl Arene



alkylarene — halogenoalkane

Alkyl Arene



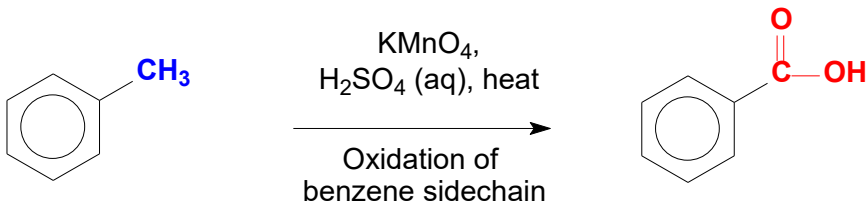
alkylarene nitroarene

Note:

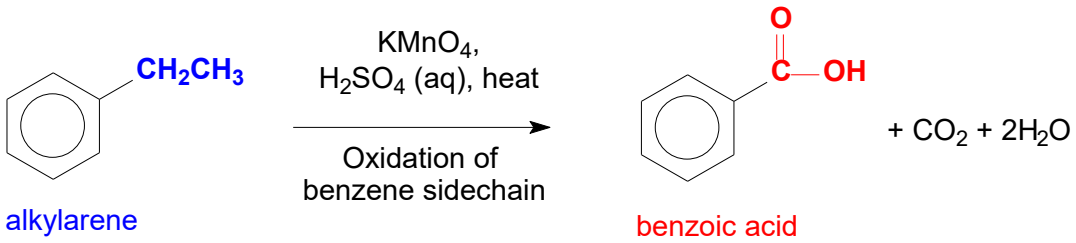
1) alkyl group is 2/4-directing (Refer to Data Booklet), hence the new electrophiles would substitute the benzene H atom at C_2 and C_4 w.r.t. to $-CH_3$.

2) alkyl group is weakly activating (Refer to Data Booklet), hence nitration of methyl benzene can occur at 30°C.

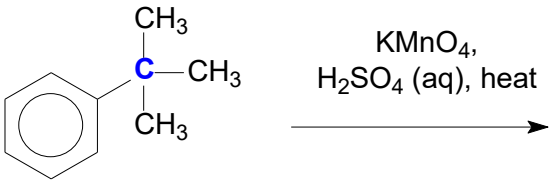
Alkyl Arene



alkylarene benzoic acid

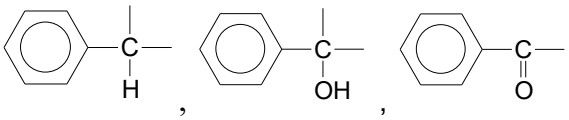


alkylarene benzoic acid



NO REACTION

alkylarene



groups can undergo side chain oxidation by hot acidified $KMnO_4$ to give benzoic acid.

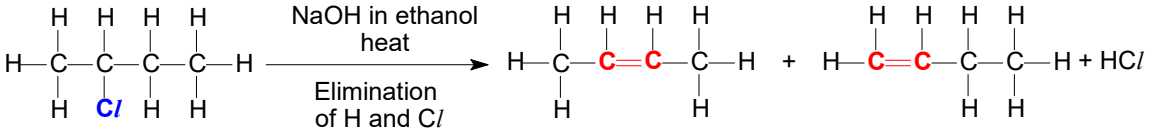
Any additional C or H atom beyond the first carbon in the side chain will be oxidized to CO_2 and H_2O.

<Distinguishing Test>

In acidic medium, purple $KMnO_4$ decolourised.

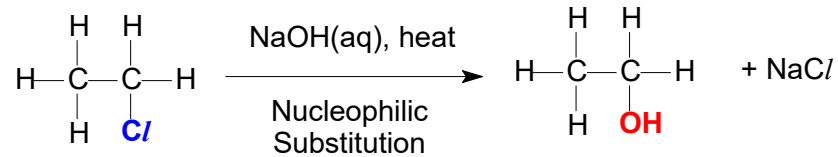
effervescence of $CO_2(g)$ that forms white ppt with limewater.

Halogenoalkane

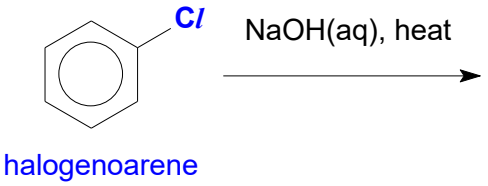


*NaOH in ethanol leads to elimination reaction
Elimination reaction would prefer the formation of alkene with more alkyl groups attached to the C=C.

Halogenoalkane

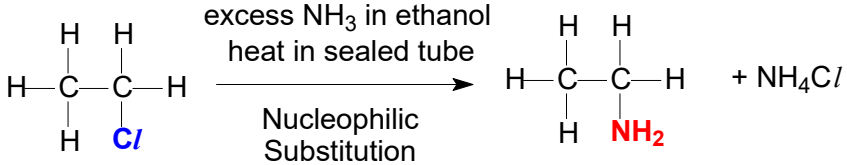


*NaOH in aqueous leads to nucleophilic substitution reaction
<Distinguishing Test> for halogenoalkane:
1) NaOH(aq), heat [Nu Sub]
2) excess HNO_3(aq) [remove unreacted OH^-]
3) $AgNO_3$ [precipitation of AgCl white ppt / AgBr cream ppt / AgI yellow ppt]



No nucleophilic substitution
(partial double bond in benzene C-Cl)

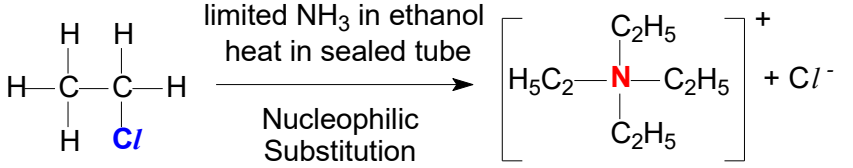
Halogenoalkane



halogenoalkane (limited)

amine

*If limited NH_3 is used, R−X would be present in excess. The amine produced would act as a nucleophile and undergo further rounds of nucleophilic substitution with R−X to give quaternary ammonium salt.



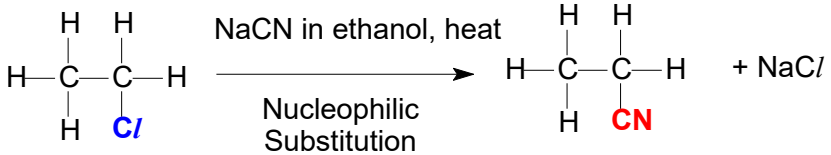
halogenoalkane in excess

quaternary ammonium salt

*If NH_3(aq) is used, NH_3 would react with H_2O to give OH^-, another nucleophile that would interfere with the nucleophilic substitution reaction.

*NH_3 is volatile, a sealed tube is required to prevent evaporation of NH_3 during heating

Halogenoalkane



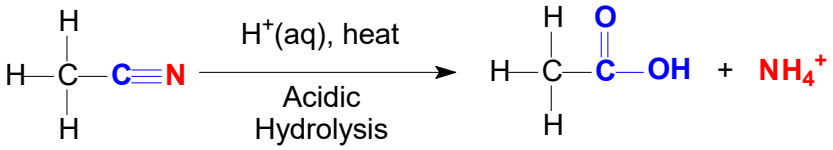
halogenoalkane

nitrile

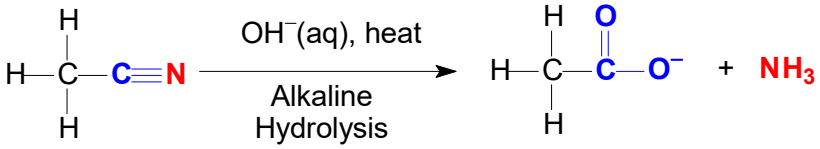
*If NaCN(aq) is used, −CN group will undergo hydrolysis when heated in presence of H_2O

Nitrile

Note:
Hydrolysis of −C≡N group in RCN produces RCOOH and NH_3.
During hydrolysis, δ+ C gains OH while δ− N gains H.
Acidic or alkaline medium is required to speed up the hydrolysis reaction.
RCOOH and NH_3 would undergo further acid-base reaction with the acidic/alkaline medium.

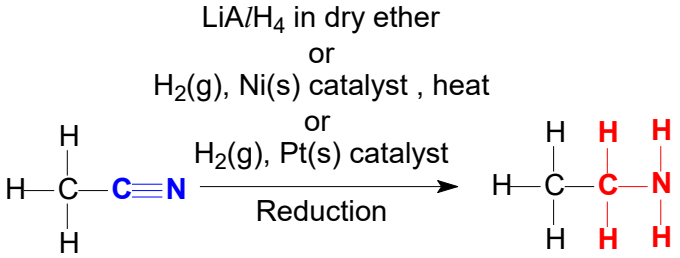


nitrile carboxylic acid



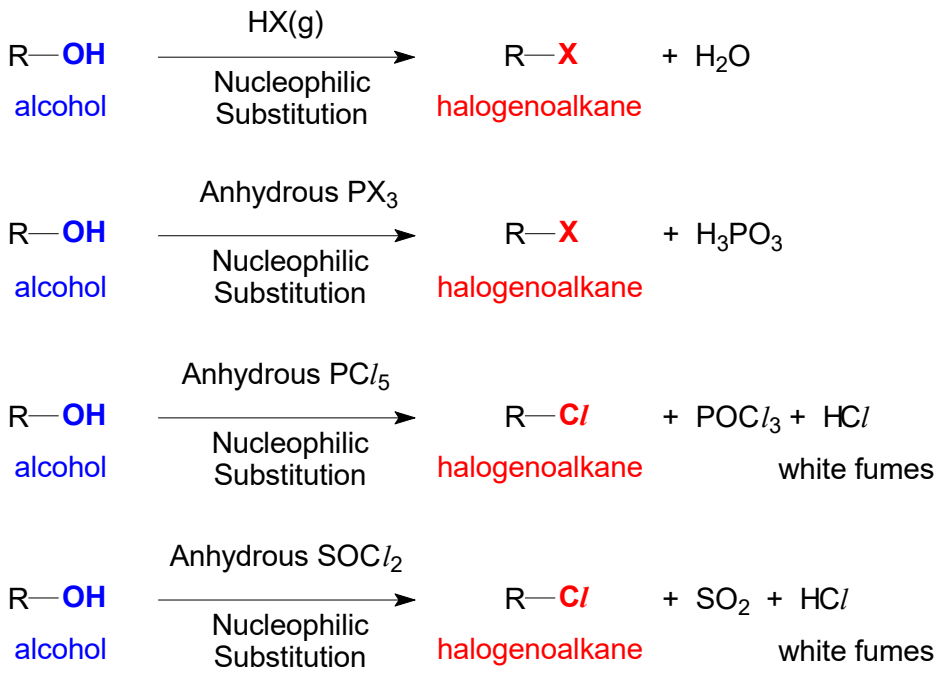
nitrile carboxylate ion

Nitrile



nitrile amine

Alcohol

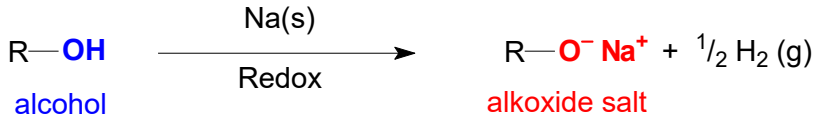


<Distinguishing Test>

Reaction of alcohol with PCl_5 and $SOCl_2$ produces white fumes of HCl(g).

*Anhydrous conditions are required for $SOCl_2$/PCl_3/PCl_5 as these compounds react readily with H_2O (Refer to Periodicity Notes)

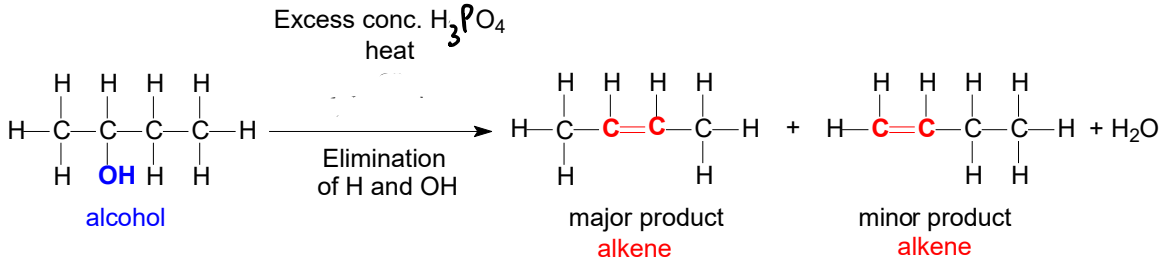
Alcohol



<Distinguishing Test>

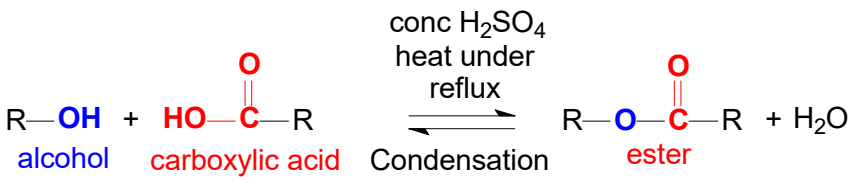
Effervescence of H_2(g) that "pops" with lighted splint

Alcohol

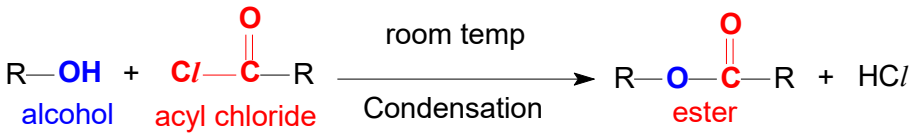


Elimination reaction would prefer the formation of alkene with more alkyl groups attached to the C=C.

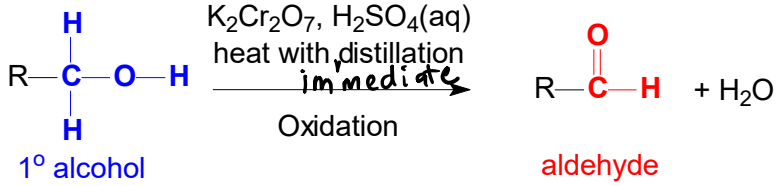
Alcohol



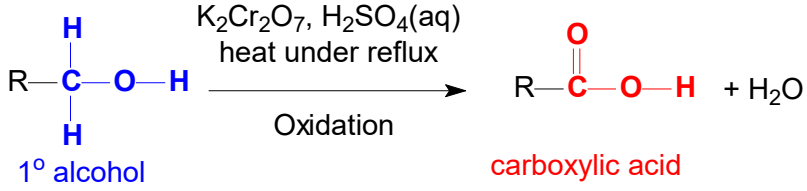
Alcohol

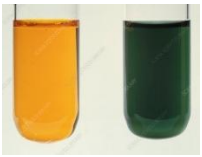


1° Alcohol



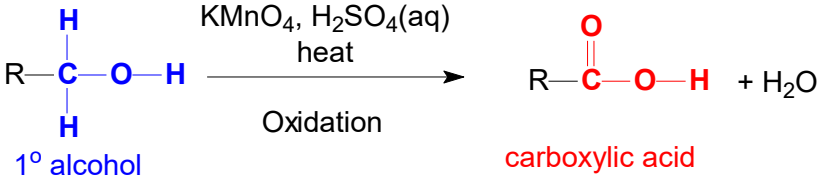
1° alcohol is oxidised to aldehyde. Aldehyde can be isolated via distillation due to its lower boiling point.





<Distinguishing Test>

In acidic medium, orange $K_2Cr_2O_7$ turns green.

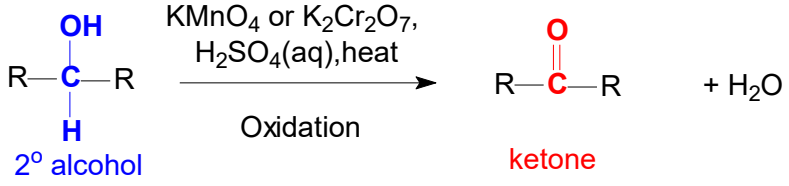


<Distinguishing Test>

In acidic medium, purple $KMnO_4$ decolourised.

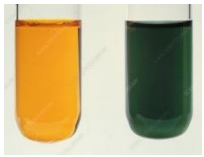
$KMnO_4$ is a stronger oxidising agent than $K_2Cr_2O_7$, 1° alcohol is oxidised directly to carboxylic acid.

2° Alcohol



<Distinguishing Test>

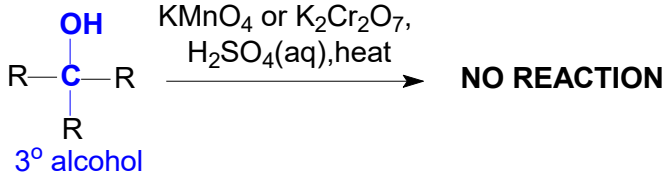
In acidic medium, purple $KMnO_4$ decolourised.



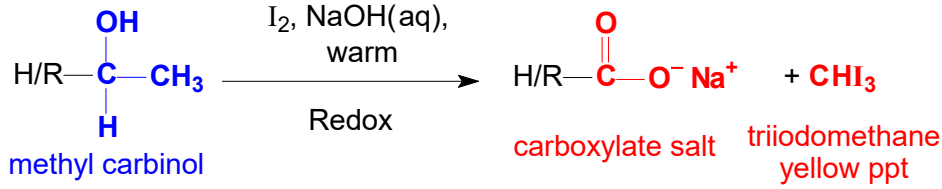
<Distinguishing Test>

In acidic medium, orange $K_2Cr_2O_7$ turns green.

3° Alcohol



Methyl carbinol



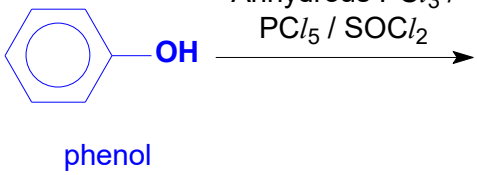
Methyl carbinol is oxidized to carboxylic acid, RCOOH. However, RCOOH undergoes acid-base reaction with the alkaline medium to give $RCOO^-$.

<Distinguishing Test>

Yellow ppt of CHI_3

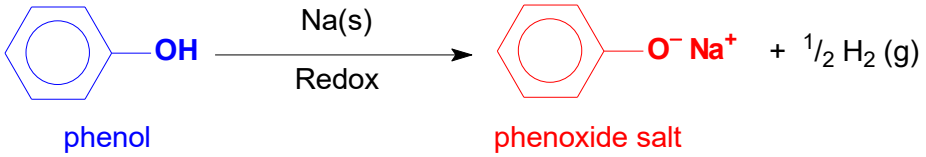
CH_3CH_2OH and $CH_3CH(OH)CH_3$ both give yellow ppt when reacted with warm alkaline I_2.

Phenol



No nucleophilic substitution (partial double bond in benzene C-OH)

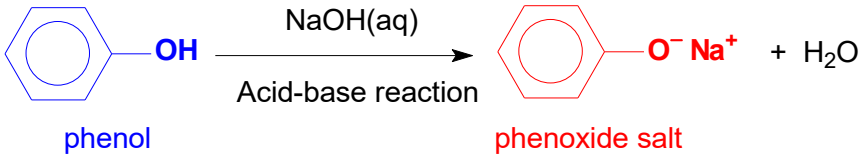
Phenol



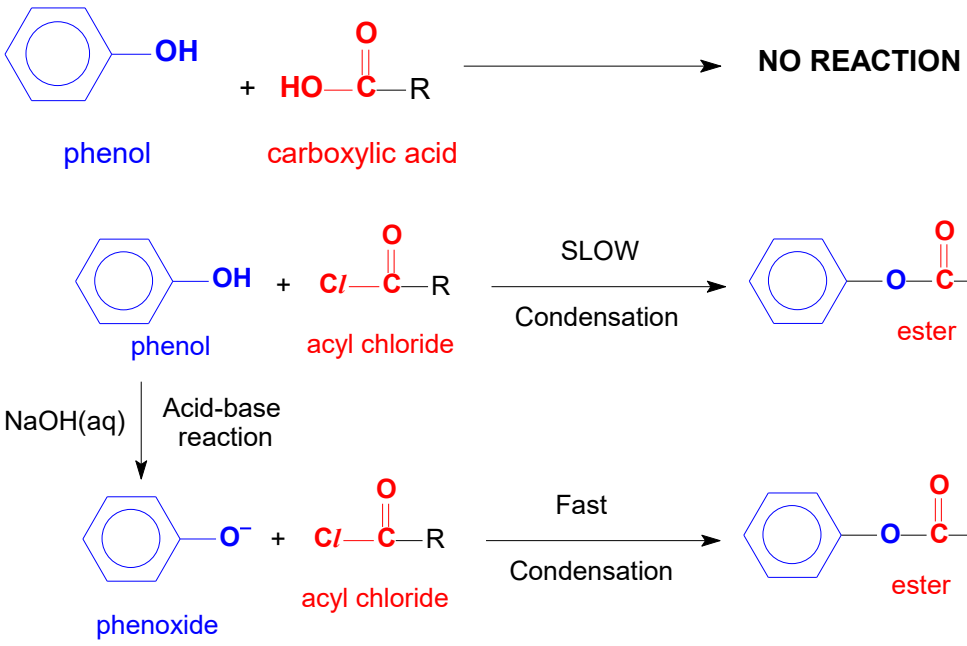
<Distinguishing Test>

Effervescence of $H_2(g)$ that "pops" with lighted splint

Phenol

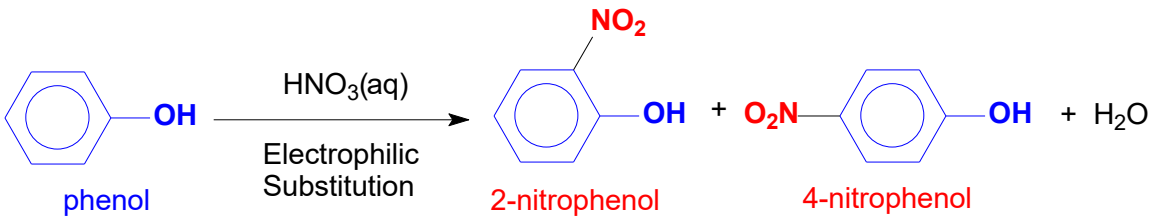


Phenol

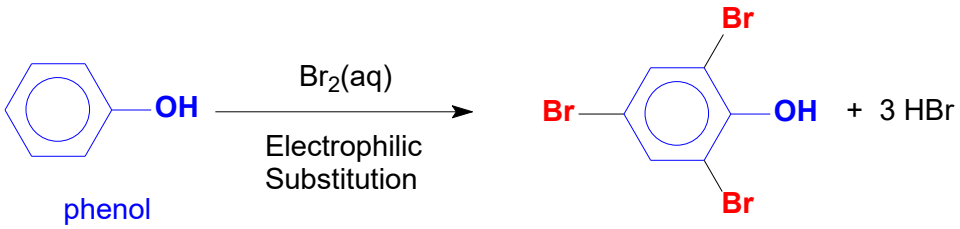


Note: phenoxide ion is a stronger nucleophile than phenol due to increase in electron density at the O atom. Compared to phenol, phenoxide can react **more readily** with the acyl chloride.

Phenol



phenol — 2-nitrophenol — 4-nitrophenol

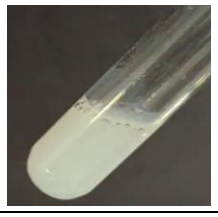


phenol — 2,4,6-trinitrophenol

Note:

1) −OH group is 2/4-directing (Refer to Data Booklet), hence the new electrophiles would substitute the benzene H atom at C_2 and C_4 w.r.t. to −OH.

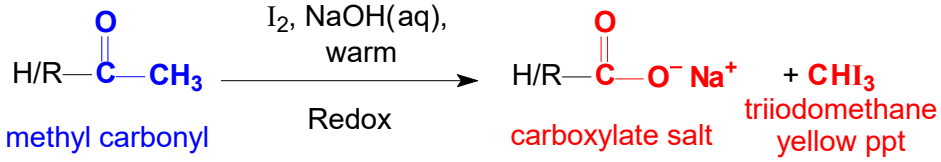
2) −OH group is strongly activating (Refer to Data Booklet), hence electrophilic substitution of phenol can occur at room temp without conc H_2SO_4 or anhydrous $FeBr_3$ catalyst.



<Distinguishing Test>

Decolorisation of orange $Br_2(aq)$ and formation of white ppt of 2,4,6-tribromophenol

Methyl carbonyl



methyl carbonyl — carboxylate salt — triiodomethane yellow ppt

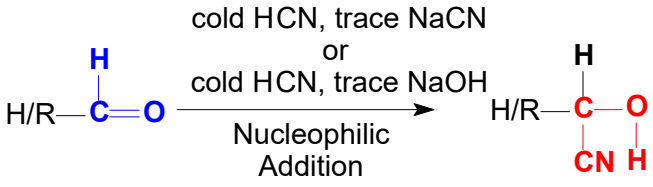
Methyl carbonyl is oxidized to carboxylic acid, RCOOH. However, RCOOH undergoes acid-base reaction with the alkaline medium to give $RCOO^-$.

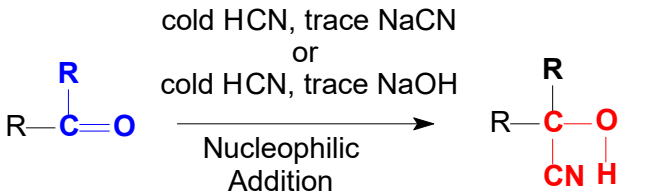
<Distinguishing Test>

Yellow ppt of CHI_3

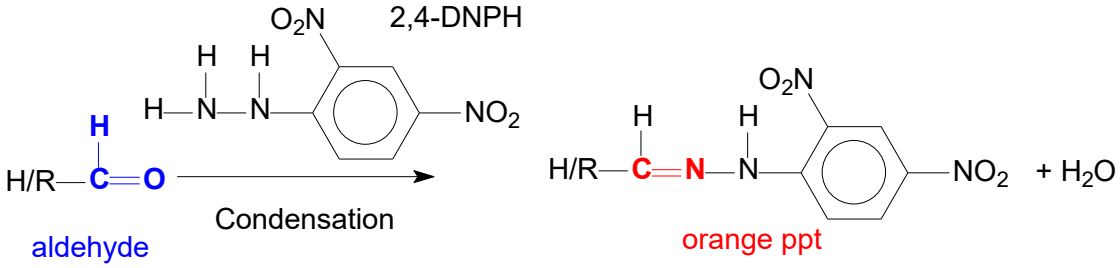
Ethanal and propanone both give yellow ppt when reacted with warm alkaline I_2

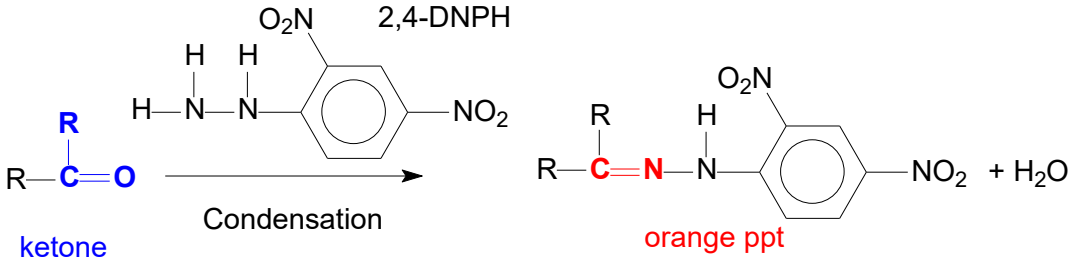
Aldehyde & Ketone





Aldehyde & Ketone

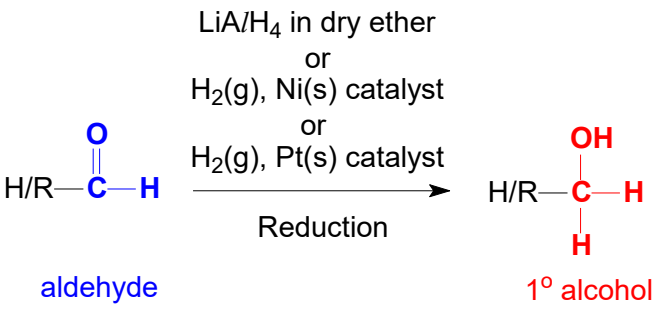


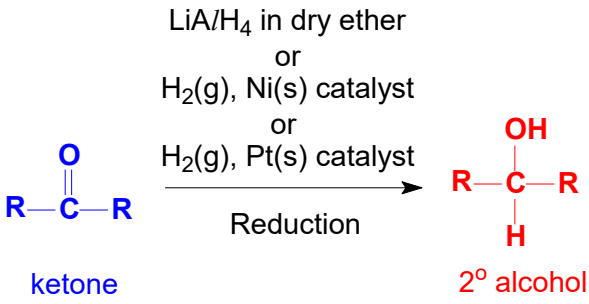


<Distinguishing Test>

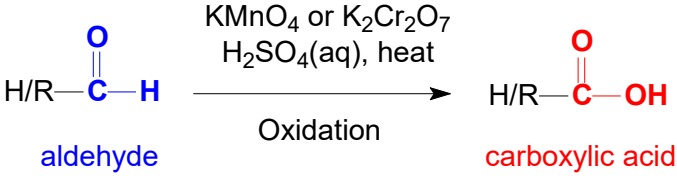
Formation of orange ppt with 2,4-dinitrophenylhydrazine (2,4-DNPH)

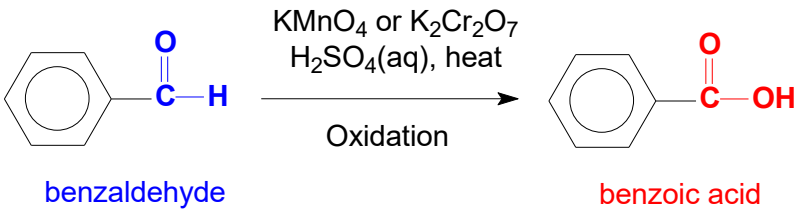
Aldehyde & Ketone





Aldehyde & Benzaldehyde





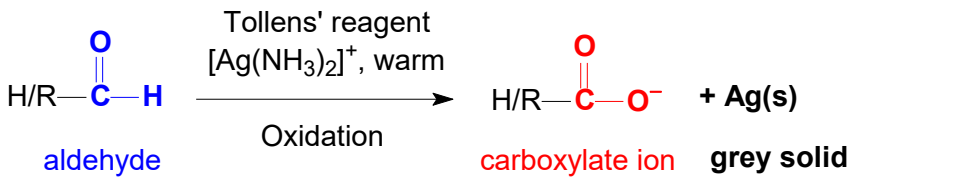
<Distinguishing Test>

In acidic medium, purple $KMnO_4$ decolourised.

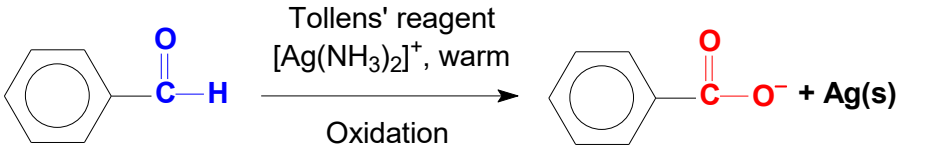
<Distinguishing Test>

In acidic medium, orange $K_2Cr_2O_7$ turns green.

Aldehyde & Benzaldehyde



aldehyde carboxylate ion **grey solid**

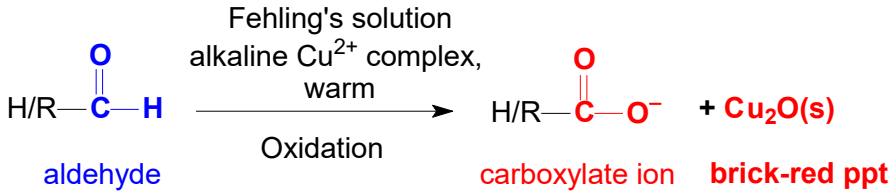


benzaldehyde benzoate ion **grey solid**

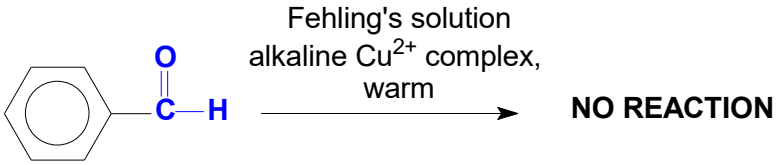
Note:
Tollens' reagent is a good oxidising agent that can oxidise aliphatic aldehyde and benzaldehyde.
Aliphatic Aldehyde and benzaldehyde are oxidized to carboxylic acid, RCOOH. However, RCOOH undergoes acid-base reaction with the alkaline medium to give $RCOO^-$.

<Distinguishing Test>
Grey solid / silver mirror formed.

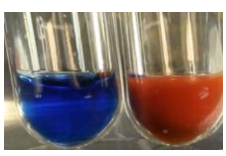
Aldehyde



aldehyde carboxylate ion **brick-red ppt**

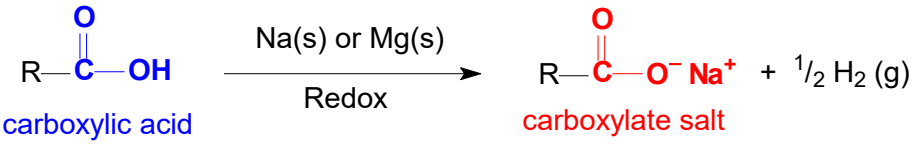


Note:
Fehling's solution is a weak oxidising agent that can only oxidise aliphatic aldehyde. No oxidation with benzaldehyde.
Aliphatic aldehyde is oxidized to carboxylic acid, RCOOH. However, RCOOH undergoes acid-base reaction with the alkaline medium to give $RCOO^-$.



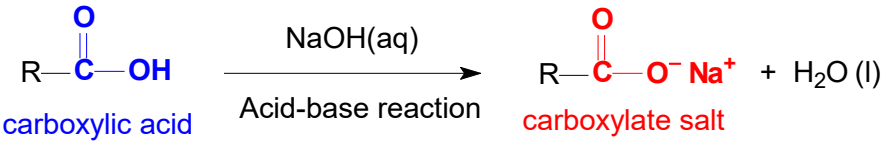
<Distinguishing Test>
Brick-red ppt formed.

Carboxylic acid

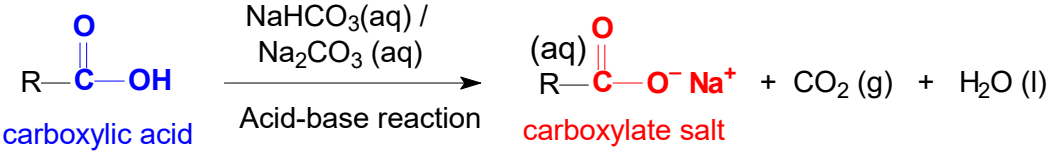


<Distinguishing Test>
Effervescence of $H_2(g)$ that "pops" with lighted splint

Carboxylic acid

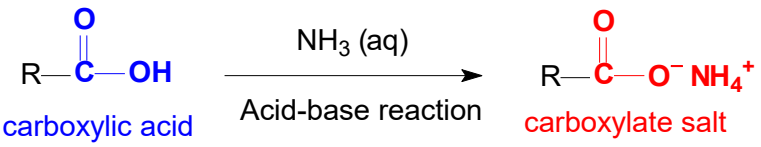


Carboxylic acid

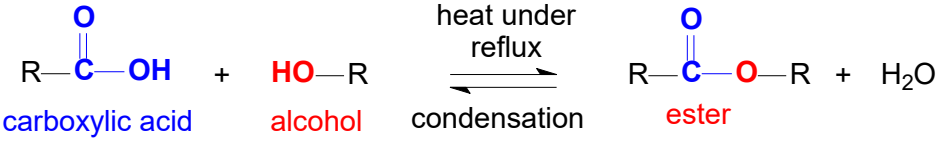


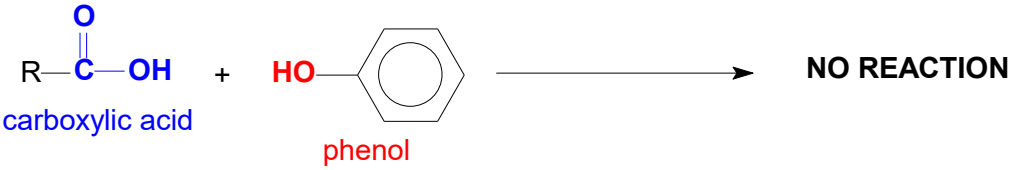
<Distinguishing Test>
Effervescence of $CO_2(g)$ that gives white ppt with limewater

Carboxylic acid

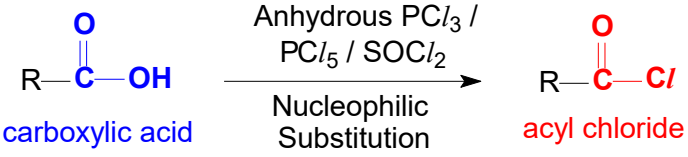


Carboxylic acid





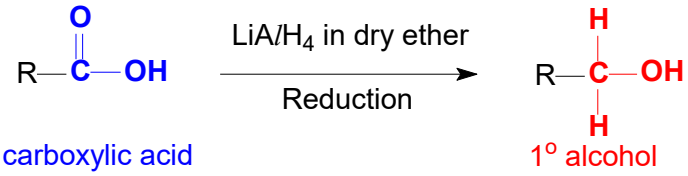
Carboxylic acid



<Distinguishing Test>

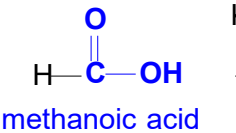
Reaction with PCl_5 and $SOCl_2$ produces white fumes of HCl (g)

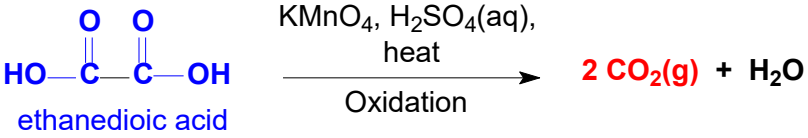
Carboxylic acid



Carboxylic acid cannot be reduced by H_2(g), Pt/Ni
(-COOH is resonance stabilized, more resistant towards reduction)

Methanoic and ethanedioic acid

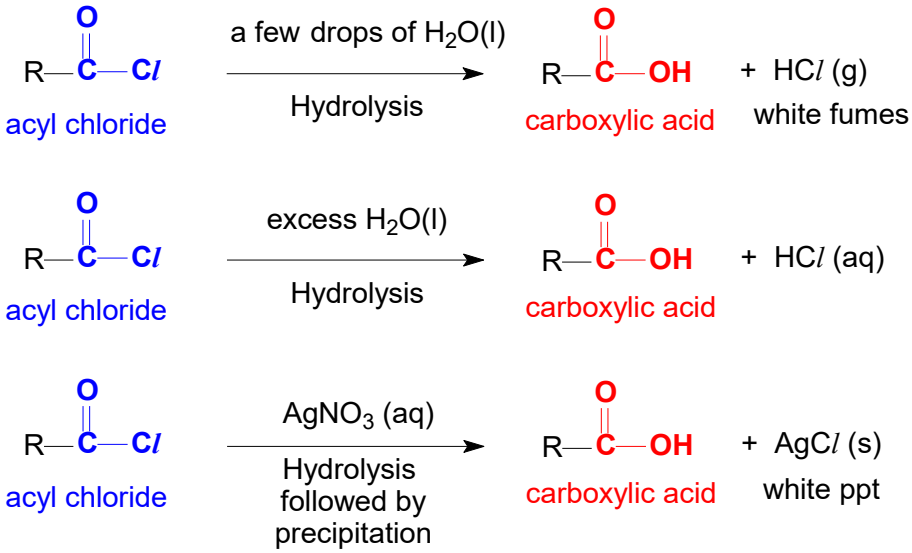




<Distinguishing Test>

In acidic medium, purple $KMnO_4$ decolourised.
Effervescence of CO_2(g) that forms white ppt with limewater.

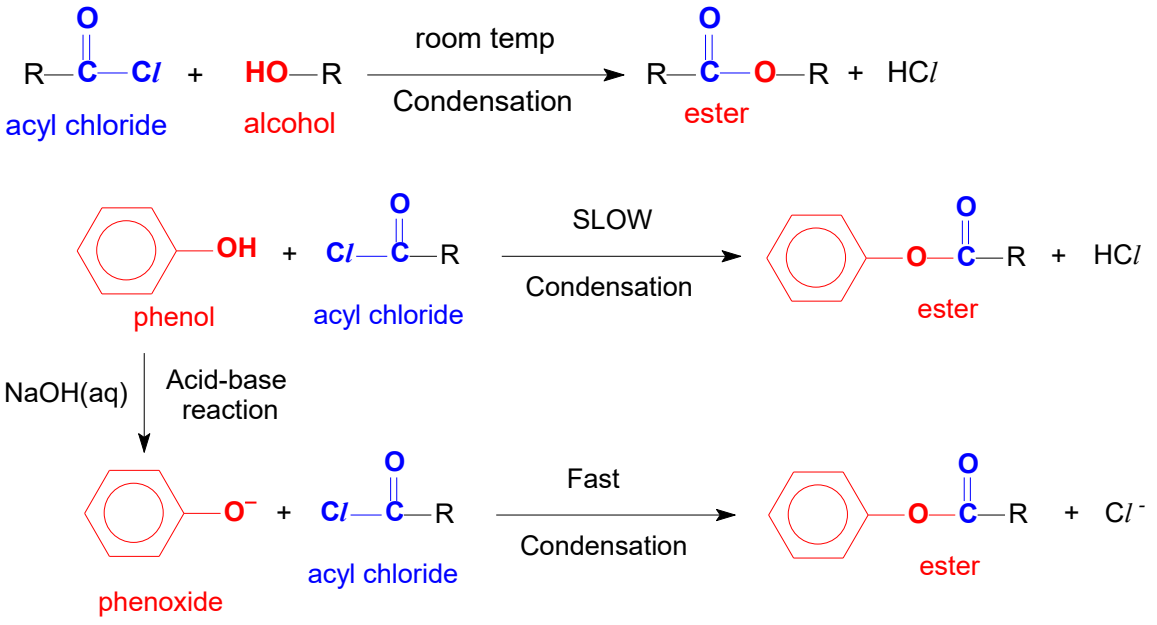
Acyl chloride



<Distinguishing Test>

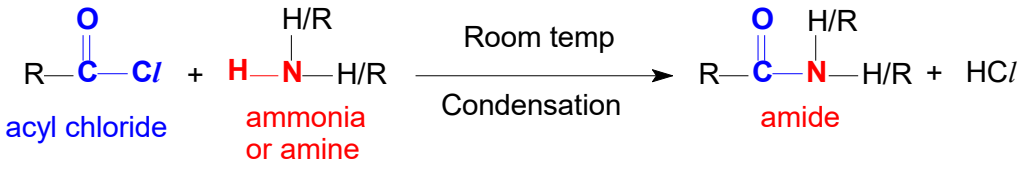
Reaction with $AgNO_3$ (aq) via hydrolysis with excess H_2O to produce HCl(aq) that undergoes precipitation immediately with Ag^+ to form white ppt of AgCl (s).

Acyl chloride



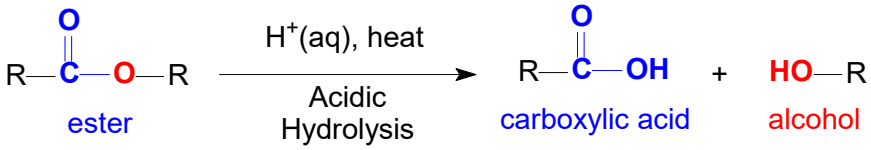
Note: phenoxide ion is a stronger nucleophile than phenol due to increase in electron density at the O atom. Compared to phenol, phenoxide can react **more readily** with the acyl chloride.

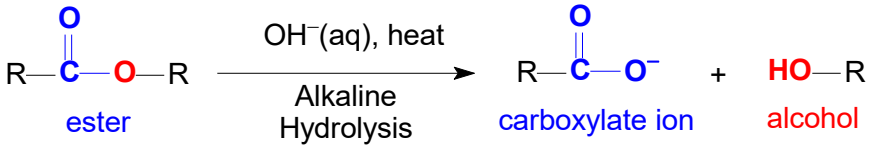
Acyl chloride



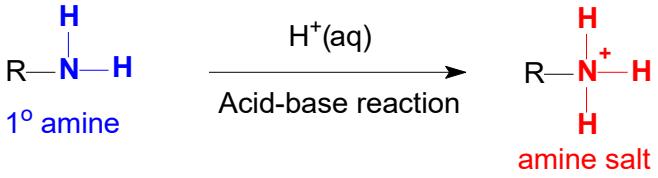
Ester

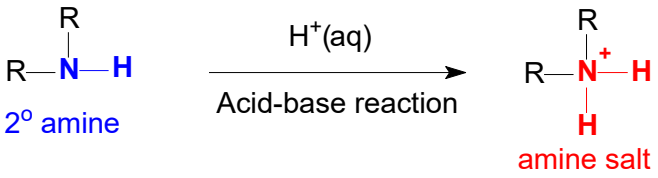
Note:
Hydrolysis of ester functional group produces RCOOH and ROH.
During hydrolysis, δ+ C gains OH while δ− O gains H.
Acidic or alkaline medium is required to speed up the hydrolysis reaction.
RCOOH undergoes further acid-base reaction with the alkaline medium to give $RCOO^-$.

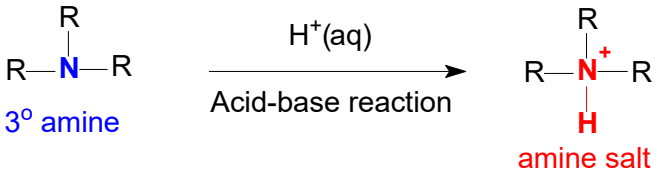




Amine

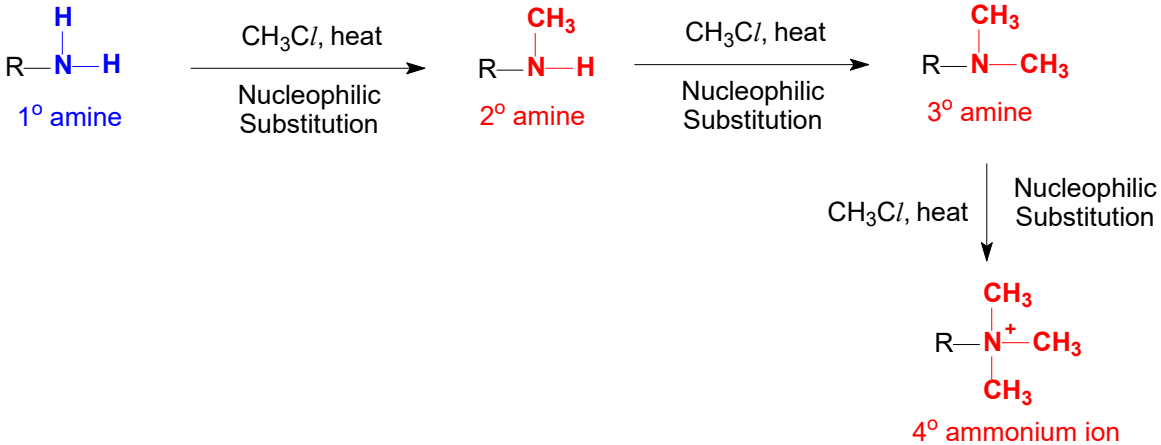






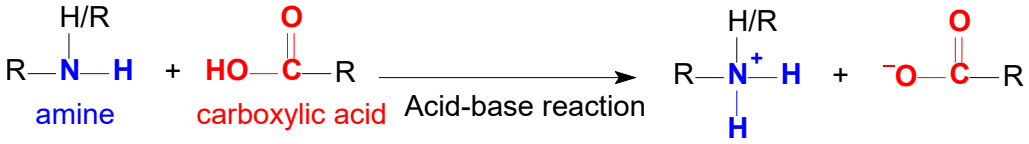
Amines are basic as they use the lone pair electrons on N atom to accept/donate to H^+

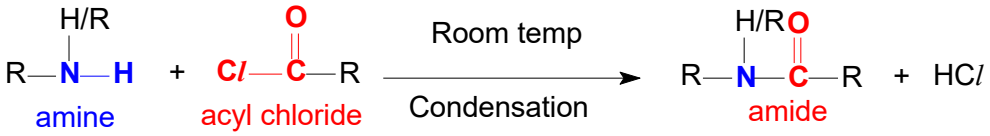
Amine



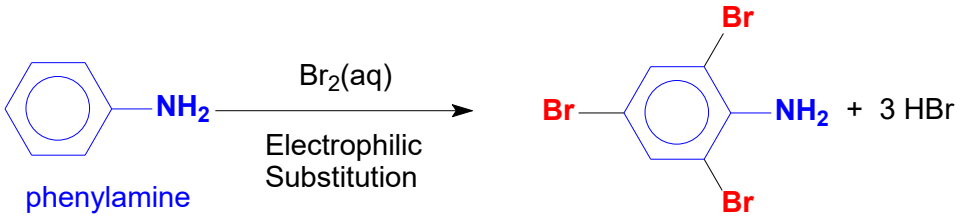
Amines are nucleophiles as they use the lone pair electrons on N atom for reaction

Amine





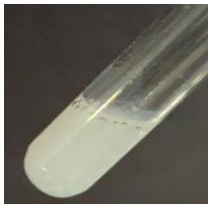
Phenylamine



Note:

1) $-NH_2$ group is 2/4-directing (Refer to Data Booklet), hence the new electrophiles would substitute the benzene H atom at C_2 and C_4 w.r.t. to $-NH_2$.

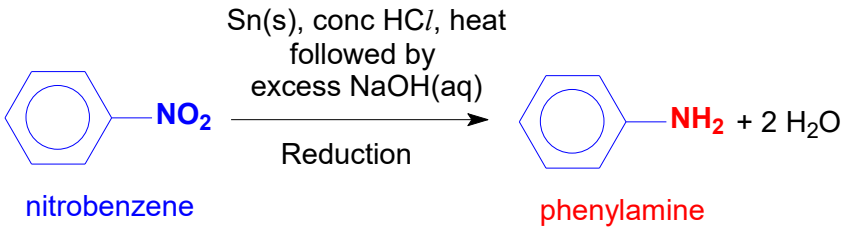
2) $-NH_2$ group is strongly activating (Refer to Data Booklet), hence electrophilic substitution of phenylamine can occur at room temp without anhydrous $FeBr_3$ catalyst.



<Distinguishing Test>

Decolorisation of orange $Br_2(aq)$ and formation of white ppt of 2,4,6-tribromophenylamine

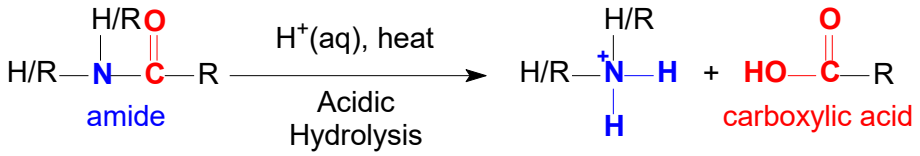
Nitrobenzene

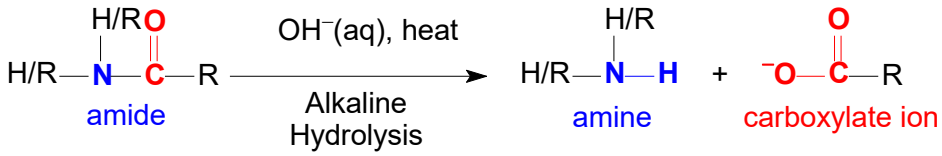


Nitrobenzene cannot be reduced by typical reducing agents such as $H_2(g)$, Ni or $LiAlH_4$.

Amide

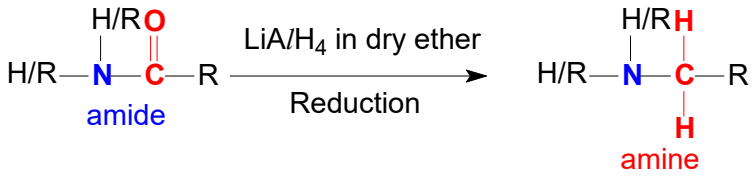
Note:
Hydrolysis of amide functional group produces RCOOH and NH_3 / amine.
During hydrolysis, $\delta+$ C gains OH while $\delta-$ N gains H.
Acidic or alkaline medium is required to speed up the hydrolysis reaction.
RCOOH and NH_3 / amine undergoes further acid-base reaction with the acidic / alkaline medium.



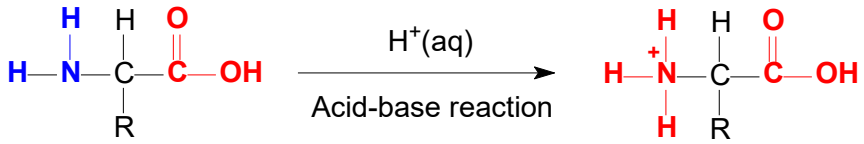


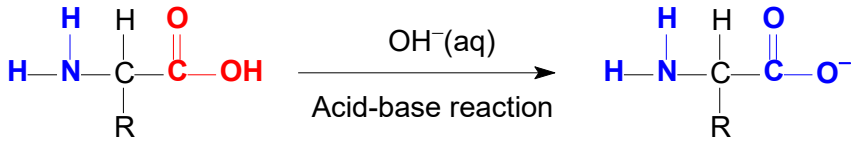
<Distinguishing Test>
During alkaline hydrolysis of amide, NH_3 / amine gas turns moist red litmus paper blue

Amide

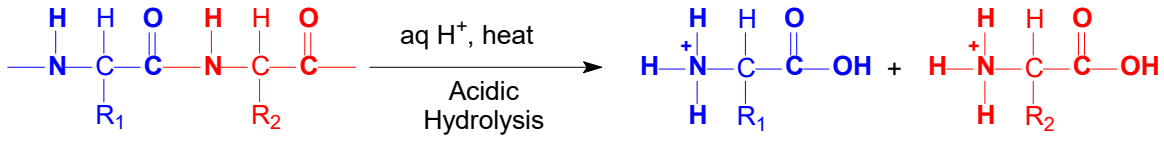


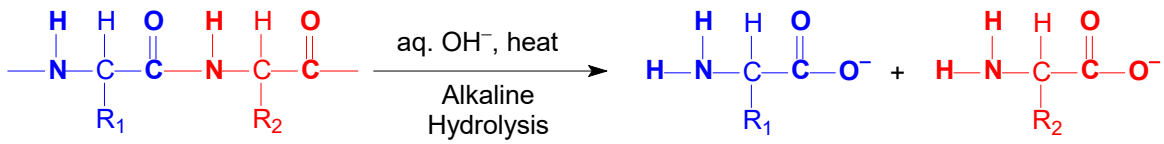
Amino acid





Polypeptide

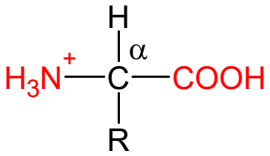




Note: Heat for prolonged time to ensure complete hydrolysis of the multiple peptide (amide) linkages in the polypeptide.

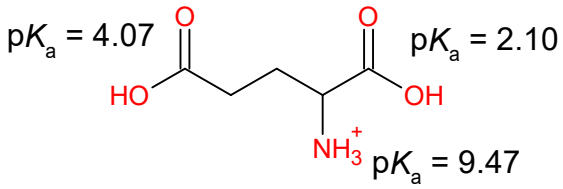
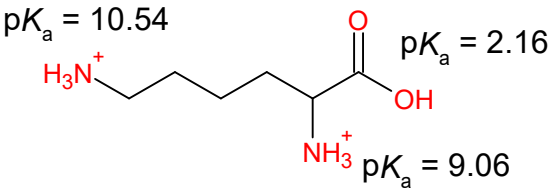
pH vs pK_a OF AMINO ACIDS

pK_a values of amino acids are meant for the **protonated form** of the amino acids where the amino groups exist as its conjugate acid $-NH_3^+$.



General guideline for relative pK_a values of acidic groups in protonated amino acids.

- $-COOH$ groups have a lower pK_a (more acidic) than $-NH_3^+$ group

For amino acid containing $-COOH$ in the side chain, $\alpha-COOH$ has a lower pK_a (more acidic) than side chain $-COOH$	For amino acid containing amine group in the side chain, $\alpha-NH_3^+$ has a lower pK_a (more acidic) than side chain protonated amine
 **Glutamic acid**	 **Lysine**

Predominant form of amino acids at different pH

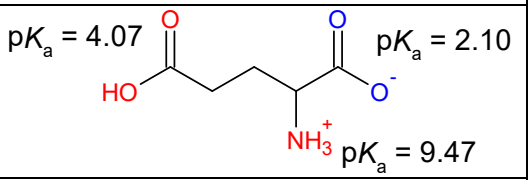
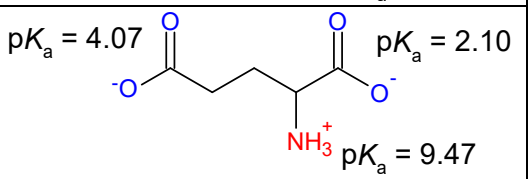
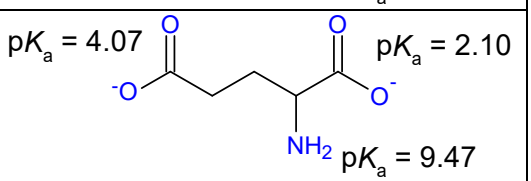
pH affects the ratio of weak acid and its conjugate base in a buffer system
(To be covered in more details in ***Acid Base Equilibrium***)

$$pH = pK_a + \lg \frac{[\text{conj. base}]}{[\text{acid}]}$$

When pH = pK_a, it is a maximum buffer capacity where [conj. base] = [acid].

When pH < pK_a (a more acidic environment), [acid] is more than [conj. base].

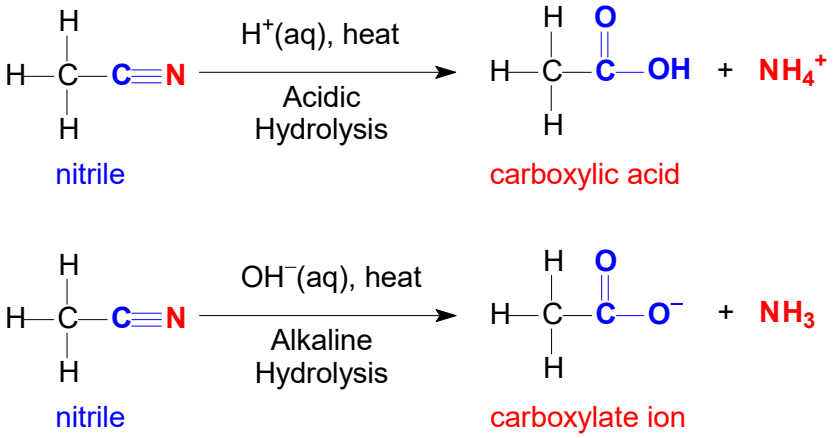
When pH > pK_a (a more alkaline environment), [conj. base] is more than [acid].

pH of solution	Predominant form of Glutamic acid	Structure
pH = 2.8	$\alpha-COO^-$ (pH > pK_a 2.10) Side chain $-COOH$ (pH < pK_a 4.07) $\alpha-NH_3^+$ (pH < pK_a 9.47)	
pH = 7.0	$\alpha-COO^-$ (pH > pK_a 2.10) Side chain $-COO^-$ (pH > pK_a 4.07) $\alpha-NH_3^+$ (pH < pK_a 9.47)	
pH = 12.0	$\alpha-COO^-$ (pH > pK_a 2.10) Side chain $-COO^-$ (pH > pK_a 4.07) $\alpha-NH_2$ (pH > pK_a 9.47)	

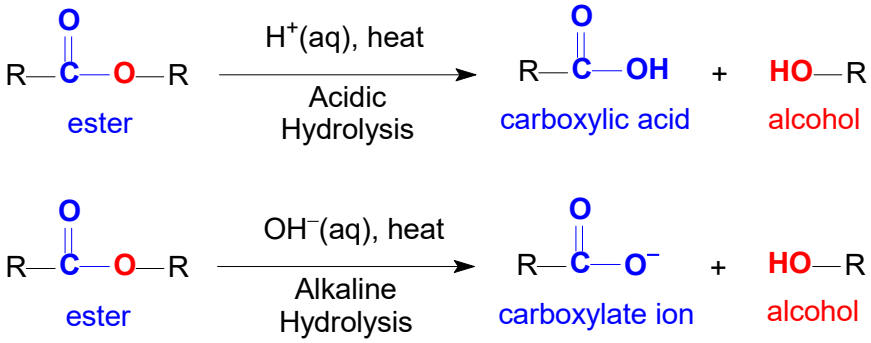
Comparing hydrolysis reactions of nitrile, ester and amide

During hydrolysis reactions, the polar C≡N, C–O and C–N bonds are broken.
δ+ C gains OH while δ− N/O gains H.
Acidic or alkaline medium is required to speed up the hydrolysis reaction. The products RCOOH and NH_3 / amine undergo further acid-base reaction with the acidic / alkaline medium.

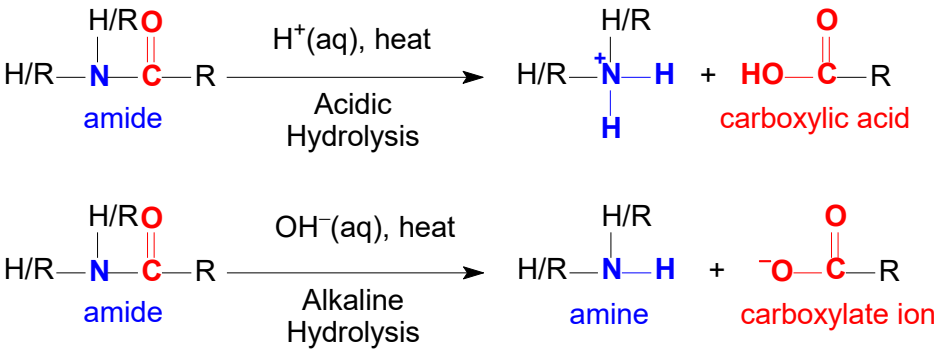
Nitrile



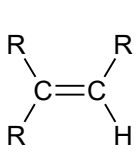
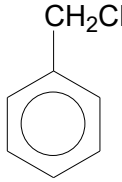
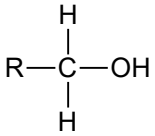
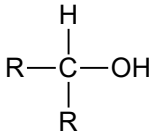
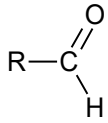
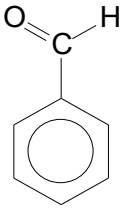
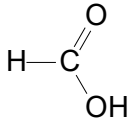
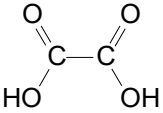
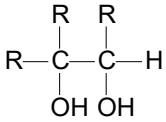
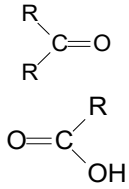
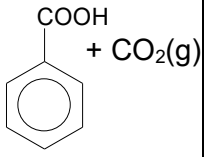
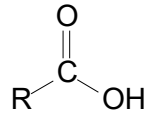
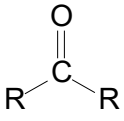
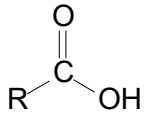
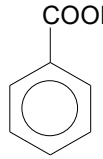
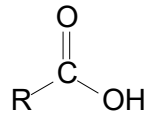
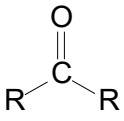
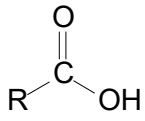
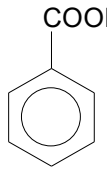
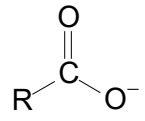
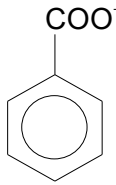
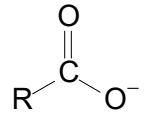
Ester



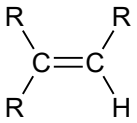
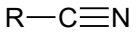
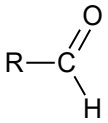
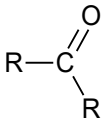
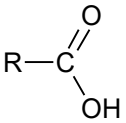
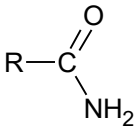
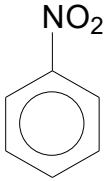
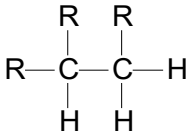
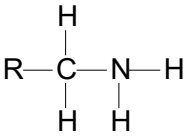
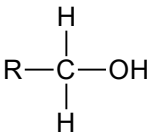
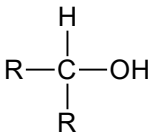
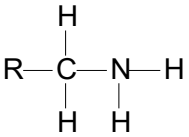
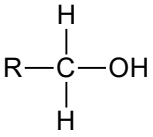
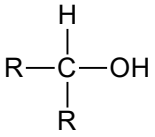
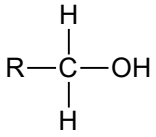
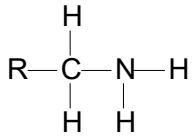
Amide



Comparing oxidation reactions

	 **Alkene**	 **Alkylbenzene**	 **1° Alcohol**	 **2° Alcohol**	 **Aliphatic Aldehyde**	 **Aromatic Aldehyde**	 **Methanoic acid**	 **Ethanedioic acid**
$KMnO_4$, NaOH (aq), cold								
$KMnO_4$, H_2SO_4 (aq), heat							$CO_2 + H_2O$	$2\ CO_2 + H_2O$
$K_2Cr_2O_7$, H_2SO_4 (aq), heat under **reflux**								
$[Ag(NH_3)_2]^+$ complex, **warm** (Tollens' reagent)								
Cu^{2+} alkaline complex, **warm** (Fehling's solution)								

Comparing reduction reactions

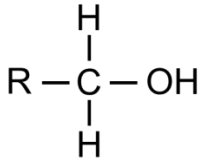
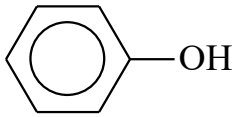
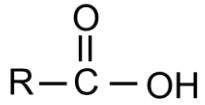
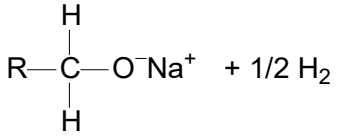
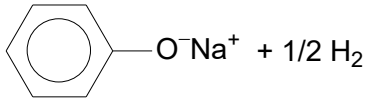
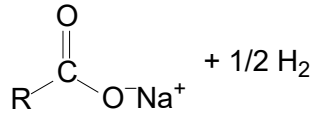
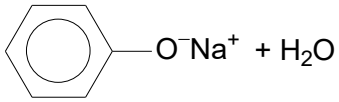
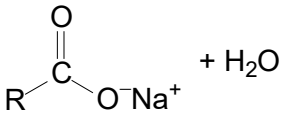
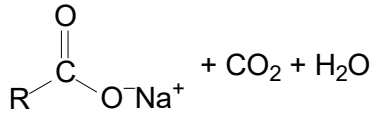
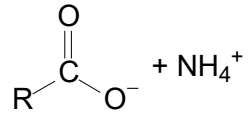
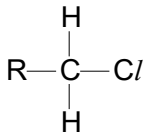
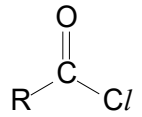
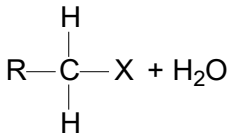
	 Alkene	 Nitrile	 Aldehyde	 Ketone	 Carboxylic acid	 Amide	 Nitrobenzene
H_2 (g), Ni			 (1° alcohol)	 (2° alcohol)			
LiA*l*H_4 in dry ether			 (1° alcohol)	 (2° alcohol)	 (1° alcohol)		

** Alkene cannot be reduced by LiA*l*H_4 (C=C is electron rich, and will repel the H^- ion from LiA*l*H_4)

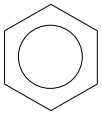
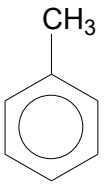
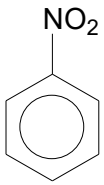
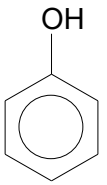
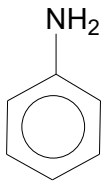
*** Carboxylic acid and amide are resonance stabilized, they can only be reduced by LiA*l*H_4.

****nitrobenzene can only be reduced using Sn, conc HC*l*, heat, followed by excess NaOH(aq).

Comparing reactions of alcohol, phenol and carboxylic acid

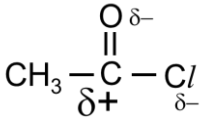
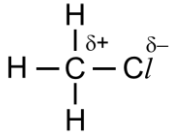
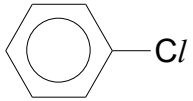
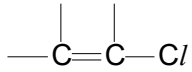
	Alcohol (Neutral) 	**Phenol (Very weak acid)** 	**Carboxylic acid (Weak acid)** 
Na metal			
NaOH(aq) (strong base)			
$NaHCO_3/Na_2CO_3$ (aq) (weak base)			
NH_3 (weak base)			
Anhydrous $PCl_5/PCl_3/SOCl_2$			
HX (g)			

Relative reactivity of Arene towards electrophilic substitution (Refer to Data Booklet)

					
Electron density in benzene	Normal	Slightly higher	Lower	**Significantly** higher	**Significantly** higher
Reagents and conditions for Substitution by -Br	Br_2 with anhydrous $FeBr_3$ **catalyst**	Br_2 with anhydrous $FeBr_3$ **catalyst**	Br_2 with anhydrous $FeBr_3$ **catalyst**	Br_2(aq) **[No catalyst]**	Br_2(aq) **[No catalyst]**
Reagents and conditions for Substitution by $–NO_2$	conc HNO_3 conc H_2SO_4 **catalyst** heat	conc HNO_3 conc H_2SO_4 **catalyst** 30°C	conc HNO_3 conc H_2SO_4 **catalyst** 50°C	HNO_3 (aq) **[No catalyst]**	Acid base reaction with HNO_3

*Alkyl groups are weakly activating while −OH and $−NH_2$ groups are strongly activating as a result of resonance.

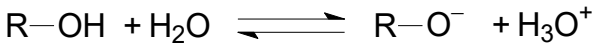
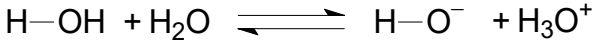
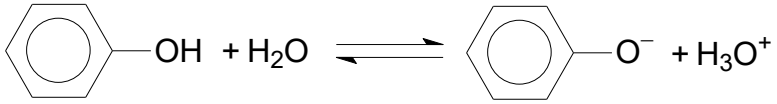
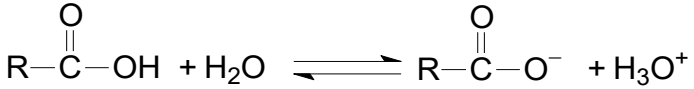
Relative reactivity of C−C*l* towards nucleophile/hydrolysis

Acyl chlorides	Alkyl chlorides	Chlorobenzene / Chloroalkene
		 
The presence of highly electronegative O atom and C*l* atom attached to the carboxyl C atom makes the C atom highly electron-deficient (δ+), hence most susceptible to nucleophilic attack.	Reacts less readily than acyl chlorides. Rate of reaction of C–I > C–Br > C–C*l* Depends on the **strength of C–X bond (refer to Bond Energy in Data Booklet)**	**Resistant** towards nucleophilic substitution. 1) C atom of C–C*l* is electron rich due to delocalized π electrons of benzene/ electron rich C atom in C=C. This repels nucleophile. 2) **Partial double bond character** of C–C*l* bond due to the overlapping of the p orbital of C*l* with the π electron cloud of the benzene ring/C=C

<u>Relative strength of acids</u> [An acid is a proton (H^+) donor]

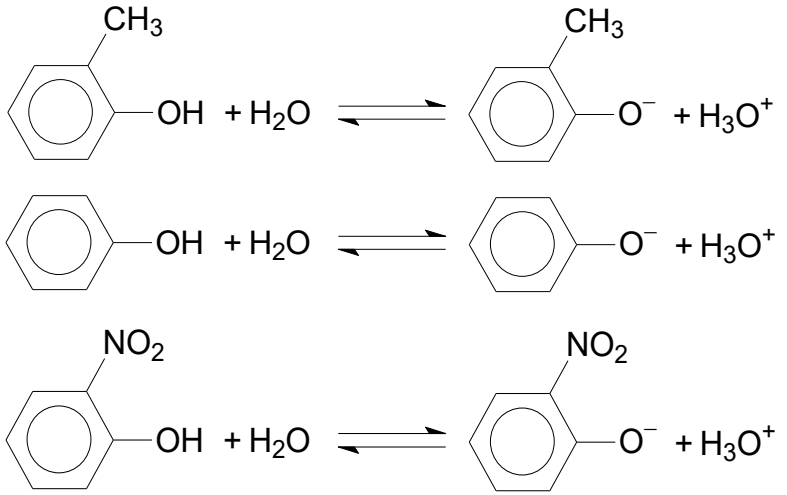
1) Show the acid dissociation equilibrium for all acids.
2) Compare the **relative stability of the conjugate bases** formed during acid dissociation. (e.g. CH_3O^- vs $C_6H_5O^-$)
3) The more stable the conjugate base is **(with respect to the other conjugate base),** the acid dissociates more readily into H^+ and its conjugate base.
4) Conclude on relative strength of the acid.

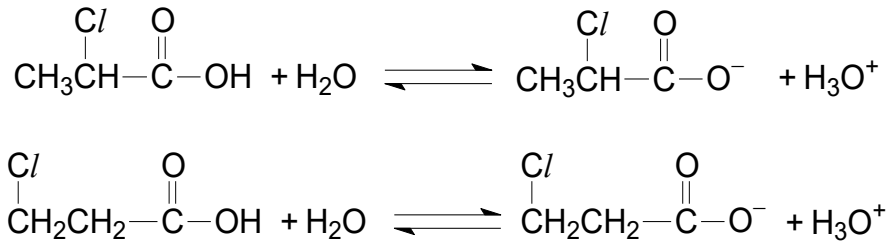
Comparing between different functional groups:

Alcohol (Neutral)		The electron-donating alkyl group (R-) destabilize the alkoxide ion by **intensifying its negative charge**. $R\text{-}O^-$ is less stable than HO^-. Alcohol dissociates less readily into H^+ and its conjugate base as compared to water. Hence *alcohol is less acidic than water. Alcohol is neutral.*
Water (Neutral)		
Phenol (Very weak acid)		**Negative charge on the phenoxide ion is dispersed into the benzene ring** as a result of resonance, resulting in phenoxide ion being more stable than HO^- ion. Phenol dissociates more readily into H^+ and its conjugate base as compared to water. Hence *phenol is more acidic than water.*
Carboxylic acid (Weak acid)		**Negative charge on carboxylate ion is <u>dispersed significantly over 2 highly electronegative O atoms</u>** as a result of resonance, resulting in carboxylate ion being more stable than HO^- and phenoxide ion. Carboxylic acid dissociates more readily into H^+ and its conjugate base as compared to water and phenol. Hence *carboxylic acid is more acidic than water and phenol.*

Relative strength of acids [An acid is a proton (H^+) donor]

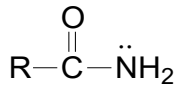
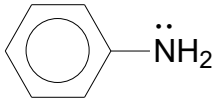
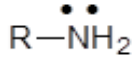
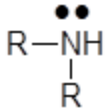
Comparing between compounds with same functional group

Presence of additional electron-donating and electron-withdrawing groups	
	• Electron-donating groups (−alkyl) **increase the intensity of the negative charge** on the conjugate base, thus the **dissociation** into H^+ and conjugate base is **less favourable**. Hence this **decreases the acidity** of the compound. • Electron-withdrawing groups ($-NO_2$) **decrease the intensity of the negative charge** on the conjugate base, thus the **dissociation** into H^+ and conjugate base is **more favourable**. Hence this **increases the acidity** of the compound.

Distance of electron-withdrawing groups	
	• The **nearer** the electron-withdrawing groups, the **greater** the extent of **dispersing the intensity of the negative charge** on the conjugate base, thus the **dissociation** into H^+ and conjugate base is **more favourable**. • Hence this **increases the acidity** of the compound.

Relative strength of bases in aqueous [A Bronsted base is a proton (H^+) acceptor]

compare relative strength of bases by comparing the **relative availability of lone pair electrons on N to accept H^+**.
The greater the electron density on N atom, the more available the lone pair electrons on N to accept H^+ **(with respect to the other base),** the stronger the base.

Amide (neutral) 	Due to **significant delocalization to adjacent C=O (highly electronegative O atom)**, the lone pair of electrons on N in amide is **NOT available** to accept H^+. Hence amide is **neutral**.
Phenylamine **(Very weak base)** 	Due to **delocalization of lone pair of electrons on N into the benzene ring**, this **decreases the electron density** on N atom and the lone pair of electrons on N is **less available** to accept H^+ as compared to ammonia. Hence phenylamine is a **weaker base than ammonia**.
Ammonia (weak base) 	
Primary amine **(weak base)** 	The **electron-donating alkyl group (R-) increases the electron density** on N atom and the lone pair of electrons on N is more available to accept H^+ as compared to ammonia. Hence amine is a **stronger base than ammonia**.
Secondary amine **(weak base)** 	The **greater number of electron-donating alkyl group** (R-) bonded to N atom, the greater the electron density on N atom and the lone pair of electrons on N is more available to accept H^+. Hence **secondary amine is a stronger base than primary amine**.

Relative strength of bases in gaseous state [A Lewis base is electron pair donor]

Similar explanation as above, CANNOT mention "H^+" for gaseous state, focus on availability of lone pair electron for donation.