GENERAL REACTION MECHANISM

1. Transition States and Intermediates

Transition state is an imaginary state through which any single step reaction (or each step of reaction) is assumed to proceed. Structurally transition state of any step resembles reactant as well as products of that step. However, energy of transition state is always higher than energy of reactant as well as product of that step. Therefore, its stability is always lesser than the stability of reactant as well as products. Transition state has structure more close to the reactants if its energy is more close to reactants (exothermic reaction). Transition state has structure more close to the products if its energy is more close to products (endothermic reaction).

Transition State	Intermediate State
It is an imaginary and hypothetical state which exists in between the reactants and products of a single step reaction.	It is a species which is actually formed for some time (may be very small) during a multi-step reaction.
It resembles with reactant as well as product of that step. Its existence cannot be proved.	It can be experimentally proved.
It cannot be isolated or trapped.	Intermediate can be sometimes isolated or trapped.

1.1 Importance of Transition State and Intermediates

Use of transition state helps us to understand the process of reaction with time without describing the entire process in detail. Let us discuss how use of transition state helps us understanding a reaction:

$R—Cl + E^+ \rightarrow R^+ + E—Cl$. This reaction can occur in five different ways:

(i)   Suppose the reaction occurs in two steps. In the first step, the lone pair of Cl forms a bond with E^+ and in the second step, heterolytic cleavage of R—Cl bond takes place.
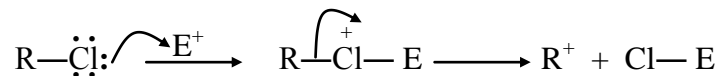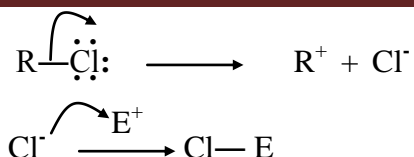

When the lone pairs of Cl will start bond formation with electrophile (E^+), formation of positive charge starts at Cl and the positive charge on E^+ will start decreasing. The Transition state of this step is shown as TS_1. In the second step, when the heterolytic cleavage of R— Cl bond will start, positive charge on Cl will start decreasing and formation of positive charge will start at R. The transition state of this step is shown as TS_2. The '-----' represents partially formed bond $\delta+$ represents partial positive charge. TS_1 represents the view when the step 1 is still continued while TS_2 represents the view when the step 2 is still continued.
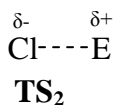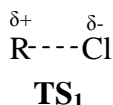

(ii) Suppose the reaction occurs in two steps. In the first step, heterolytic cleavage of R—Cl bond takes place and in the second step, the lone pair of Cl^- forms a bond with E^+.

$$R\text{—}\ddot{C}l: \longrightarrow R^+ + Cl^-$$
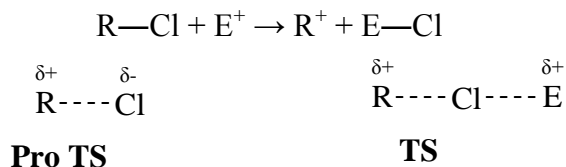
$$Cl^- \xrightarrow{\quad E^+ \quad} Cl\text{—}E$$

In the first step, when the heterolytic cleavage of R— Cl bond will start, formation of negative charge on Cl will start and formation of positive charge will start at R. The transition state of this step is shown as TS_1. In second step when the lone pairs of Cl^- will start bond formation with electrophile (E^+), negative charge at Cl and the positive charge on E^+ will start decreasing. The Transition state of this step is shown as TS_2. The '-----' represents partially formed bond δ- represents partial negative charge. TS_1 represents the view when the step 1 is still continued while TS_2 represents the view when the step 2 is still continued.

$$\overset{\delta+}{R}\text{----}\overset{\delta-}{Cl}$$
$$TS_1$$

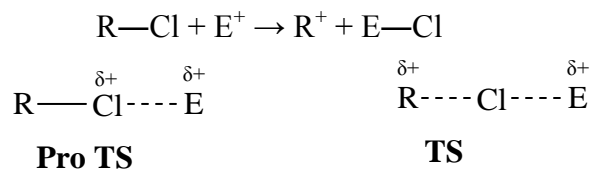$$\overset{\delta-}{Cl}\text{----}\overset{\delta+}{E}$$
$$TS_2$$

(iii) Suppose the reaction occurs in one step. The heterolytic cleavage of R—Cl bond and the formation of bond between Cl and E^+ start simultaneously and gets completed in one step. When these bond cleavage and bond formation start, the positive charge of E will start decreasing and formation of positive charge will start at R. TS represents the view when the process is still continued.

$$R\text{—}Cl \xrightarrow{\quad E^+ \quad} R^+ + Cl\text{—}E$$

$$\overset{\delta+}{R}\text{----}\overset{}{Cl}\text{----}\overset{\delta+}{E}$$
$$TS$$
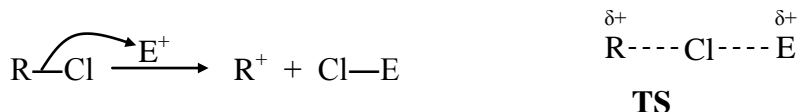
(iv) Suppose the reaction occurs in one step. However, the heterolytic cleavage of R—Cl bond and the formation of bond between Cl and E^+ do not start simultaneously. If the R — Cl bond cleavage starts initially and before its completion, formation of Cl — E bond also starts, the entire process gets completed in one step. Pro transition state represents the initial view and transition state represents the later view when the process is still continued.

$$R\text{—}Cl + E^+ \rightarrow R^+ + E\text{—}Cl$$

$$\overset{\delta+}{R}\text{----}\overset{\delta-}{Cl}$$
$$\textbf{Pro TS}$$

$$\overset{\delta+}{R}\text{----}\overset{}{Cl}\text{----}\overset{\delta+}{E}$$
$$TS$$

(v) Suppose the reaction occurs in one step. However, the heterolytic cleavage of R—Cl bond and the formation of bond between Cl and E^+ does not start simultaneously. If the Cl — E bond formation starts initially and before its completion, cleavage of R — Cl bond also starts, the entire process gets completed in one step. Pro transition state represents the initial view and transition state represents the later view when the process is still continued.
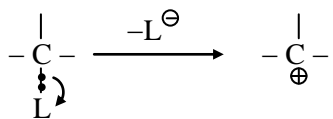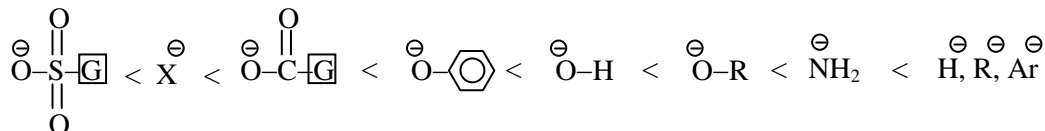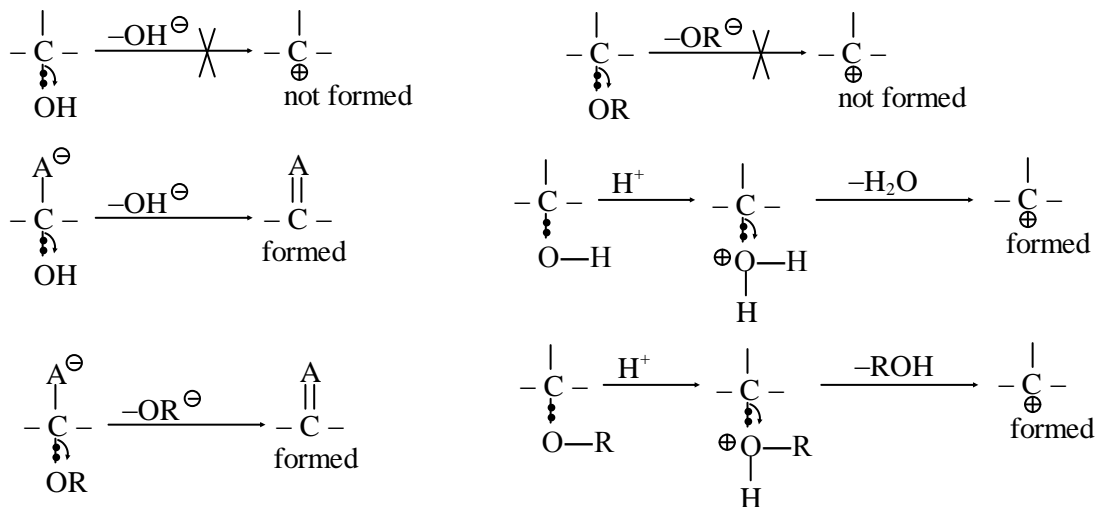
$$R\text{—}Cl + E^+ \rightarrow R^+ + E\text{—}Cl$$

$$R\text{——}\overset{\delta+}{Cl}\text{----}\overset{\delta+}{E}$$
$$\textbf{Pro TS}$$

$$\overset{\delta+}{R}\text{----}\overset{}{Cl}\text{----}\overset{\delta+}{E}$$
$$TS$$

2. LEAVING GROUP & LEAVING TENDENCY

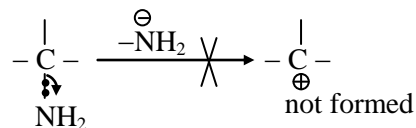$$-\overset{|}{\underset{L}{C}}- \xrightarrow{-L^{\ominus}} -\overset{|}{\underset{\oplus}{C}}-$$

The group which is removed with the bonding electron is called leaving group and is represented by 'L'. The ease of removal of $L^{\ominus}$ (leaving tendency) is inversely related to the basic strength of $L^{\ominus}$. Weaker bases are better leaving groups whereas stronger bases are poorer leaving groups. The basic strength of few leaving groups increases as below:
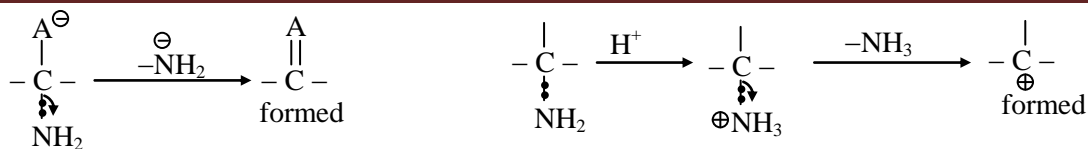
$$\overset{\ominus}{O}-\overset{O}{\underset{O}{\overset{||}{S}}}-\boxed{G} \;<\; \overset{\ominus}{X} \;<\; \overset{\ominus}{O}-\overset{O}{\overset{||}{C}}-\boxed{G} \;<\; \overset{\ominus}{O}-\hexagon \;<\; \overset{\ominus}{O}-H \;<\; \overset{\ominus}{O}-R \;<\; \overset{\ominus}{N}H_2 \;<\; \overset{\ominus}{H}, \overset{\ominus}{R}, \overset{\ominus}{Ar}$$

(i) From the order of basic strength we can say that halides are very good leaving groups and their leaving tendency is $I^{\ominus} > Br^{\ominus} > Cl^{\ominus}$ as their basic strength is $I^{\ominus} < Br^{\ominus} < Cl^{\ominus} < F^{\ominus}$. $F^{\ominus}$ is considered as bad leaving group among halides.

(ii) $RCOO^{\ominus}$ is weak base and hence a good leaving group. This group can be removed easily.

(iii) $HO^{\ominus}$ and $RO^{\ominus}$ are strong bases and hence bad leaving groups as such. They are not generally removed as such from neutral molecules but can be removed from anions. From neural molecules, they can be removed very easily after their protonation in the form of H_2O and ROH which are very weak bases (almost neutral).

$$-\overset{|}{\underset{OH}{C}}- \xrightarrow[\text{\Large $\times$}]{-OH^{\ominus}} -\overset{|}{\underset{\oplus}{C}}- \quad \text{not formed}$$

$$-\overset{|}{\underset{OR}{C}}- \xrightarrow[\text{\Large $\times$}]{-OR^{\ominus}} -\overset{|}{\underset{\oplus}{C}}- \quad \text{not formed}$$

$$-\overset{A^{\ominus}}{\underset{OH}{C}}- \xrightarrow{-OH^{\ominus}} -\overset{A}{\overset{||}{C}}- \quad \text{formed}$$

$$-\overset{|}{\underset{O-H}{C}}- \xrightarrow{H^+} -\overset{|}{\underset{\overset{\oplus}{O}-H}{\underset{H}{C}}}- \xrightarrow{-H_2O} -\overset{|}{\underset{\oplus}{C}}- \quad \text{formed}$$

$$-\overset{A^{\ominus}}{\underset{OR}{C}}- \xrightarrow{-OR^{\ominus}} -\overset{A}{\overset{||}{C}}- \quad \text{formed}$$

$$-\overset{|}{\underset{O-R}{C}}- \xrightarrow{H^+} -\overset{|}{\underset{\overset{\oplus}{O}-R}{\underset{H}{C}}}- \xrightarrow{-ROH} -\overset{|}{\underset{\oplus}{C}}- \quad \text{formed}$$

(iv) Removal of $^{\ominus}NH_2$ is very difficult as it is a very strong base. It cannot be removed as such from neutral molecules but can be removed (not so easily) from anions. It may also be removed (not so easily) from neutral molecules after its protonation in the form of ammonia which is a weak base.
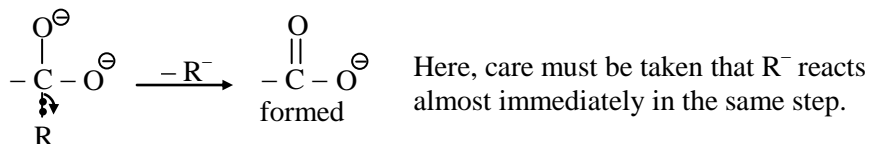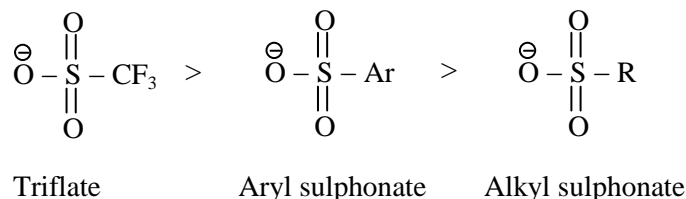
$$-\overset{|}{\underset{NH_2}{C}}- \xrightarrow[\text{\Large $\times$}]{-\overset{\ominus}{N}H_2} -\overset{|}{\underset{\oplus}{C}}- \quad \text{not formed}$$

$$-\overset{\overset{\displaystyle A^{\ominus}}{|}}{\underset{\underset{\displaystyle NH_2}{\curvearrowright}}{C}}- \xrightarrow{\overset{\ominus}{-NH_2}} -\overset{\overset{\displaystyle A}{||}}{C}- \quad \text{formed}$$

$$-\overset{|}{\underset{\underset{\displaystyle NH_2}{\vdots}}{C}}- \xrightarrow{H^+} -\overset{|}{\underset{\underset{\displaystyle \oplus NH_3}{\curvearrowright}}{C}}- \xrightarrow{-NH_3} -\overset{|}{\underset{\oplus}{C}}- \quad \text{formed}$$

(v)   Removal of $H^{\ominus}$, $R^{\ominus}$ and $Ar^{\ominus}$ is very-very difficult as these are very-very strong bases and they cannot be even protonated. Hence $H^{\ominus}$, $R^{\ominus}$ and $Ar^{\ominus}$ are not generally considered as leaving groups. Their removal is almost impossible (almost a last option) even from anion.
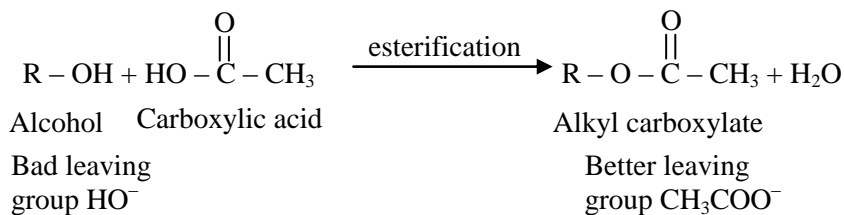
However, they can be removed from dianion. Moreover, if at all they are removed (from dianions), their further reaction (nucleophilic or basic action) takes place in same step.

$$-\overset{\overset{\displaystyle O^{\ominus}}{|}}{\underset{\underset{\displaystyle R}{\curvearrowright}}{C}}-O^{\ominus} \xrightarrow{-R^-} -\overset{\overset{\displaystyle O}{||}}{C}-O^{\ominus} \quad \begin{array}{l}\text{Here, care must be taken that } R^- \text{ reacts}\\ \text{almost immediately in the same step.}\end{array}$$
$$\text{formed}$$

(vi) Sulphonic acids are extremely strong acids. Therefore, sulphonates are very weak bases and extremely good leaving groups. Triflate (shown below in order of leaving tendency) is called super leaving group.
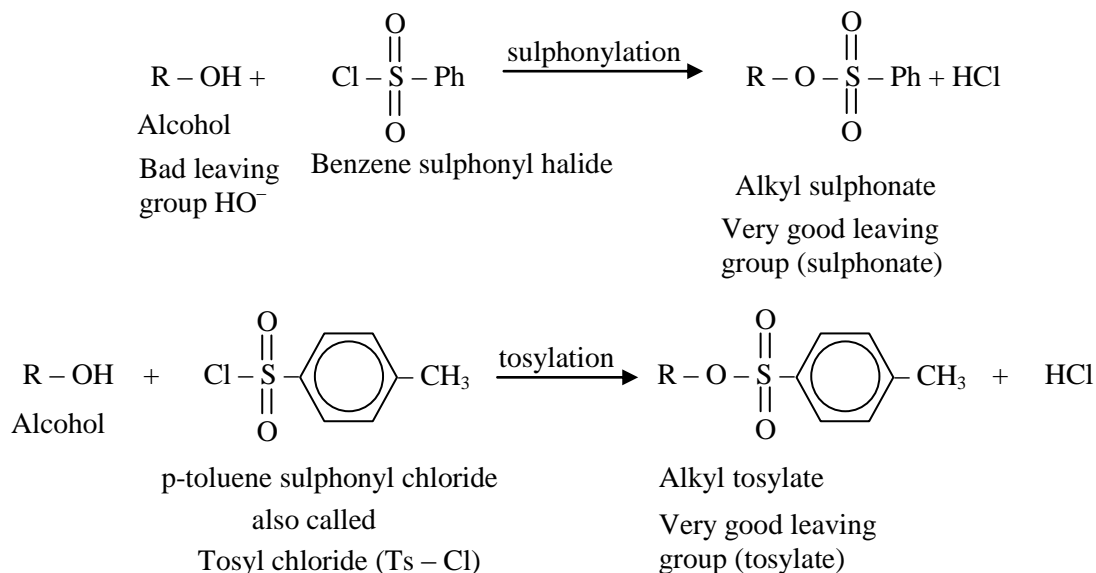
$$\overset{\ominus}{O}-\overset{\overset{\displaystyle O}{||}}{\underset{\underset{\displaystyle O}{||}}{S}}-CF_3 \quad > \quad \overset{\ominus}{O}-\overset{\overset{\displaystyle O}{||}}{\underset{\underset{\displaystyle O}{||}}{S}}-Ar \quad > \quad \overset{\ominus}{O}-\overset{\overset{\displaystyle O}{||}}{\underset{\underset{\displaystyle O}{||}}{S}}-R$$

Triflate   Aryl sulphonate   Alkyl sulphonate

A bad leaving group ($-OH$) can be converted to a better leaving group through formation of ester of carboxylic acids.

$$R-OH + HO-\overset{\overset{\displaystyle O}{||}}{C}-CH_3 \xrightarrow{\text{esterification}} R-O-\overset{\overset{\displaystyle O}{||}}{C}-CH_3 + H_2O$$

Alcohol   Carboxylic acid   Alkyl carboxylate

Bad leaving   Better leaving
group HO^- group CH_3COO^-

$$R-OH + Cl-\overset{\overset{\displaystyle O}{||}}{C}-CH_3 \xrightarrow{\text{esterification}} R-O-\overset{\overset{\displaystyle O}{||}}{C}-CH_3 + HCl$$

Alcohol   Carboxylic acid halide   Alkyl carboxylate

Bad leaving   Better leaving
group HO^- group CH_3COO^-
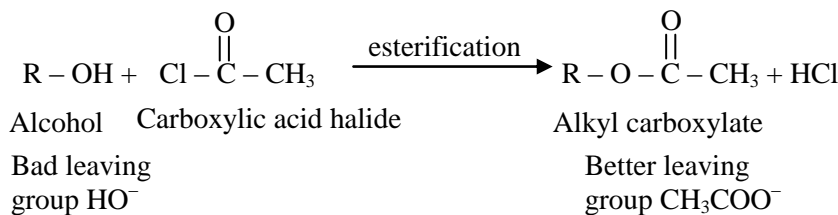
A bad leaving group (– OH) can be converted to a very good leaving group through formation of ester of sulphonic acids.

$$R-OH + \underset{\substack{\text{Benzene sulphonyl halide}}}{\text{Cl}-\overset{\overset{O}{\|}}{\underset{\underset{O}{\|}}{S}}-\text{Ph}} \xrightarrow{\text{sulphonylation}} R-O-\overset{\overset{O}{\|}}{\underset{\underset{O}{\|}}{S}}-\text{Ph} + HCl$$

R – OH + (Alcohol, Bad leaving group HO$^-$)

Alkyl sulphonate
Very good leaving group (sulphonate)

$$R-OH + \text{Cl}-\overset{\overset{O}{\|}}{\underset{\underset{O}{\|}}{S}}-\text{C}_6\text{H}_4-\text{CH}_3 \xrightarrow{\text{tosylation}} R-O-\overset{\overset{O}{\|}}{\underset{\underset{O}{\|}}{S}}-\text{C}_6\text{H}_4-\text{CH}_3 + HCl$$

R – OH (Alcohol)

p-toluene sulphonyl chloride
also called
Tosyl chloride (Ts – Cl)

Alkyl tosylate
Very good leaving group (tosylate)

2.1   Rate Determining Step in Multi Step Reaction

The rate of any multistep reaction is equal to the rate of slowest step in that reaction. Therefore, the slowest step in the reaction mechanism is called rate determining step. Rate determining step is identified by experiments. However, following logics may help in prediction of the RDS.

(i) RDS must involve dissociation of at least one bond.

(ii) Formation of stable species is usually fast while formation of unstable species is usually slow.

(iii) Proton exchange reactions are usually fast and not rate determining step.

NOTE: some time (ii) and (iii) points given above contradict each other. In such cases prediction of RDS is very difficult.

3. Organic Intermediates

3.1 Carbocation

It is a species having positively charged carbon with three bond pairs and one vacant orbital (6 valence electrons). It is generally sp^2 hybridized and has trigonal planar shape.

sp^2 hybridised and trigonal planar

sp hybridized and linear
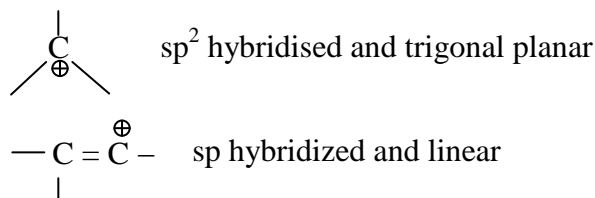
Stability of Carbocation

Stability of carbocation depends on factors affecting electron density. Any factor decreasing the positive charge will increase the stability. Effect of resonance is generally much more, direct inductive effect dominates over hyperconjugation but hyperconjugation generally dominates over indirect inductive effect. Aromatic carbocations will be highly stable while antiaromatic carbocations will be highly unstable.

Tertiary Carbocation > Secondary Carbocation > Primary Carbocation > Methyl Carbocation
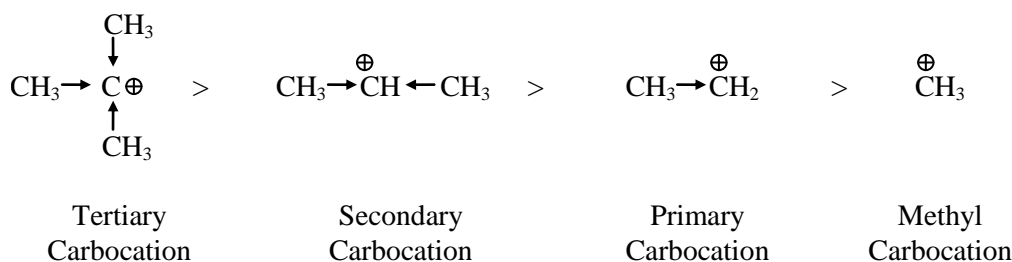
The stability order $3^o > 2^o > 1^o >$ methyl can be explained due to positive inductive effect of alkyl groups. Alternatively it can also be explained on the basis of hyperconjugation effect with 9, 6, 3 and zero hyper conjugation in above 3° , 2° , 1° and methyl carbocations.

3 hyperconjugation effects and one direct inductive effect < 2 direct inductive effects

3 hyperconjugation effects > 2 hyperconjugation effects > 1 hyperconjugation effect > no hyperconjugation effects
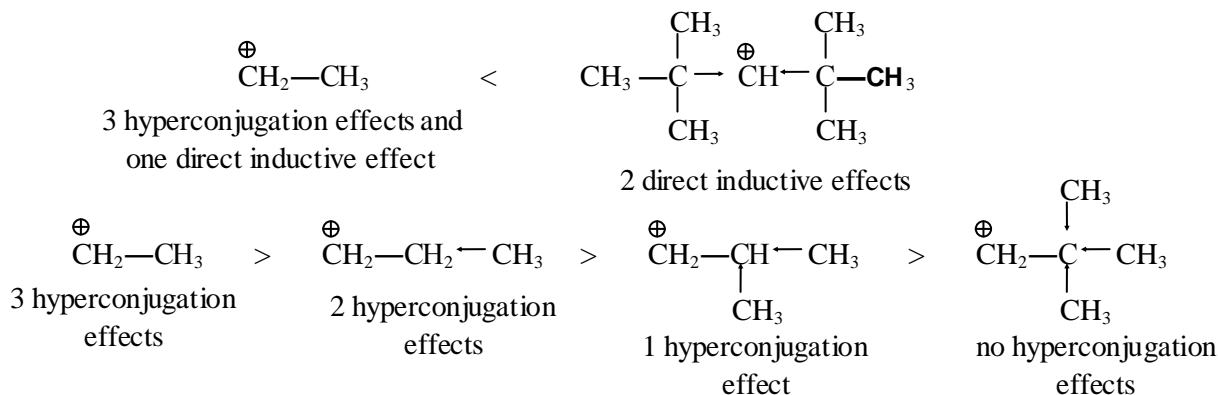
These carbocations have one direct inductive effect but the difference is in the hyperconjugation and indirect inductive effects of additional methyl groups.

$$\overset{+}{CH_2}—CH_3 \quad > \quad \overset{+}{C}H_3 \quad > \quad \overset{+}{CH_2}\overset{\frown}{—F} \quad > \quad \overset{+}{CH_2}\overset{\frown}{—Cl}$$
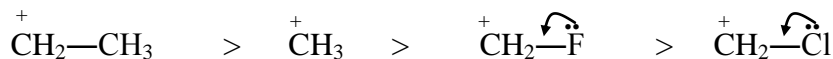
Negative inductive effect of halogen dominates over their +M effect. However, smaller halogen will have more tendency to form π bond due to which F will have more +M. The difference in M effect dominates over difference in I effect, particularly when moving 2nd period to 3rd period.
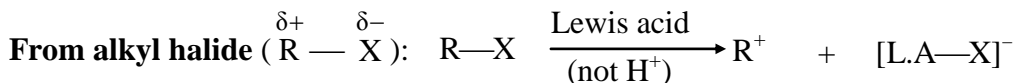
$$\overset{+}{C}H_3 \quad < \quad \overset{+}{CH_2}—CH_3 \quad < \quad \overset{+}{CH_2}\overset{\frown}{—\ddot{S}H} \quad < \quad \overset{+}{CH_2}\overset{\frown}{—\ddot{O}H}$$
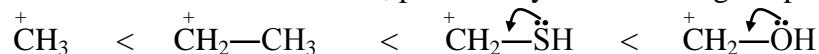
Positive mesomeric effect dominates over negative inductive effect. However, smaller oxygen will have more tendency to form π bond due to which OH will have more +M. The difference in M effect dominates over difference in I effect, particularly when moving 2nd period to 3rd period.

$$\overset{+}{C}H_3 \quad < \quad \overset{+}{CH_2}—CH_3 \quad < \quad \overset{+}{CH_2}\overset{\frown}{—\ddot{O}H} \quad < \quad \overset{+}{CH_2}\overset{\frown}{—\ddot{N}H_2}$$
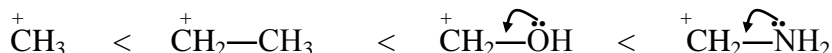
Positive mesomeric effect dominates over negative inductive effect. However, lesser electronegative N will have more tendency to give electron by M effect and lesser tendency to take electron by –I effect.

$$\overset{+}{C}H_3 \quad < \quad \overset{+}{C}H=CH_2 \quad < \quad \overset{+}{CH_2}—CH_3$$
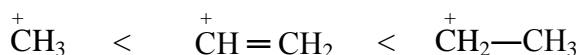
Carbon of vinyl carbocation is more electronegative (due to more s character) but due to 2 hyperconjugation effects vinyl carbocation is more stable than methyl carbocation.

| Tertiary Carbocation | Benzyl Carbocation | Allyl Carbocation |

5 equivalent structures But antiaromatic $<$ 2 equivalent structures $<$ 3 equivalent structures But aromatic
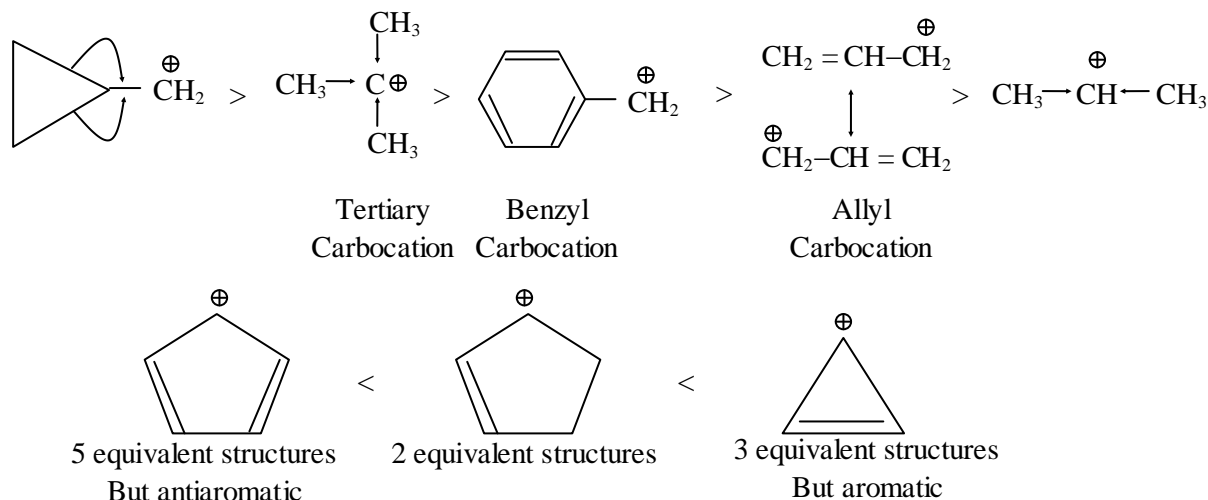
Formation of Carbocation

From alkyl halide ($\overset{\delta+}{R}—\overset{\delta-}{X}$): $R—X \xrightarrow[\text{(not } H^+)]{\text{Lewis acid}} R^+ \quad + \quad [L.A—X]^-$

H^+ cannot be used to remove X^- because $HX \longrightarrow H^+ + X^-$ has very high tendency to occur in forward direction and very low tendency to occur in backward direction.
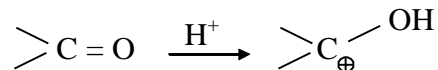
From alcohol: $-\overset{|}{\underset{|}{C}}\text{:}OH \xrightarrow[\text{(}H^+ \text{ can also be used)}]{AlX_3 \text{ (Lewis acid)}} -\overset{|}{\underset{|}{C}}\oplus$
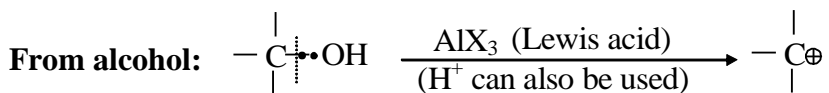
H^+ can be used to remove OH^- because it ($H_2O \longrightarrow H^+ + OH^-$) has very low tendency to occur in forward direction and very high tendency to occur in backward direction.
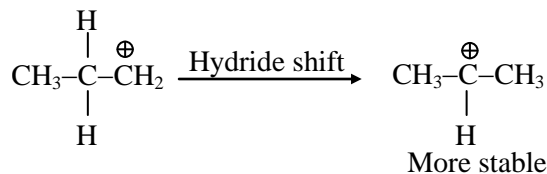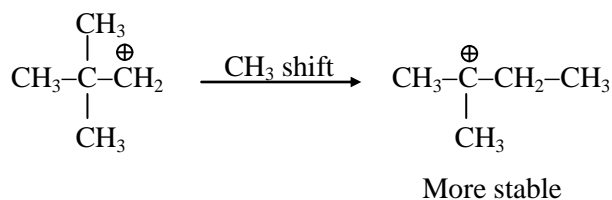
$$R-OH \xrightarrow[\text{H}_2\text{SO}_4]{\text{Lewis acid}} R^+ + OH^-$$

H_3PO_4 can also be used but not HNO_3 because it is an oxidizing agent and can oxidize alcohols.

From aldehyde and ketones:

$$\underset{}{>}C=O \xrightarrow{H^+} \underset{\oplus}{>}C \diagup^{OH}$$

From alkene: $CH_3-CH=CH_2 \xrightarrow{H_2SO_4} CH_3-CH_2-\overset{\oplus}{C}H_2 \,\&\, CH_3-\overset{\oplus}{C}H-CH_3$
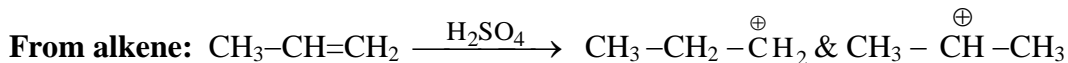
Behaviour of Carbocation

(i) Carbocation prefers to undergo rearrangement to more stable carbocation by shifting an atom or group from adjacent atom along with electrons of the bond.

$$\underset{\underset{CH_3}{|}}{\overset{\overset{CH_3}{|}\,\oplus}{CH_3-C-CH_2}} \xrightarrow{CH_3 \text{ shift}} \underset{\underset{CH_3}{|}}{\overset{\oplus}{CH_3-C-CH_2-CH_3}}$$

More stable

$$\underset{\underset{H}{|}}{\overset{\overset{H}{|}\,\oplus}{CH_3-C-CH_2}} \xrightarrow{\text{Hydride shift}} \underset{\underset{H}{|}}{\overset{\oplus}{CH_3-C-CH_3}}$$

More stable

(ii) Carbocation can react with nucleophiles or can react like electrophiles.

$$\overset{\oplus}{CH_3-CH-CH_3} \xrightarrow{Nu^-} \underset{}{\overset{\overset{Nu}{|}}{CH_3-CH-CH_3}}$$

$$\underset{\underset{CH_3}{|}}{CH_3-C=CH_2} \xrightarrow{\overset{\oplus}{R}} \underset{\underset{CH_3}{|}}{\overset{\oplus}{CH_3-C-CH_2-R}} + \underset{\underset{CH_3}{|}}{\overset{\overset{R}{|}}{CH_3-C-CH_2}}\overset{\oplus}{}$$

More stable (Major)   less stable
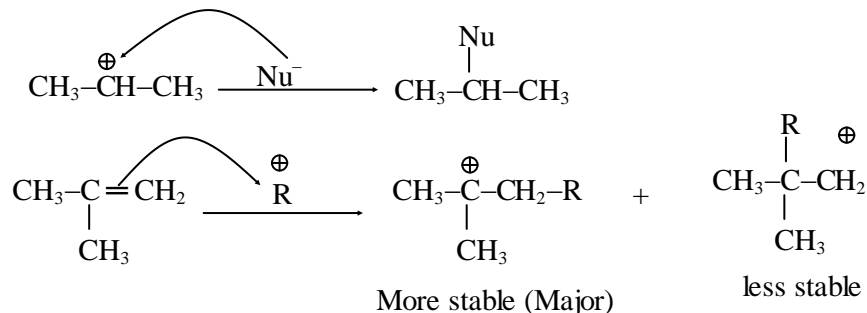
(iii) Carbocations can lose H^+, even in presence of weak bases like H_2O, ROH etc; from adjacent atom to form a π bond.

$$\overset{\oplus}{CH_3-CH} \overset{\overset{H}{\frown}}{-CH_2} \xrightarrow{-H^+} CH_3-CH=CH_2$$
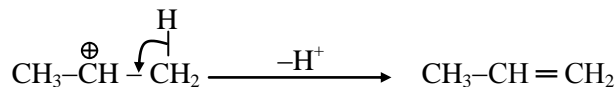
GENERAL REACTION MECHANISM

3.2 Carbon Free Radicals

It is a species having neutral carbon with three bond pairs and one unshared electron. Carbon free radicals are generally sp^2 hybridized as the unpaired electron of carbon is not generally involved in hybridization. However, sometimes in special cases this unpaired electron is involved in hybridization.
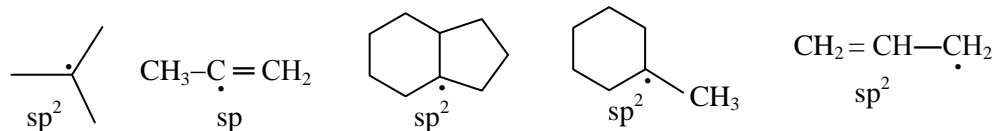
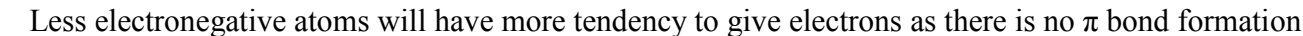Some examples where unpaired electron of carbon is involved in hybridization are given below:

Unpaired electron on triply bonded carbon	Atom of smaller ring can not be sp hybrid	Bridgehead atom cannot be sp^2 hybrid	unpaired electron when adjacent atom has lone pair
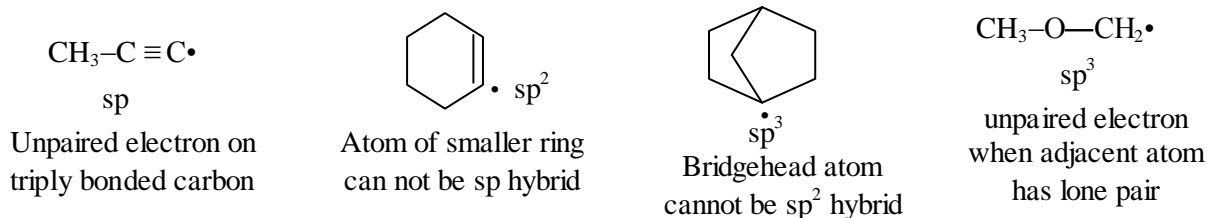
Stability of Carbon free Radicals

Stability of free radicals mainly depends on resonance effect and hyperconjugation. The inductive effect has very little role in stability of free radicals.

Benzyl free radical	Allyl free radical	Tertiary free radical	Secondary free radical	Primary free radical	Methyl free radical
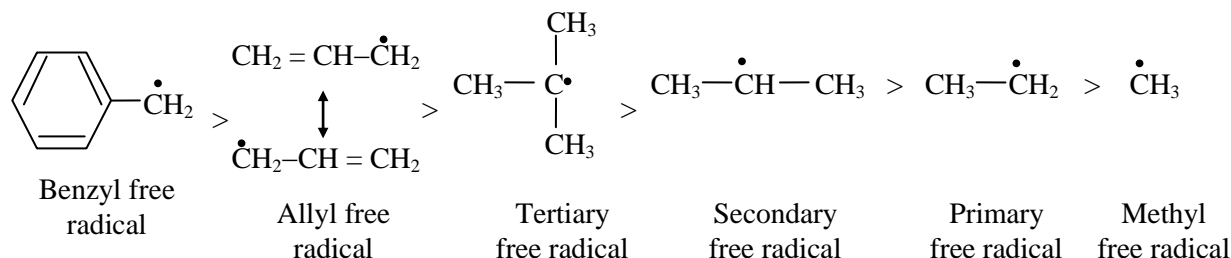
The stability order of free radicals $3^o > 2^o > 1^o >$ methyl can be explained on the basis of inductive effect. It can, however, be explained on the basis of hyper conjugation effect with 9, 6, 3 and zero hyper conjugation in 3°, 2°, 1° and methyl free radicals. The stability of allyl and benzyl free radicals is due to resonance.
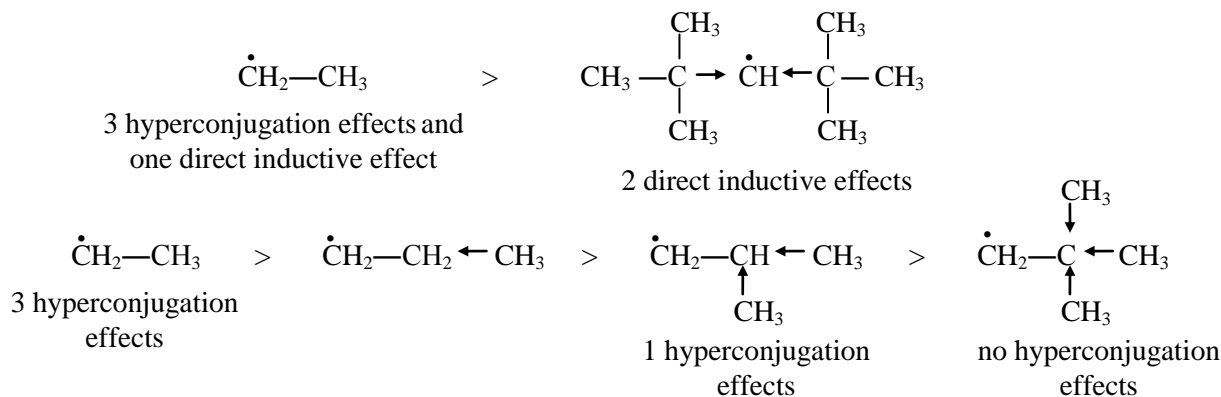
In carbon free radicals (neutral species), hyperconjugation effect dominates over direct inductive effect also.

$$\overset{\cdot\cdot}{CH_2}-\overset{\cdot\cdot}{F} \quad < \quad \overset{\cdot\cdot}{CH_2}-\overset{\cdot\cdot}{O}H \quad < \quad \overset{\cdot\cdot}{CH_2}-\overset{\cdot\cdot}{N}H_2 \quad < \quad \overset{\cdot\cdot}{CH_2}-\overset{\cdot\cdot}{S}H$$

$$\overset{\cdot}{CH_2}-\overset{\cdot\cdot}{F} \quad < \quad \overset{\cdot}{CH_2}-\overset{\cdot\cdot}{C}l \quad < \quad \overset{\cdot}{CH_2}-\overset{\cdot\cdot}{B}r \quad < \quad \overset{\cdot}{CH_2}-\overset{\cdot\cdot}{I}$$

Less electronegative atoms will have more tendency to give electrons as there is no π bond formation

Formation of Carbon free radical

By homolytic cleavage of a bond of carbon:

$$-\overset{|}{\underset{|}{C}}-H \quad \xrightarrow{A\bullet} \quad -\overset{|}{\underset{|}{C}}\bullet \quad + \quad [HA]$$

From Alkyl Halides:

We know that RX give R^+ so if we add one electron, we may get neutral alkyl free radical. Hence we should add a metal which can give one electron.

$$R-X \xrightarrow[\text{dry ether}]{Na} R\bullet$$

Dry ether is used because sodium is very reactive metal and can liberate hydrogen from protic solvent.

$$Na + H_2O \rightarrow NaOH + H_2 \uparrow$$

Li → Li can not be used as it can form a covalent bond with alkyl radical formed in the reaction to give RLi (R^- and Li^+). Sodium can not form covalent bond

By Homolytic cleavage of a π (carbon-carbon pi) bond:

$$\underset{}{\overset{}{>}}C \overset{}{\underset{\cdots}{=\!\!=}} C\overset{}{\underset{}{<}} \quad \xrightarrow{A\bullet} \quad \underset{\bullet}{\overset{\backslash}{/}}C - \underset{\underset{A}{|}}{C}\overset{}{\underset{}{<}}$$

Behaviour of Carbon free radical

Carbon free radical will behave as a usual radical i.e. it can either combine with another radical or can do homolytic cleavage of a covalent bond.

3.3 Carbanion

It is a species having negatively charged carbon with three bond pairs and one lone pair. It is generally sp^3 hybridized. It is trigonal pyramidal (like NH_3). But sometimes it is also sp^2 and sp hybridized. The lone pair is generally involved in hybridization but if it is delocalized it will not be involved in hybridization.

$$-\overset{\ominus}{\underset{\cdot\cdot}{C}}=\overset{}{\underset{|}{C}}- \quad sp^2 \text{ hybridized (angular)}$$

$$:\overset{\ominus}{C}\equiv C- \quad sp \text{ hybridized (linear shape)}$$

$$CH_3-C\equiv C^{\ominus}$$
sp

delocalized lone pair

sp^2

sp^2

Bridgehead atom cannot be sp^2 hybrid

sp^3

delocalized lone pair

sp^2

GENERAL REACTION MECHANISM

STABILITY OF CARBANIONS
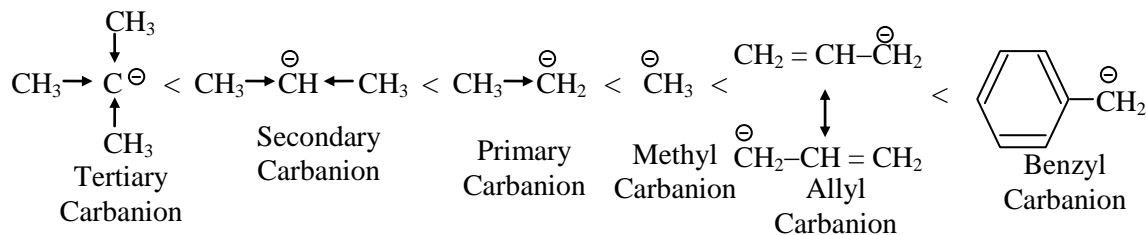
The stability order $3^o < 2^o < 1^o <$ methyl can be explained on the basis of +I effect of alkyl groups (electron-releasing) which increases −ve charge and decreases stability. The stability of allyl and benzyl carbanions is due to resonance.
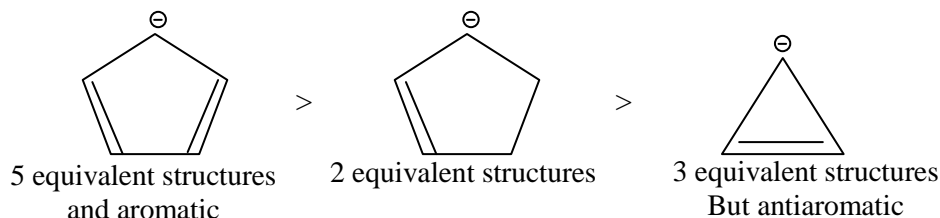
Formation of Carbanion
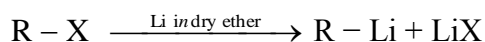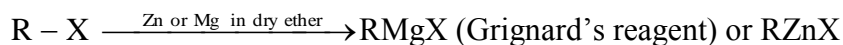
By removal of H^+ from a carbon:

$$-\overset{|}{\underset{|}{C}} - H \xrightarrow{\text{Base}} -\overset{|}{\underset{|}{C}}^{\ominus} + HB$$
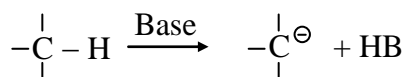
Carbanion itself is very strong base hence this method is not generally useful. However, this method can be used in some cases where the carbanion is very stable (if that hydrogen is acidic).

$$-\overset{O}{\overset{||}{C}}-\overset{|}{\underset{|}{C}}-H \xrightarrow{B^{\ominus}} -\overset{O}{\overset{||}{C}}-\overset{\ominus}{\underset{|}{C}}-$$

$$H-\overset{X}{\underset{X}{\overset{|}{\underset{|}{C}}}}-X \xrightarrow{\text{Base}} \overset{X}{\underset{X}{\overset{|}{\underset{|}{\ominus C}}}}-X$$

$$-C \equiv \underset{sp}{C} - H \xrightarrow{\overset{\ominus}{N H_2}} -C \equiv C^{\ominus} + NH_3$$
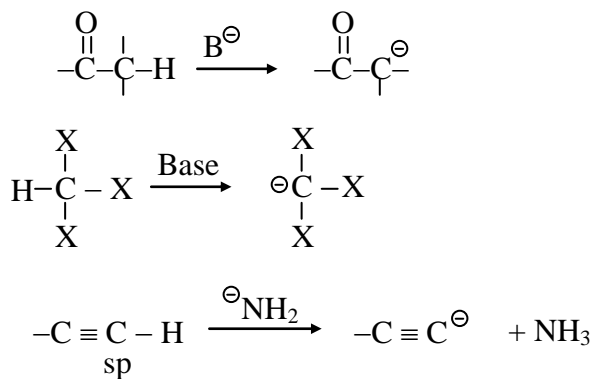
From alkyl halide:

We know that RX give R^+ so if we add two electrons, we may get alkyl carbanion. Hence we should add a metal which can give two electrons. Water cannot be used as solvent because metal can liberate H_2 gas.

$$R - X \xrightarrow{\text{Zn or Mg in dry ether}} RMgX \text{ (Grignard's reagent) or RZnX}$$

$$R - X \xrightarrow{\text{Li in dry ether}} R - Li + LiX$$

Behaviour of carbanions

Carbanions are very strong nucleophile and very strong bases. They prefer to abstract any acidic hydrogen whose acidic strength is comparable to ammonia or larger. They can also lose a leaving group from adjacent position.

3.4   Carbene

It is a species having a neutral carbon with two bond pairs and two unshared electrons. It is of two types: Singlet and triplet.

Singlet Carbene: Total spin $= +\dfrac{1}{2}, -\dfrac{1}{2} = 0$, only one value

Triplet Carbene: It is more stable according to Hund's rule.

$+\dfrac{1}{2} + \dfrac{1}{2}$, total spin $= 1$

$-\dfrac{1}{2} - \dfrac{1}{2}$, total spin $= -1$ Three different values of total spin.

$-\dfrac{1}{2} + \dfrac{1}{2}$, total spin $= 0$

Both the unpaired electrons have parallel spins in ground state of triplet carbene.

singlet carbene (sp^2)   triplet carbene (sp)
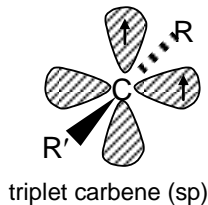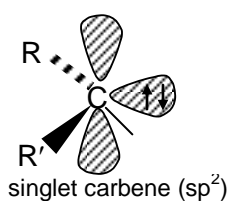
Question:

Although triplet form of carbene is more stable, carbene is generally formed in singlet state. Explain.

Answer:

(two homolytic bond cleavages are not highly favoured).

After homolytic cleavage of one bond radical will be formed which will prefer to combine with the radical reagent used for the second homolytic bond cleavage.

(two heterolytic bond cleavage are possible).

After heterolytic cleavage of one bond heterolytic cleavage of another bond will occur and a singlet carbene is formed.

Formation of Carbene

By dehydrohalogenation of Alkyl halide using a base:

$$-\underset{X}{\overset{|}{C}} - H \xrightarrow{\text{Base (B}^-)} -\overset{|}{C}\text{:}^- \quad + HB + X^-$$
$$\qquad\qquad\qquad\qquad\qquad\text{(carbene)}$$
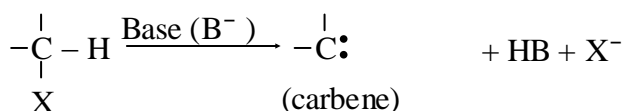
Note: Removal of H$^+$ and X$^-$ from same atom occurs only if their removal from adjacent atoms is not possible.

$$CH_3-\underset{\underset{Cl}{|}}{CH_2} \xrightarrow{\ B^-\ } CH_2 = CH_2 \qquad + HB + X^-$$

$$CH_3 - \underset{\underset{CH_3}{|}}{\overset{\overset{CH_3}{|}}{C}} - \underset{\underset{Cl}{|}}{CH_2} \xrightarrow{\ B^-\ } CH_3 - \underset{\underset{CH_3}{|}}{\overset{\overset{CH_3}{|}}{C}} - \overset{\bullet\bullet}{C} - H \qquad + HB + X^-$$

$$H - \underset{\underset{Cl}{|}}{\overset{\overset{Cl}{|}}{C}} - Cl \xrightarrow{\ B^-\ } \underset{\bullet\bullet}{\overset{\overset{Cl}{|}}{C}} - Cl \qquad + HB + X^-$$

By Dehalogenation of geminal dihalides using Mg or Zn:

$$-\underset{\underset{X}{\vdots}}{\overset{|}{C}}\cdots X \xrightarrow{\ 2e^-Mg\ } \longrightarrow -\overset{|}{C}\!\!: \quad MgX_2$$
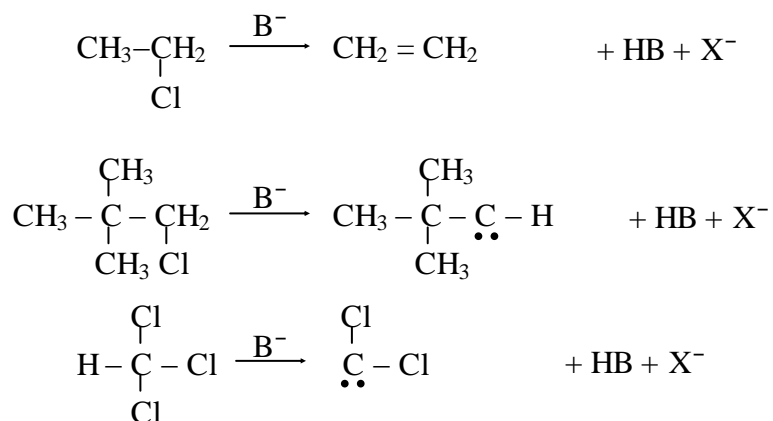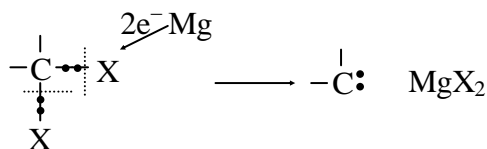
Note: Removal two halogen atoms from adjacent carbons is more favourable than removal from one atom. Therefore, removal of two halogen atoms from same atom occurs only if their removal from adjacent atoms is not possible.

$$\underset{\underset{Cl}{|}}{CH_2} - \underset{\underset{Cl}{|}}{CH} - Cl \xrightarrow{\ Mg\ } CH_2 = CHCl$$

$$CH_3 - \underset{\underset{Cl}{|}}{\overset{\overset{Cl}{|}}{CH}} - Cl \xrightarrow{\ Mg\ } CH_3 \overset{\bullet\bullet}{C} - H$$

$$H - \underset{\underset{Cl}{|}}{\overset{\overset{Cl}{|}}{C}} - Cl \xrightarrow{\ Mg\ } H - \overset{\bullet}{C}\!\!:$$

$$\underset{\underset{Cl}{|}}{CH_2} - \underset{\underset{Cl}{|}}{CH_2} \xrightarrow{\ Mg\ } CH_2 = CH_2$$
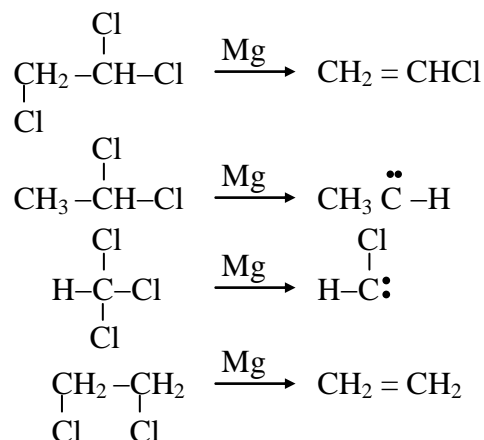
By photolysis or pyrolysis of Ketene:
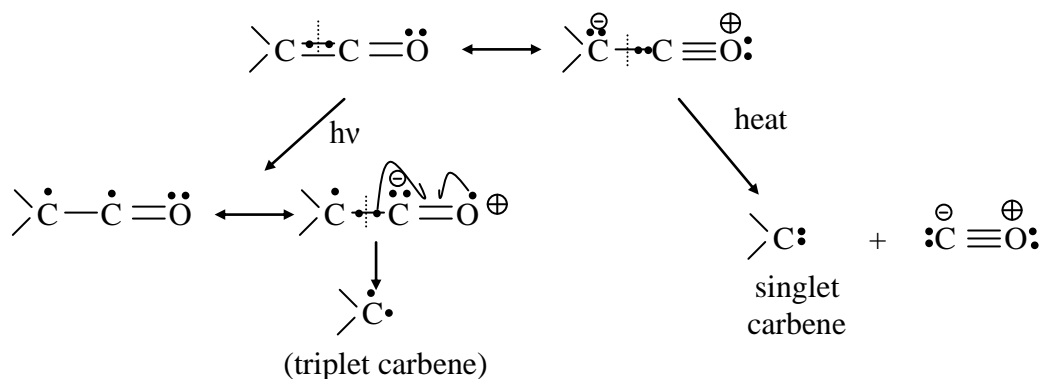
(triplet carbene)

singlet carbene

By photolysis or pyrolysis of Diazoalkane:
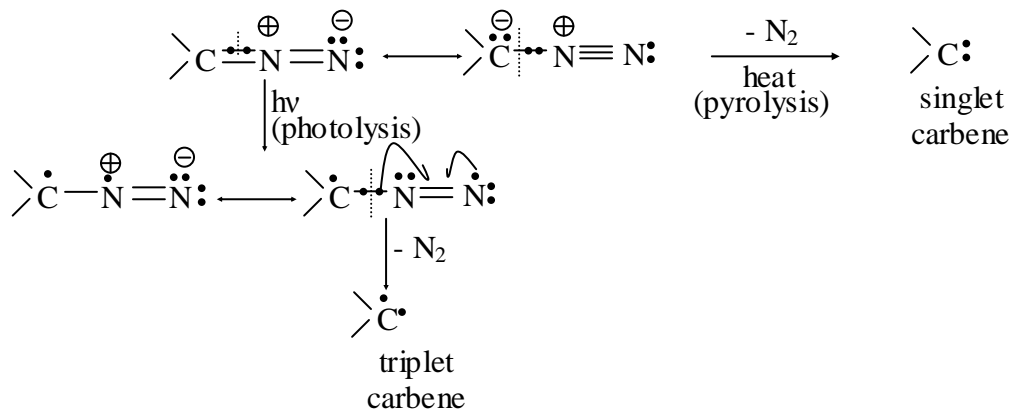
Behaviour of Carbene

(i)   Singlet carbene prefers to undergo shifting of a group or atom from adjacent position.
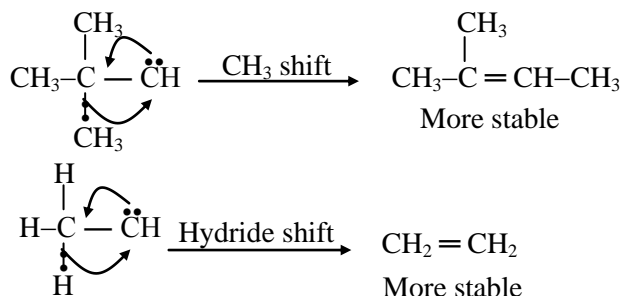
(ii)   Singlet carbene can behave either like electrophile only (due to presence of vacant orbital) or like electrophile as well as like nucleophile in same step (due to presence of vacant orbital as well as lone pair)
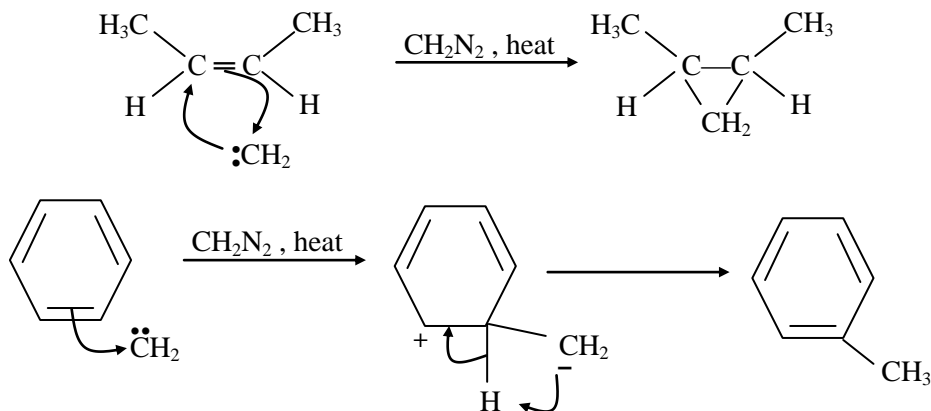
(iii)   Singlet carbene can slowly convert to more stable triplet carbene. This is significant only if singlet carbene is unable to react in singlet state itself.

(iv)   Triplet carbene can react like a diradical.
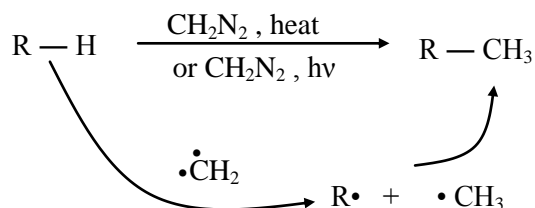
3.5   Nitrene

It is a species having neutral Nitrogen atom with one bond pair and four unshared electrons. Its structure, formation and behaviour is similar to that of carbene.

Formation of Nitrene

By heating alkyl azides or by dehydrohalogenation from N-halo derivative by treating with a base:

$$\overset{\ominus}{\ddot{\text{N}}} = \overset{\oplus}{\text{N}} = \ddot{\ddot{\text{N}}}$$

Azide ion

$$R{-}\overset{\oplus}{\ddot{\text{N}}} = \overset{\ominus}{\text{N}} = \ddot{\ddot{\text{N}}} \longrightarrow R{-}\overset{\ominus}{\ddot{\text{N}}} {+}{\cdot}{\cdot} \overset{\oplus}{\text{N}} {\equiv} \text{N}{\colon} \xrightarrow{\text{Heat}} R{-}\ddot{\ddot{\text{N}}}$$

$$R{-}X \xrightarrow{\text{NaN}_3} RN_3 \xrightarrow{\text{Heat}} R{-}\ddot{\ddot{\text{N}}}$$

$$\underset{X}{-}\overset{\cdot\cdot}{\text{N}}{-}H \xrightarrow{B^-} {-}\ddot{\text{N}}{\colon} \;\; + HB + X^-$$

$$R{-}\overset{\overset{O}{\parallel}}{C}{-}\underset{X}{\overset{\cdot\cdot}{N}}{-}H \xrightarrow{B^-} R{-}\overset{\overset{O}{\parallel}}{C}{-}\ddot{\text{N}}{\colon} \;\; + HB + X^-$$
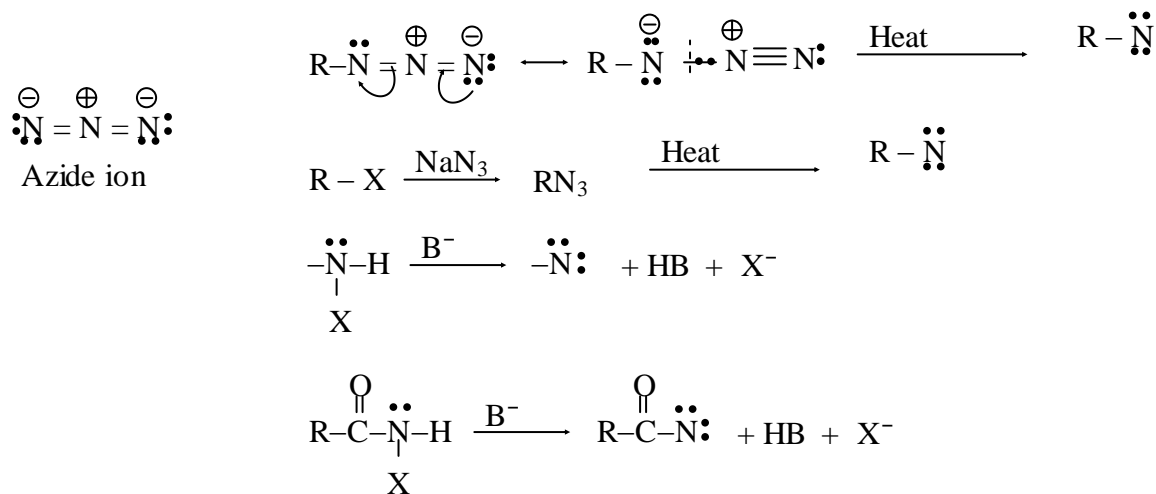
3.6   Benzyne

Benzyne is very different from what can be expected from simple concepts of chemical bonding.

All six carbon atoms are sp^2 hybridized. Three normal π bonds are formed by p orbitals of each carbon. These π bonds are completely delocalized in the benzene ring. However, sp^2 hybrid orbitals of two carbon atoms overlap in sideways manner to form a special π bond. This special π bond is very weak because the sp^2 hybrid orbitals were directed slightly away and the extent of overlapping is very poor. The presence of six completely delocalized π electrons makes benzyne aromatic. On the other hand, presence of a very weak π bond makes it highly unstable (it cannot be isolated and acts as intermediate only).
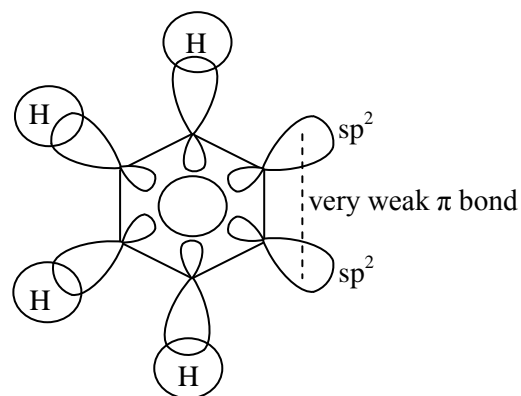
Benzyne Intermediate

Formation of Benzyne

(i)   **By dehydrohalogenation of halobenzene:**
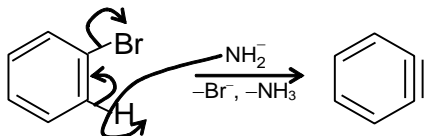
(ii)   **By dehalogenation of o-dihalobenzene:**
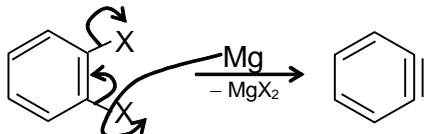
Behaviour of Benzyne

Inspite of high π electron density, benzyne does not react with electrophile because it will generate a cation having sp hybrid atom in six membered ring (not generated due to very large strain).

Highly unstable
(not formed)
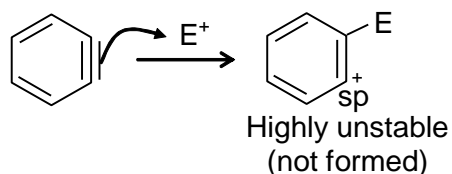
In spite of high π electron density, benzyne can react with nucleophile because it will generate sp^2 hybrid carbanion that is stable.
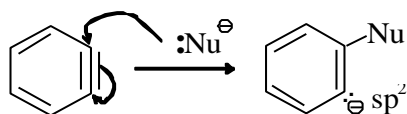
In absence of nucleophile, benzyne can undergo dimerization although it will generate anti aromatic ring.

Biphenylene
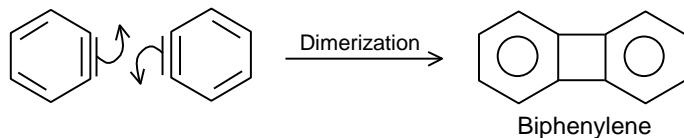
4 Rearrangement Reactions

Rearrangement refers to structural changes within a species. Rearrangements, in general are of two types:

(a) Shifting of a group from one atom to the other

(b) Rearrangement because of resonance

4.1 Shifting of a Group From One Atom to Another Atom

Although shifting of a group can occur from an atom to any other atom yet most of the shifts occur to adjacent atoms only. The main reason for this shifting is presence of six valence electrons and a vacant orbital on an atom. Such an atom has tendency to complete its octet for which the group from the adjacent atom migrates with the bonding electrons. There are two different conditions around an atom with six valence electrons.

When atom with six valence electrons do not have a lone pair

Six valence
electrons around A

Six valence
electrons around B
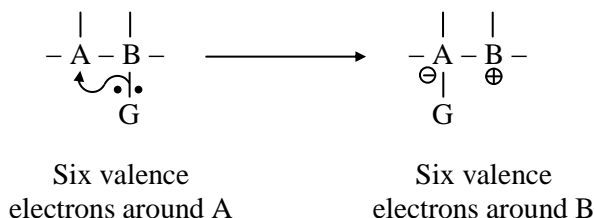
In this case when a group is shifted from atom B, the octet of B becomes incomplete which is not favourable condition. So we can say that this shift will occur only if it increases stability.
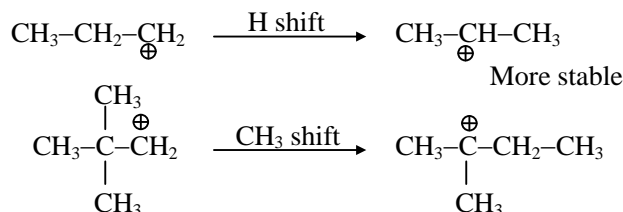
Ring expansion and ring contraction can also result because of adjacent shift.
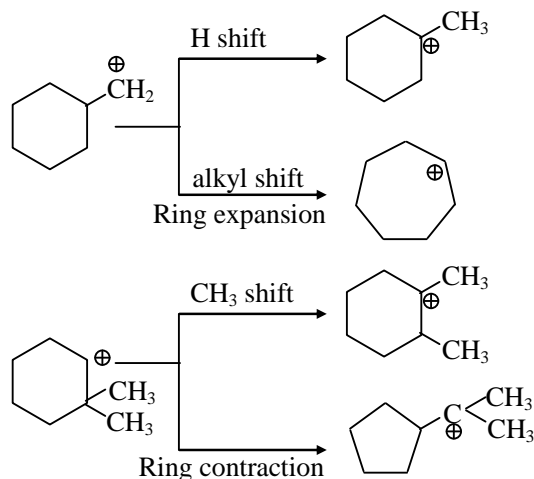
GENERAL REACTION MECHANISM

If migration of two (or more) different groups from adjacent atoms can take place, major migration depends on the migrating tendency of the migrating groups (migration of group with higher migrating tendency is favoured) and the stability of resultant species (more stable resultant species is more favoured). Migrating tendency of a group is generally higher if it is more electron rich i.e. more electron donating. The general order of migrating tendency (or migratory aptitude) is as given below:

Hydride   <   Alkyl   <   Aryl   <   Hydride

(If not involved in hyperconjugation with atom having 6 valence electrons)

$1^o\ R < 2^o\ R < 3^o R$

E.W.G   E.D.G

(If involved in hyperconjugation with atom having 6 valence electrons)
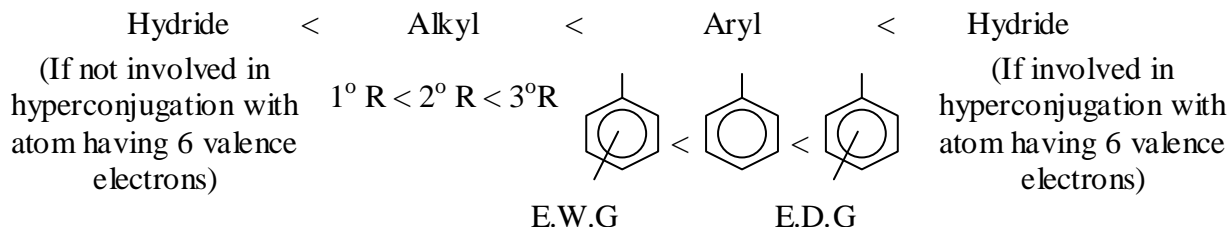
In several cases migrating tendency and the stability of resultant species favours the same migration. In such cases it will be easier to predict the major migration product.
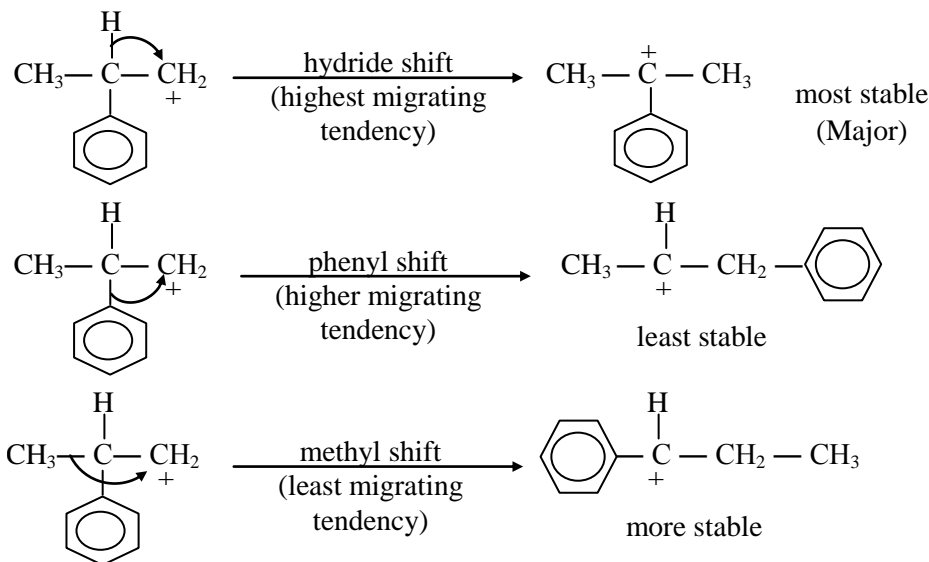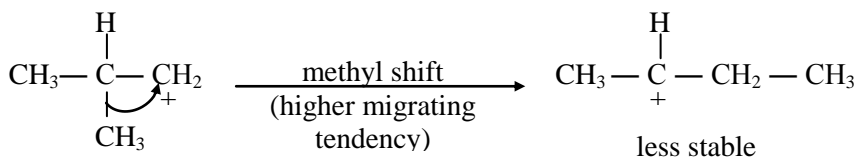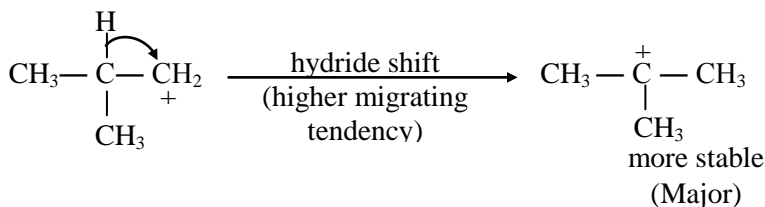
Migrating tendency versus Stability of Resultant Species

(i)   *If both resultant species are very highly stabilized (stabilized by resonance of lone pair or stabilized by formation of additional bond), small amount of stability does not matter a lot. Therefore, major migration occurs according to migrating aptitude.*
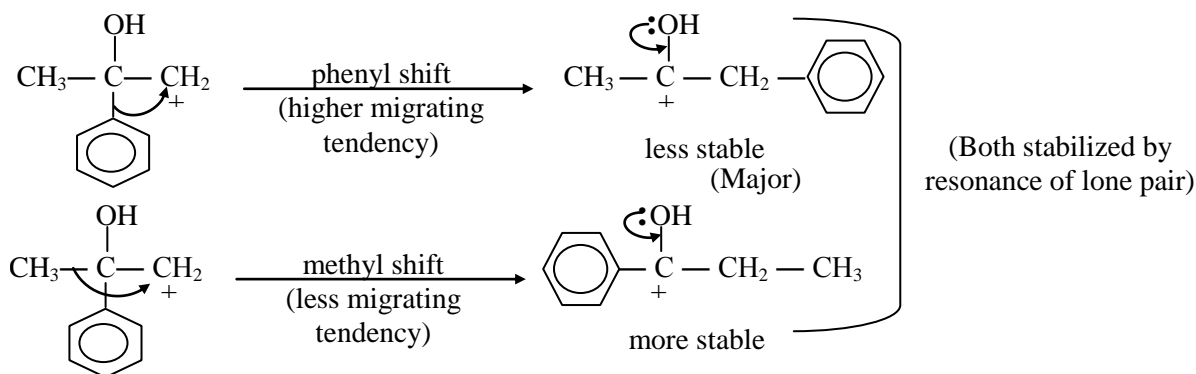
(ii) *If both resultant species are not very highly stabilized (not stabilized by resonance of lone pair or not stabilized by formation of additional bond), small amount of stability also matters a lot. Therefore, major migration occurs according to stability of resultant species.*
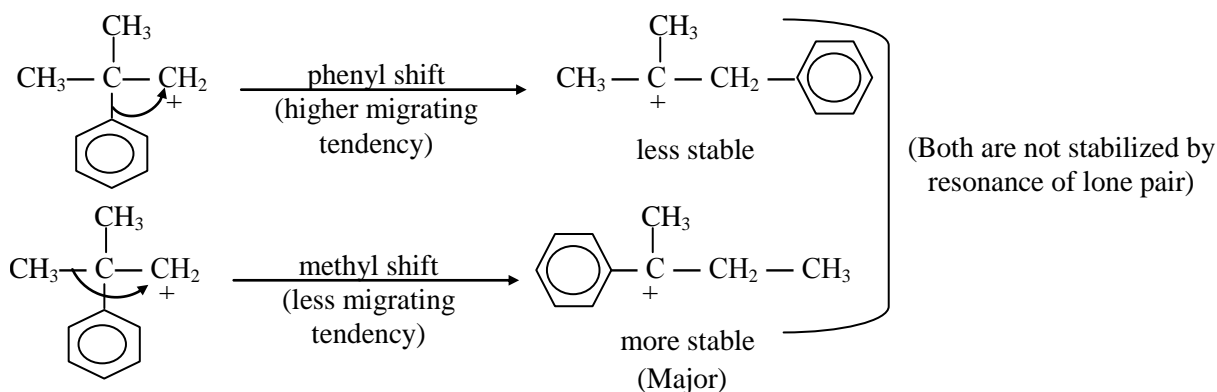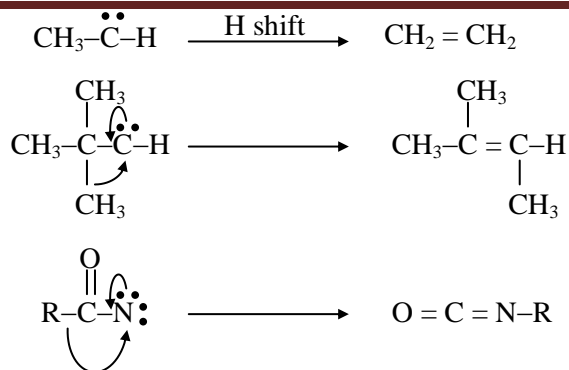

(iii) *If the difference of stability is large, stability will dominate over the migrating tendency. Therefore, groups containing lone pairs migrate rarely.*
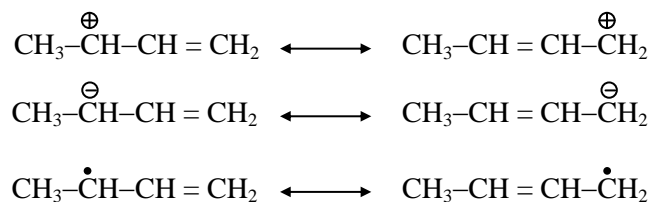
When atom with six valence electrons have lone pair
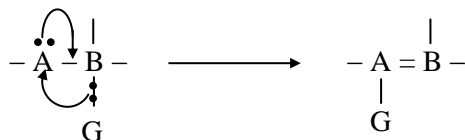
In this case when a group from atom B is shifted, octet of B becomes incomplete which can be completed (stabilized) by lone pairs present on A atom. Hence under these conditions stability increases always and these rearrangements are, in general, bound to take place in the given species. Moreover, in such cases formation of additional bond or stabilization by resonance of lone pair will be generally observed, therefore migrating tendency generally dominates.

$$CH_3-\overset{\cdot\cdot}{C}-H \xrightarrow{\text{H shift}} CH_2 = CH_2$$

$$CH_3-\overset{\overset{\displaystyle CH_3}{|}}{\underset{\underset{\displaystyle CH_3}{|}}{C}}-\overset{\cdot\cdot}{C}-H \longrightarrow CH_3-\overset{\overset{\displaystyle CH_3}{|}}{C} = \underset{\underset{\displaystyle CH_3}{|}}{C}-H$$

$$R-\overset{\overset{\displaystyle O}{||}}{C}-\overset{\cdot\cdot}{N}\overset{\cdot\cdot}{:} \longrightarrow O = C = N-R$$

4.2   Rearrangement Because Of Resonance (Allylic Rearrangement)

In these cases actually rearrangements do not occur but more than one product is formed because of the resonance in the intermediate. These rearrangements are also called pseudo rearrangements. These rearrangements are possible when the intermediates like carbocation, carbanion or carbon free radical etc. are resonance stabilized and more than one different resonating structures are possible. For example:

$$CH_3-\overset{\oplus}{C}H-CH = CH_2 \longleftrightarrow CH_3-CH = CH-\overset{\oplus}{C}H_2$$

$$CH_3-\overset{\ominus}{C}H-CH = CH_2 \longleftrightarrow CH_3-CH = CH-\overset{\ominus}{C}H_2$$

$$CH_3-\overset{\bullet}{C}H-CH = CH_2 \longleftrightarrow CH_3-CH = CH-\overset{\bullet}{C}H_2$$

Following reactions illustrate allylic rearrangements:

$$CH_3-\underset{\underset{\displaystyle OH}{|}}{C}H-CH = CH_2 \xrightarrow{\text{HCl}} CH_3-\underset{\underset{\displaystyle Cl}{|}}{C}H-CH = CH_2 \ + \ CH_3-CH = CH-\underset{\underset{\displaystyle Cl}{|}}{C}H_2$$

$$CH_3-CH_2-CH = CH_2 \xrightarrow[\text{High temp}]{\text{Cl}_2 \, / \, h\nu} CH_3-\underset{\underset{\displaystyle Cl}{|}}{C}H-CH = CH_2 \ + \ CH_3-CH = CH-\underset{\underset{\displaystyle Cl}{|}}{C}H_2$$

$$CH_3-\underset{\underset{\displaystyle Cl}{|}}{C}H-CH = CH_2 \xrightarrow[\text{(ii) H}_2\text{O}]{\text{(i) Mg/ dry ether}} CH_3-CH_2-CH = CH_2 \ + \ CH_3-CH = CH-CH_3$$

$$CH_3-\underset{\underset{\displaystyle OH}{|}}{C}H-CH = CH_2 \underset{}{\overset{H\overset{\oplus}{}}{\rightleftharpoons}} CH_3-CH = CH-\underset{\underset{\displaystyle OH}{|}}{C}H_2$$
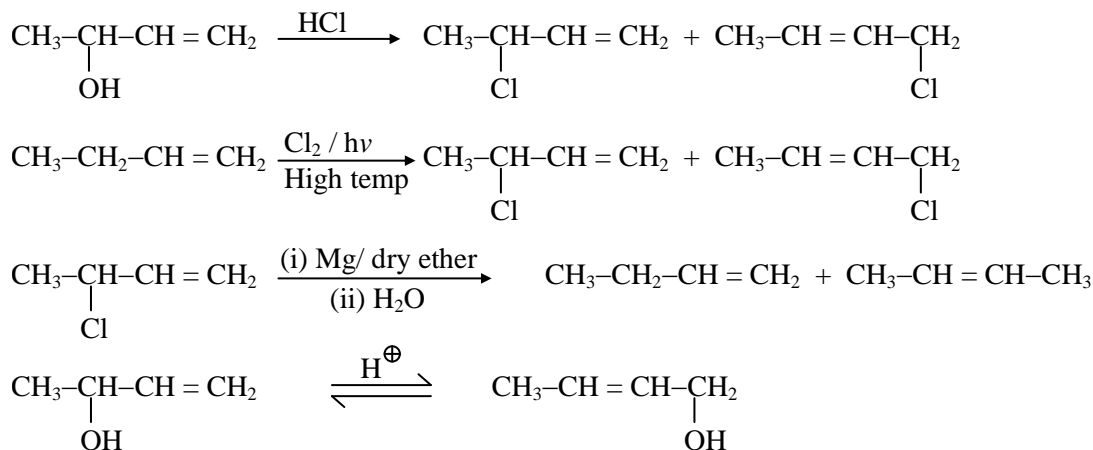
5   Acid Base Reactions

Let us consider the following two acid ionization constants:

(i)   HA (aq.) $\rightleftharpoons$ H^+(aq.) + A^-(aq.) K_a of HA

(ii)   HB (aq.) $\rightleftharpoons$ H^+(aq.) + B^-(aq.) K_a of HB

Subtracting equation (ii) from equation (i) we get:

(iii)   HA (aq.) + B^-(aq.) $\rightleftharpoons$ A^-(aq.) + HB

Equilibrium constant of equation (iii) will be K_{eq} = (K_a of HA/ K_a of HB).

GENERAL REACTION MECHANISM

If K_a of HA > K_a of HB the K_{eq} will be more than unity and the reaction is more favoured in forward direction and less favoured in backward direction. In other words a stronger acid has more tendency to produce weaker acid after proton exchange.

$$HA \text{ (aq.)} + B^- \text{(aq.)} \xrightleftharpoons{\hspace{1cm}} A^- \text{(aq.)} + HB$$
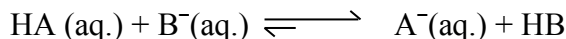
Similarly, if K_a of HA < K_a of HB the K_{eq} will be less than unity and the reaction is less favoured in forward direction and more favoured in backward direction. In other words a weaker acid has lesser tendency to produce stronger acid after proton exchange.

$$HA \text{ (aq.)} + B^- \text{(aq.)} \xleftrightharpoons{\hspace{1cm}} A^- \text{(aq.)} + HB$$
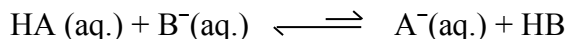
These proton exchange reactions are almost complete if a much stronger acid (several thousand time more K_a) is producing a much weaker acid. The backward extent of such reactions is negligible and the reactions are generally shown as complete reactions. As proton exchange reactions are very fast these reactions are almost instantaneous also.

$$HA \text{ (aq.)} + B^- \text{(aq.)} \longrightarrow A^- \text{(aq.)} + HB$$
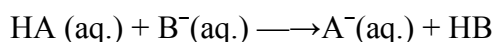
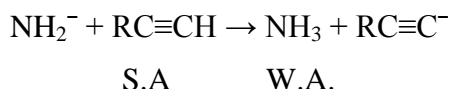## Order of acidic strength of some common acidic substances is given below:

$Ar/R—SO_3H > HX > H/Ar/R—CO_2H > H_2CO_3 > Ph—OH > H_2O > ROH > RC{\equiv}CH > NH_3 > CH_2{=}CH_2 > RH$
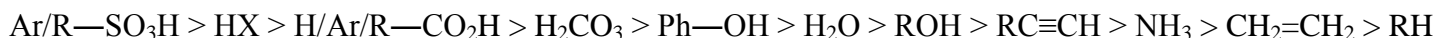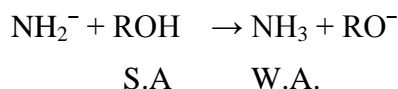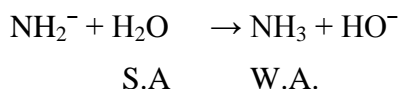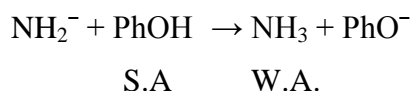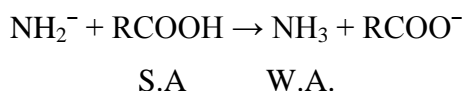
This information is quite useful for the selection of protic solvents for a particular reaction.

For example we cannot use RCOOH, PhOH, H_2O, ROH and NH_3 as solvent if we want R^- to act as nucleophile because all these are much stronger acids than RH (alkane) and following instantaneous and almost complete reactions are observed. Therefore R^- is generally used in ether as solvent.
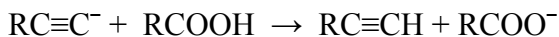
$$\begin{array}{ll}
R^- + RCOOH \rightarrow RH + RCOO^- & \qquad R^- + PhOH \rightarrow RH + PhO^- \\
\quad\text{S.A} \qquad\quad \text{W.A.} & \qquad\qquad \text{S.A} \qquad \text{W.A.}
\end{array}$$

$$\begin{array}{ll}
R^- + H_2O \rightarrow RH + HO^- & \qquad R^- + ROH \rightarrow RH + RO^- \\
\quad\text{S.A} \quad\ \text{W.A.} & \qquad\qquad \text{S.A} \quad\ \text{W.A.}
\end{array}$$

$$\begin{array}{ll}
R^- + RC{\equiv}CH \rightarrow RH + RC{\equiv}C^- & \qquad R^- + NH_3 \rightarrow RH + NH_2^- \\
\quad\text{S.A} \qquad\quad \text{W.A.} & \qquad\qquad \text{S.A} \quad\ \text{W.A.}
\end{array}$$
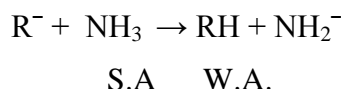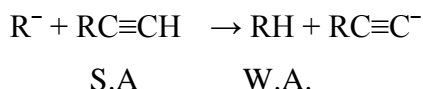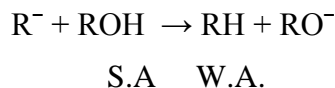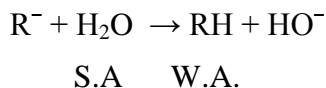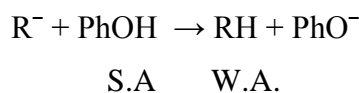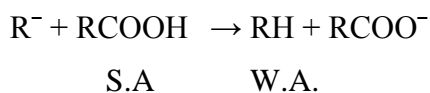
Similarly we cannot use RCOOH, PhOH, H_2O and ROH as solvent if we want NH_2^- to act as nucleophile or base because all these are much stronger acids than NH_3 and following instantaneous and almost complete reactions are observed. However, we can use NH_2^- in NH_3.
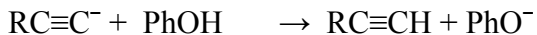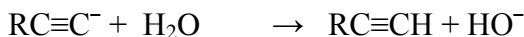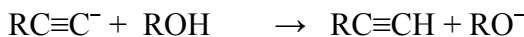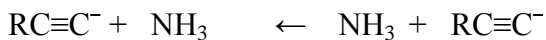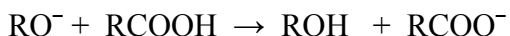
$$\begin{array}{ll}
NH_2^- + RCOOH \rightarrow NH_3 + RCOO^- & \qquad NH_2^- + PhOH \rightarrow NH_3 + PhO^- \\
\qquad\text{S.A} \qquad\quad \text{W.A.} & \qquad\qquad\ \text{S.A} \qquad\quad \text{W.A.}
\end{array}$$

$$\begin{array}{ll}
NH_2^- + H_2O \rightarrow NH_3 + HO^- & \qquad NH_2^- + ROH \rightarrow NH_3 + RO^- \\
\qquad\text{S.A} \qquad\ \text{W.A.} & \qquad\qquad\ \text{S.A} \qquad\ \text{W.A.}
\end{array}$$

$$\begin{array}{l}
NH_2^- + RC{\equiv}CH \rightarrow NH_3 + RC{\equiv}C^- \\
\qquad\text{S.A} \qquad\qquad \text{W.A.}
\end{array}$$

GENERAL REACTION MECHANISM

Similarly, we cannot use RCOOH, PhOH, H_2O and ROH as solvent if we want $RC{\equiv}C^-$ to act as nucleophile because all these are much stronger acids than $RC{\equiv}CH$ and following instantaneous and almost complete reactions are observed. However, we can use $RC{\equiv}C^-$ in NH_3.

$$RC{\equiv}C^- + RCOOH \rightarrow RC{\equiv}CH + RCOO^-$$
$$\qquad\qquad S.A \qquad\qquad\qquad W.A.$$

$$RC{\equiv}C^- + PhOH \quad\rightarrow RC{\equiv}CH + PhO^-$$
$$\qquad\qquad S.A \qquad\qquad\quad W.A.$$

$$RC{\equiv}C^- + H_2O \quad\rightarrow\ RC{\equiv}CH + HO^-$$
$$\qquad\qquad S.A \qquad\qquad\qquad W.A.$$

$$RC{\equiv}C^- + ROH \quad\rightarrow\ RC{\equiv}CH + RO^-$$
$$\qquad\qquad S.A \qquad\qquad\qquad W.A.$$

$$RC{\equiv}C^- + NH_3 \quad\leftarrow\quad NH_3 + RC{\equiv}C^-$$
$$\qquad\qquad W.A \qquad\qquad\quad S.A.$$

Similarly, we cannot use RCOOH, PhOH and H_2O as solvent if we want RO^- to act as nucleophile or base because all these are much stronger acids than ROH and following instantaneous and almost complete reactions are observed. However, we can use RO^- in ROH and in NH_3.
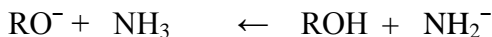
$$RO^- + RCOOH \rightarrow ROH\ +\ RCOO^-$$
$$\qquad\quad S.A \qquad\qquad W.A.$$

$$RO^- + PhOH \quad\rightarrow ROH\ +\ PhO^-$$
$$\qquad\quad S.A \qquad\qquad W.A.$$

$$RO^- +\ H_2O \quad\rightarrow\ ROH + HO^-$$
$$\qquad\quad S.A \qquad\qquad\quad W.A.$$

$$RO^- +\ NH_3 \quad\leftarrow\ ROH\ +\ NH_2^-$$
$$\qquad\quad W.A \qquad\qquad\quad S.A.$$
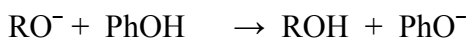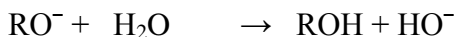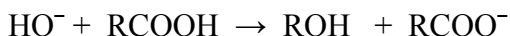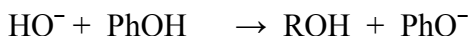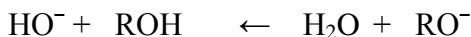
Similarly, we cannot use RCOOH and PhOH as solvent if we want HO^- to act as nucleophile or base because all these are much stronger acids than H_2O and following instantaneous and almost complete reactions are observed. However, we can use HO^- in H_2O, ROH and in NH_3.

$$HO^- + RCOOH \rightarrow ROH\ +\ RCOO^-$$
$$\qquad\quad S.A \qquad\qquad W.A.$$

$$HO^- + PhOH \quad\rightarrow ROH\ +\ PhO^-$$
$$\qquad\quad S.A \qquad\qquad W.A.$$

$$HO^- +\ ROH \quad\leftarrow\ H_2O\ +\ RO^-$$
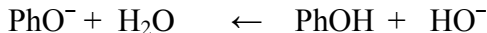$$\qquad\quad W.A \qquad\qquad\quad S.A.$$

Similarly, we cannot use RCOOH as solvent if we want PhO^- to act as nucleophile because this is much stronger acid than PhOH and following instantaneous and almost complete reaction is observed. However, we can use PhO^- in H_2O, ROH and in NH_3.

$$PhO^- + RCOOH \rightarrow PhOH + RCOO^-$$

<div align="center">S.A   W.A.</div>

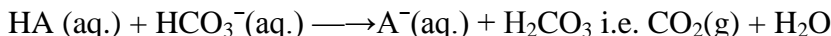$$PhO^- + H_2O \quad \leftarrow \quad PhOH + HO^-$$

<div align="center">W.A   S.A.</div>

Use of bicarbonate test

When HCO_3^- is added to any acid that is stronger than H_2CO_3 the following reaction is observed. H_2CO_3 produced in the reaction is unstable and produce CO_2 gas and H_2O. The rate of formation of CO_2 is quite high thus effervescence of CO_2 gas are observed immediately.

$$HA\ (aq.) + HCO_3^-(aq.) \longrightarrow A^-(aq.) + H_2CO_3\ i.e.\ CO_2(g) + H_2O$$

Bicarbonate test (i.e. evolution of effervescence of CO_2 on adding HCO_3^-) is given by mineral acids like H_2SO_4, HNO_3, HX etc. and organic acids like sulphonic acids, carboxylic acids, Dinitrophenol and some other acids as given below (both these are stronger acids than even carboxylic acid):

squaric acid
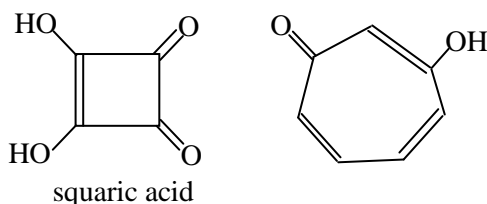
6. Elimination Reactions

These are the reactions in which small molecule like H_2O, NH_3, HX, ROH, RCOOH, X_2 etc. is removed from a compound. In these reactions two atoms or groups are removed from same or different positions of a molecule either in the form of ions or neutral molecules. These reactions generally do not proceed through free radical mechanisms as homolytic cleavage of two bonds is not favored. Based on the positions from which two groups are removed, elimination reactions are of three types:

(a)   1,2-Eliminations (Removal of two atoms or groups from adjacent positions).

(b)   1,n-Eliminations (Removal of two atoms or groups from non adjacent positions. This generally leads to the formation of cyclic compounds and is called cyclization).

(c)   1,1-Eliminations (Removal of two atoms or groups from same position).
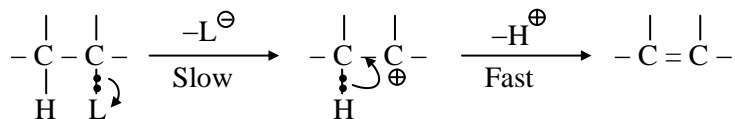
6.1 β-Elimination (1,2-Elimination)

When two atoms or groups are removed from adjacent atoms, the bond cleavage of these two atoms or groups is generally heterolytic (rarely homolytic). The group which is removed with the bonding electron is called leaving group and is represented by 'L'.
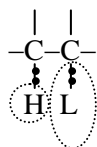
1,2-Elimination mainly occurs via three different mechanisms.

(a) Unimolecular Elimination (E_1) Mechanism

$$-\overset{|}{\underset{|}{C}}-\overset{|}{\underset{\underset{L}{H}}{C}}- \xrightarrow[\text{Slow}]{-L^{\ominus}} -\overset{|}{\underset{\underset{H}{|}}{C}}\underset{\oplus}{\overset{|}{C}}- \xrightarrow[\text{Fast}]{-H^{\oplus}} -\overset{|}{C}=\overset{|}{C}-$$

In unimolecular elimination, leaving group is first expelled in slow (rate determining) step followed by abstraction of a proton. Some important characteristics of E_1 mechanism are:

(i)   *Better the leaving group, faster will be rate of E_1 reaction* because leaving group is expelled in rate determining step.

$$R\text{—}I > R\text{—}Br > R\text{—}Cl \qquad (E_1 \text{ reactivity})$$

(ii)   As the product of rate determining step is carbocation, we can interpret that *more the stability of carbocation, more will be rate of E_1 reaction.*
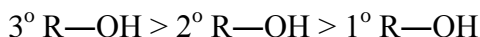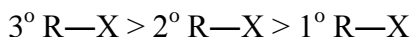
$$3^o\ R\text{—}X > 2^o\ R\text{—}X > 1^o\ R\text{—}X$$

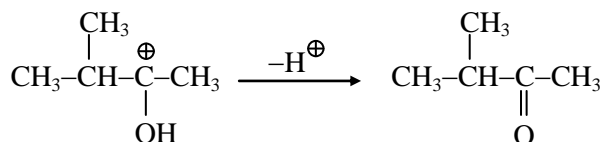$$3^o\ R\text{—}OH > 2^o\ R\text{—}OH > 1^o\ R\text{—}OH$$

(iii)   Polar aprotic solvents will solvate and stabilize cation only. Positively charged carbocation is solvated more than transition state while neutral reactant is not affected. This leads to decrease in activation energy and increase in E_1 reactivity. Polar protic solvent can solvate cation as well as anion. Therefore, effect of solvation and decrease in activation energy is more (*as shown in energy profile of rate determining step*).
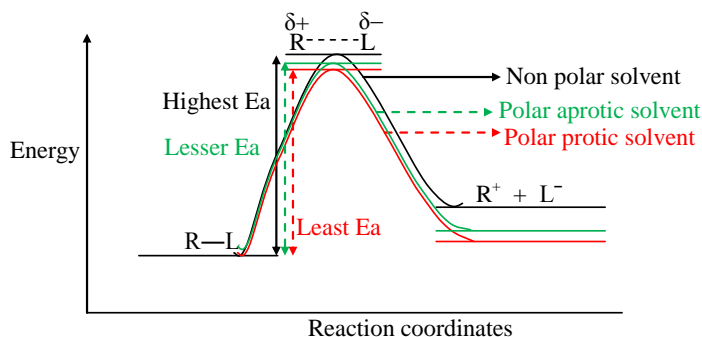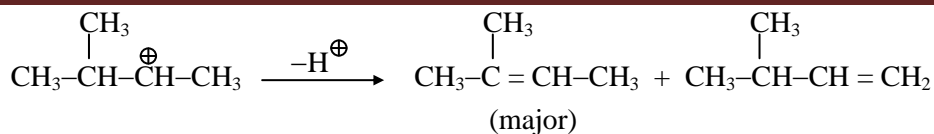
Therefore, order of E_1 reactivity will be: Non polar < Polar aprotic < Polar protic.

Further increase in polarity will increase in E_1 reactivity.

(iv)   As a carbocation (containing six valence electrons and a vacant orbital) is formed, rearrangements are possible before the loss of H^+.

(v)   As proton has to be removed from adjacent atom of a carbocation (which is an easy process), a weak base like H_2O, ROH etc. can also act as base. A strong base is not required for E_1 reaction. Moreover, increase in basic strength of the base or its concentration will not increase the rate of E_1 reaction.

(vi)   As carbocation is planar, removal of H^+ from both the sides of plane is equally favoured. Therefore, E_1 reaction can be **Anti Elimination** (removal of two groups from opposite sides) or **Syn Elimination** (removal of two groups from same sides).

(vii)   If removal of a proton from two different adjacent atoms is possible, removal of proton occurs almost exclusively from more electronegative atom. If adjacent atoms are same, more stable (more substituted alkene) product is major product.
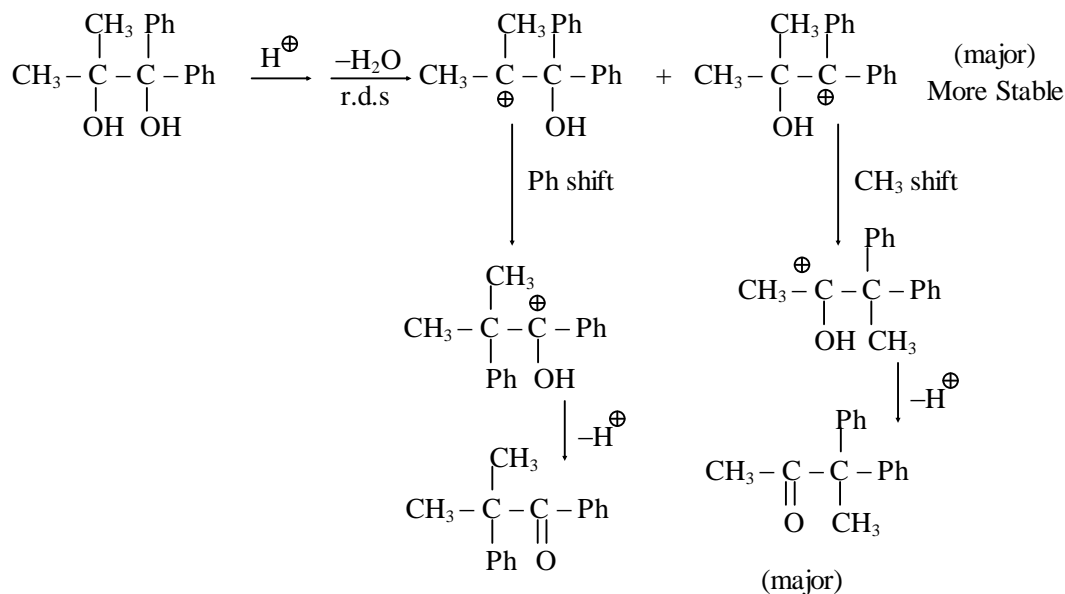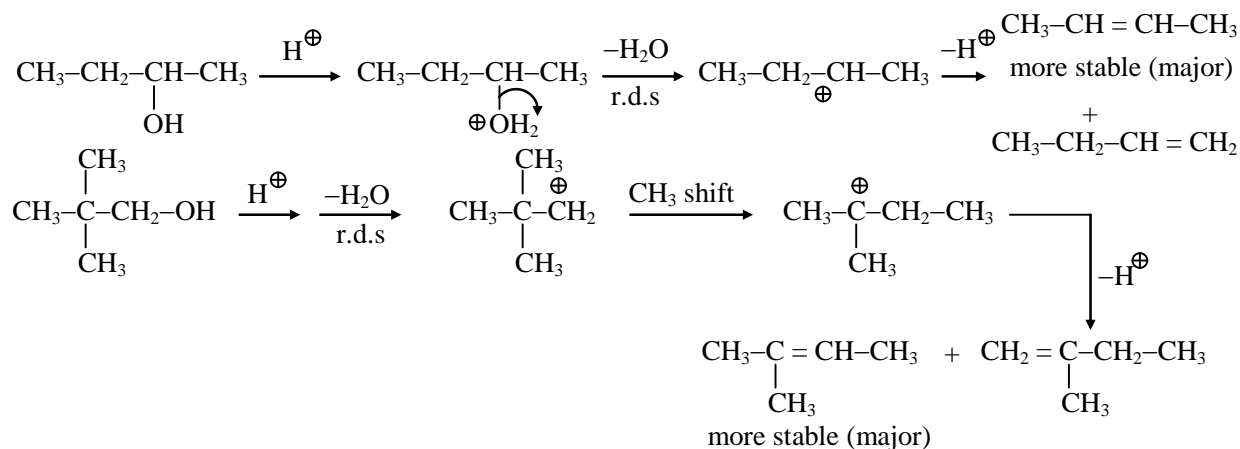
$$\underset{\underset{OH}{|}}{\overset{\overset{CH_3}{|}}{CH_3\text{–}CH\text{–}\overset{\oplus}{C}\text{–}CH_3}} \xrightarrow{-H^{\oplus}} \underset{\underset{O}{\|}}{\overset{\overset{CH_3}{|}}{CH_3\text{–}CH\text{–}C\text{–}CH_3}}$$

$$CH_3-\overset{\overset{\displaystyle CH_3}{|}}{CH}-\overset{\oplus}{CH}-CH_3 \xrightarrow{-H^{\oplus}} CH_3-\overset{\overset{\displaystyle CH_3}{|}}{C}=CH-CH_3 \;+\; CH_3-\overset{\overset{\displaystyle CH_3}{|}}{CH}-CH=CH_2$$
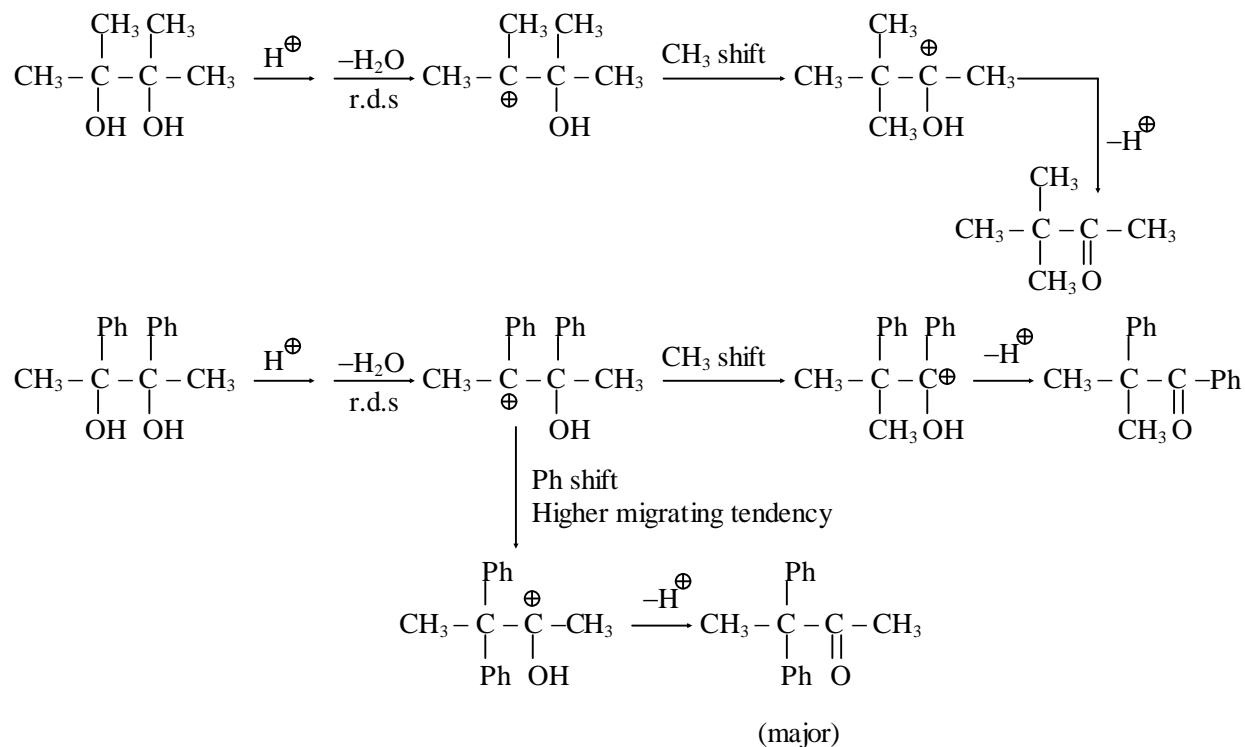
(major)

(viii)   Unimolecular nucleophilic substitution (S_N1) will be the competing reaction.

Examples of E_1 Mechanism

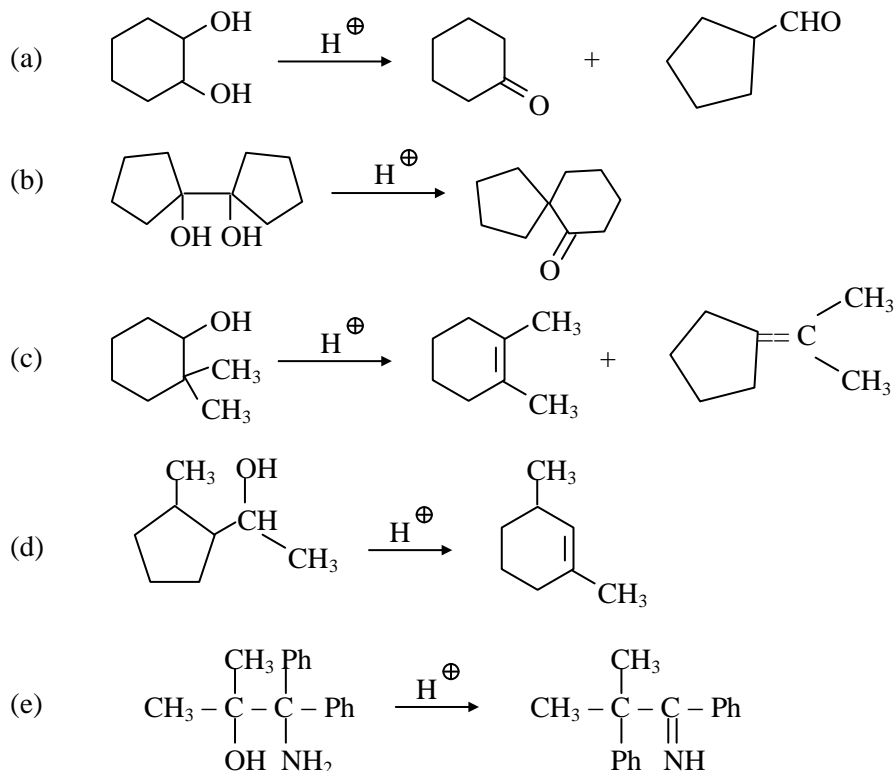**Acid catalysed dehydration of most alcohols except smaller primary alcohols.**

$$CH_3-CH_2-\overset{\overset{\displaystyle }{|}}{\underset{\underset{\displaystyle OH}{|}}{CH}}-CH_3 \xrightarrow{H^{\oplus}} CH_3-CH_2-\underset{\underset{\displaystyle \overset{\oplus}{O}H_2}{|}}{CH}-CH_3 \xrightarrow[\text{r.d.s}]{-H_2O} CH_3-CH_2-\overset{\oplus}{C}H-CH_3 \xrightarrow{-H^{\oplus}} \begin{array}{l}CH_3-CH=CH-CH_3 \\ \text{more stable (major)} \\ + \\ CH_3-CH_2-CH=CH_2\end{array}$$

$$CH_3-\overset{\overset{\displaystyle CH_3}{|}}{\underset{\underset{\displaystyle CH_3}{|}}{C}}-CH_2-OH \xrightarrow[\text{r.d.s}]{\overset{\displaystyle H^{\oplus}}{} \;\; -H_2O} CH_3-\overset{\overset{\displaystyle CH_3}{|}}{\underset{\underset{\displaystyle CH_3}{|}}{C}}-\overset{\oplus}{C}H_2 \xrightarrow{CH_3 \text{ shift}} CH_3-\overset{\overset{\displaystyle \oplus}{}}{\underset{\underset{\displaystyle CH_3}{|}}{C}}-CH_2-CH_3$$

$$\xrightarrow{-H^{\oplus}} CH_3-\overset{\overset{\displaystyle }{}}{\underset{\underset{\displaystyle CH_3}{|}}{C}}=CH-CH_3 \;+\; CH_2=\overset{\overset{\displaystyle }{}}{\underset{\underset{\displaystyle CH_3}{|}}{C}}-CH_2-CH_3$$

more stable (major)

$$CH_3-\overset{\overset{\displaystyle CH_3}{|}}{\underset{\underset{\displaystyle OH}{|}}{C}}-\overset{\overset{\displaystyle Ph}{|}}{\underset{\underset{\displaystyle OH}{|}}{C}}-Ph \xrightarrow[\text{r.d.s}]{\overset{\displaystyle H^{\oplus}}{} \; -H_2O} CH_3-\overset{\overset{\displaystyle CH_3}{|}}{\underset{\underset{\displaystyle \oplus}{}}{C}}-\overset{\overset{\displaystyle Ph}{|}}{\underset{\underset{\displaystyle OH}{|}}{C}}-Ph \;+\; CH_3-\overset{\overset{\displaystyle CH_3}{|}}{\underset{\underset{\displaystyle OH}{|}}{C}}-\overset{\overset{\displaystyle Ph}{|}}{\underset{\underset{\displaystyle \oplus}{}}{C}}-Ph$$

(major) More Stable

Ph shift

CH₃ shift

$$CH_3-\overset{\overset{\displaystyle CH_3}{|}}{\underset{\underset{\displaystyle Ph}{|}}{C}}-\overset{\oplus}{\underset{\underset{\displaystyle OH}{|}}{C}}-Ph$$

$$CH_3-\overset{\oplus}{\underset{\underset{\displaystyle OH}{|}}{C}}-\overset{\overset{\displaystyle Ph}{|}}{\underset{\underset{\displaystyle CH_3}{|}}{C}}-Ph$$

$-H^{\oplus}$

$-H^{\oplus}$

$$CH_3-\overset{\overset{\displaystyle CH_3}{|}}{\underset{\underset{\displaystyle Ph}{|}}{C}}-\overset{}{\underset{\underset{\displaystyle O}{||}}{C}}-Ph$$

$$CH_3-\overset{}{\underset{\underset{\displaystyle O}{||}}{C}}-\overset{\overset{\displaystyle Ph}{|}}{\underset{\underset{\displaystyle CH_3}{|}}{C}}-Ph$$

(major)

First scheme (pinacol-type rearrangement):

$$CH_3-\underset{OH}{\underset{|}{\overset{CH_3}{\overset{|}{C}}}}-\underset{OH}{\underset{|}{\overset{CH_3}{\overset{|}{C}}}}-CH_3 \xrightarrow[\text{r.d.s}]{H^\oplus \quad -H_2O} CH_3-\underset{\oplus}{\overset{CH_3}{\overset{|}{C}}}-\underset{OH}{\underset{|}{\overset{CH_3}{\overset{|}{C}}}}-CH_3 \xrightarrow{CH_3\text{ shift}} CH_3-\underset{CH_3}{\underset{|}{\overset{CH_3}{\overset{|}{C}}}}-\underset{OH}{\underset{|}{\overset{\oplus}{C}}}-CH_3$$

$$\xrightarrow{-H^\oplus} CH_3-\underset{CH_3}{\underset{|}{\overset{CH_3}{\overset{|}{C}}}}-\underset{O}{\overset{||}{C}}-CH_3$$

Second scheme:

$$CH_3-\underset{OH}{\underset{|}{\overset{Ph}{\overset{|}{C}}}}-\underset{OH}{\underset{|}{\overset{Ph}{\overset{|}{C}}}}-CH_3 \xrightarrow[\text{r.d.s}]{H^\oplus \quad -H_2O} CH_3-\underset{\oplus}{\overset{Ph}{\overset{|}{C}}}-\underset{OH}{\underset{|}{\overset{Ph}{\overset{|}{C}}}}-CH_3 \xrightarrow{CH_3\text{ shift}} CH_3-\underset{CH_3}{\underset{|}{\overset{Ph}{\overset{|}{C}}}}-\underset{OH}{\underset{|}{\overset{Ph}{\overset{|}{C}^\oplus}}} \xrightarrow{-H^\oplus} CH_3-\underset{CH_3}{\underset{|}{\overset{Ph}{\overset{|}{C}}}}-\underset{O}{\overset{||}{C}}-Ph$$

Ph shift
Higher migrating tendency

$$CH_3-\underset{Ph}{\underset{|}{\overset{Ph}{\overset{|}{C}}}}-\underset{OH}{\underset{|}{\overset{\oplus}{C}}}-CH_3 \xrightarrow{-H^\oplus} CH_3-\underset{Ph}{\underset{|}{\overset{Ph}{\overset{|}{C}}}}-\underset{O}{\overset{||}{C}}-CH_3$$

(major)

Practice Problems

Write the mechanism for the following transformations:

(a) [cyclohexane-1,2-diol] $\xrightarrow{H^\oplus}$ [cyclohexanone] + [cyclopentane-CHO]

(b) [1,1'-bi(cyclopentyl)-diol] $\xrightarrow{H^\oplus}$ [spiro ketone]

(c) [1-methyl-2,2-dimethyl cyclohexanol] $\xrightarrow{H^\oplus}$ [1,2-dimethylcyclohexene] + [isopropylidene cyclopentane]

(d) [2-(1-hydroxyethyl)-1-methylcyclopentane] $\xrightarrow{H^\oplus}$ [1,3-dimethylcyclohexene]

(e) $CH_3-\underset{OH}{\underset{|}{\overset{CH_3}{\overset{|}{C}}}}-\underset{NH_2}{\underset{|}{\overset{Ph}{\overset{|}{C}}}}-Ph \xrightarrow{H^\oplus} CH_3-\underset{Ph}{\underset{|}{\overset{CH_3}{\overset{|}{C}}}}-\underset{NH}{\overset{||}{C}}-Ph$

GENERAL REACTION MECHANISM

Bimolecular Elimination (E₂) Mechanism

$$-\underset{H}{\overset{|}{C}} \underset{L}{\overset{|}{C}} - \xrightarrow{B^{\ominus}} -\overset{|}{C} = \overset{|}{C} -$$
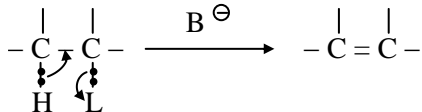
In bimolecular elimination, both atoms or groups from adjacent positions are removed simultaneously in a single step. Some important characteristics of E₂ mechanism are:

(i) *Better the leaving group, faster will be rate of E₂ reaction* because leaving group is expelled in rate determining step.

$$R—I > R—Br > R—Cl$$

(ii) As the product of rate determining step in E₂ reaction is alkene, *more the stability of alkene, more will be rate of E₂ reaction.*
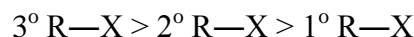
$$3^o\ R—X > 2^o\ R—X > 1^o\ R—X$$

(iii) In non-polar solvent and polar aprotic solvent, anions are not solvated. However, when polar protic solvent is used, negative reactants and products will be solvated considerably while partial negative transition state will be solvated only slightly. Therefore, energy of negatively charged reactants and products will decrease considerable while energy of transition state will decrease slightly. This results in increase of activation energy in polar protic solvent (*as shown in energy profile of rate determining step*).
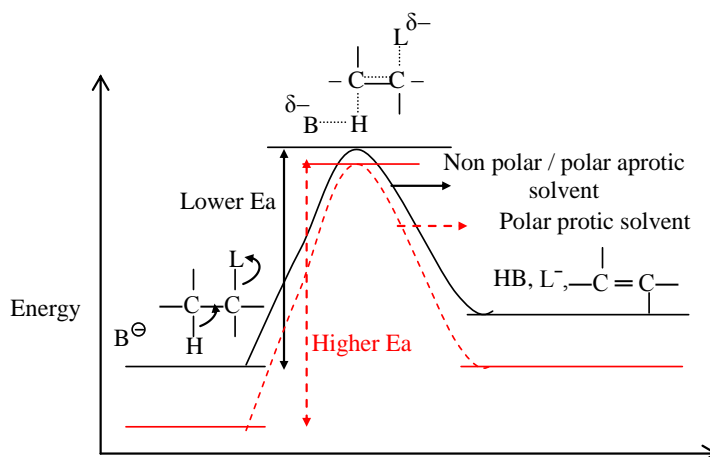
Therefore, rate of E₂ reaction will be lesser in polar protic solvent. Similarly, increase in polarity of polar protic solvent will further increase activation energy and decrease rate of E₂ reaction. E₂ reactivity in different solvents will be:

Non-polar ≈ Polar aprotic > Polar protic (less polar) > Polar protic (More polar)
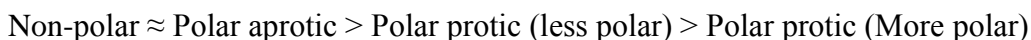
(iv) No rearrangements are observed during E₂ elimination.
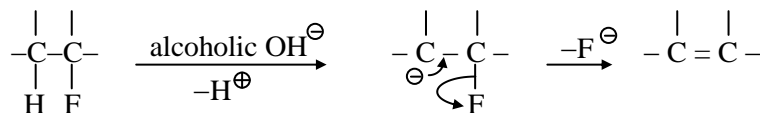
(v) As proton has to be removed from a carbon of neutral species (a difficult job), a strong base is required for E₂ reaction. Moreover, increase in the basic strength or its concentration will increase rate of E₂ elimination as base is involved in r.d.s.

(vi) E₂ elimination is preferably 'anti' although 'syn' elimination may also take place if anti configuration is not possible.

This is because when the base approaches the proton to be abstracted, it repels the bonding electrons away from leaving group in syn configuration and towards the leaving group in anti configuration.

(vii) If removal of proton from two adjacent atoms is possible, major product depends on the stability of product (alkene) as well as steric hindrance.

If active base is small (1^oR—O$^-$), steric hindrance can be neglected and the effect of stability decide the major product (*Saytzeff rule*). The elimination is called *Saytzeff elimination* and the product is called *Saytzeff product*.

If active base is bulky (3° R—O$^-$), steric hindrance will be large and dominating and will decide the major product (Hoffmann's Rule). The elimination is called *Hoffmann's elimination* and the product is called *Hoffmann's product*.
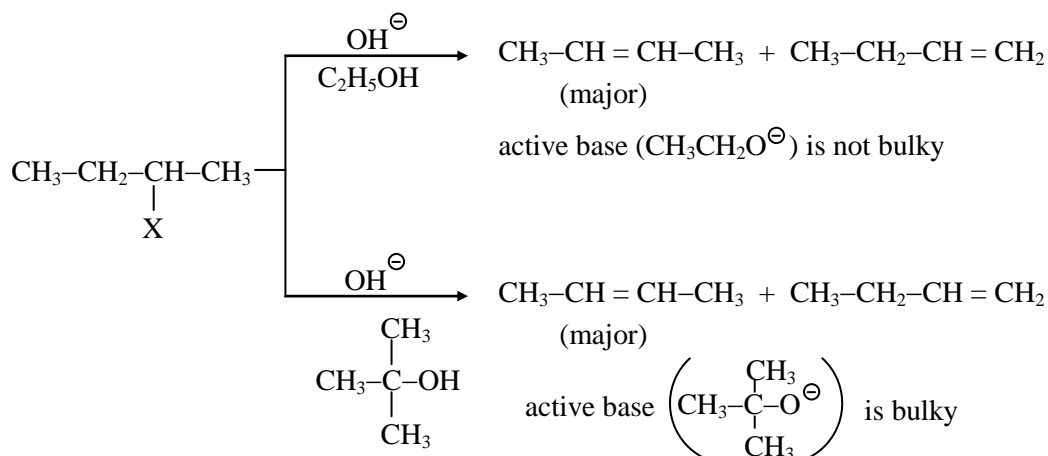
(viii) Nucleophilic substitution and E_1 are the competing reactions because strong base is generally a good nucleophile also.

Examples of E_2 Mechanism

(i) Dehydrohalogenation of alkyl halides in basic medium:
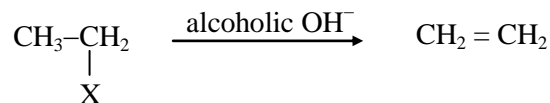
(ii) Dehalogenation of vicinal dihalide using magnesium or zinc:
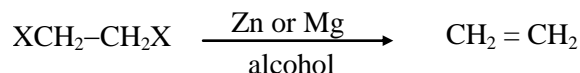
(iii) Acid catalyzed dehydration of smaller primary alcohols:

$$CH_3-CH_2-OH \xrightarrow{H^\oplus} \overset{\overset{H}{|}}{CH_2}-CH_2-\overset{\oplus}{O}H_2 \xrightarrow{-H_2O,-H^\oplus} CH_2=CH_2$$

$$\underset{\underset{OH}{|}}{CH_3-CH_2-CH_2} \xrightarrow{H^\oplus} CH_3-\overset{\overset{H}{|}}{CH}-\underset{\underset{\oplus OH_2}{|}}{CH_2} \xrightarrow{-H_2O,\ -H^\oplus} CH_3-CH=CH_2$$
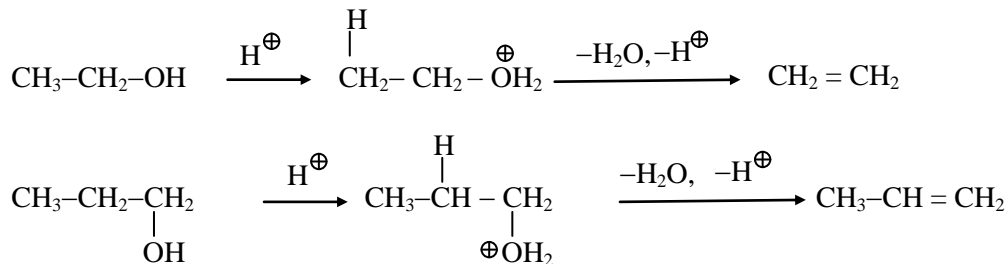
(c) Unimolecular Elimination from a Conjugate Base (E_{1CB})

$$-\overset{|}{\underset{\underset{H}{|}}{C}}-\overset{|}{\underset{\underset{L}{|}}{C}}- \underset{-BH\ k_{-1}}{\overset{B^\ominus\ k_1}{\rightleftharpoons}} -\overset{|}{\underset{\ominus}{C}}\ \overset{|}{\underset{\underset{L}{|}}{C}}- \underset{slow}{\overset{-L^\ominus\ k_2}{\longrightarrow}} -\overset{|}{C}=\overset{|}{C}-$$
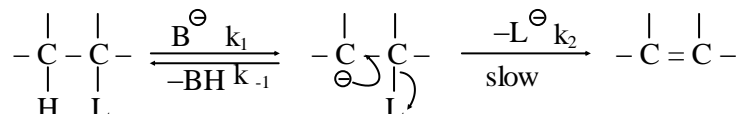
In E_{1CB} mechanism, a proton is initially abstracted to generate conjugate base which then loses L^- giving the elimination product in rate determining step.

(i)   As the proton has to be removed from a carbon of neutral species (a difficult job), a strong base is needed for E_{1CB} reaction as in E_2 reaction. Moreover, increase in basic strength and the concentration of base increases the rate of E_{1CB} reaction.

$$Rate = \frac{k_1 \times k_2}{k_{-1}}[Substarate][B^-]$$

(ii)   If removal of H^+ from two adjacent atoms is possible, more acidic hydrogen is mainly removed.

(iii)   Better the leaving group, faster will be E_{1CB} reaction (if E_{1CB} is operating).

(iv) E_{1CB} mechanism operates when *either the abstraction of proton is very easy* (removal of H^+ from highly electronegative atom or formation of resonance stabilized conjugate base) *or the expulsion of leaving group is difficult* (leaving group is bad like F^-, OH^-, RO^- etc. or if leaving group has partial double bond due to resonance).

Examples of E_{1CB} Mechanism

(i)   Dehydrofluorination: Fluoride is the poorest leaving group among all halides (strongest base).

$$-\overset{|}{\underset{\underset{H}{|}}{C}}-\overset{|}{\underset{\underset{F}{|}}{C}}- \underset{-H^\oplus}{\overset{alcoholic\ OH^\ominus}{\longrightarrow}} -\overset{|}{\underset{\ominus}{C}}-\overset{|}{\underset{\underset{F}{}}{C}}- \xrightarrow{-F^\ominus} -\overset{|}{C}=\overset{|}{C}-$$

(ii)   Dehydrohalogenation when resultant carbanion is resonance stabilized

$$-\overset{\overset{O}{||}}{C}-CH_2-\underset{\underset{X}{|}}{CH_2} \underset{-H^\oplus}{\overset{alcoholic\ OH^\ominus}{\longrightarrow}} -\overset{\overset{O}{||}}{C}-\overset{\ominus}{CH}-\underset{\underset{X}{|}}{CH_2} \xrightarrow{-X^\ominus} -\overset{\overset{O}{||}}{C}-CH=CH_2$$
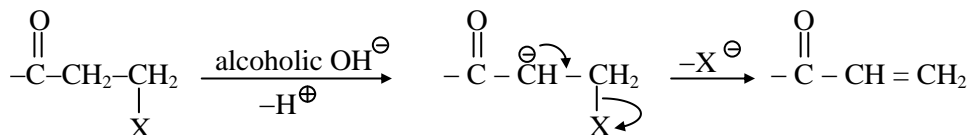
(iii) **Dehydrohalogenation when halogen has partial double bond due to resonance as in vinyl halide & aryl halides**

$$CH_2 = CH - \ddot{X}$$

$$\updownarrow$$

$$\overset{\ominus}{CH_2} = CH - \overset{\oplus}{X} \xrightarrow[-H^{\oplus}]{\text{alcoholic } OH^{\ominus}} \overset{\ominus}{CH} = CH - \ddot{X} \xrightarrow{-X^{\ominus}} CH \equiv CH$$

$$\xrightarrow{\text{alcoholic } OH^{\ominus}} \quad \xrightarrow{-X^{\ominus}}$$

Benzyne
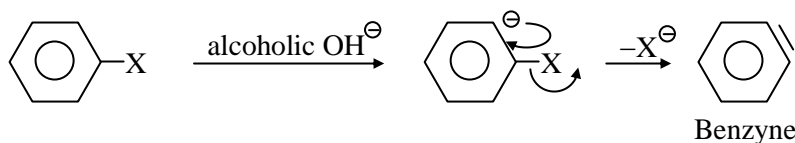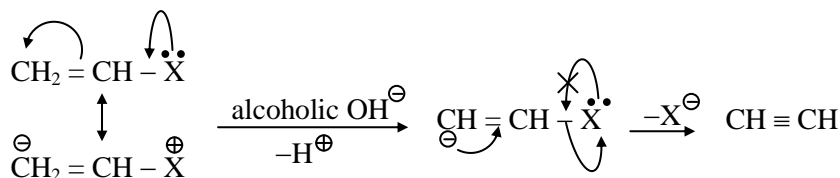
(iv) **Dehydration and deamination in basic medium**
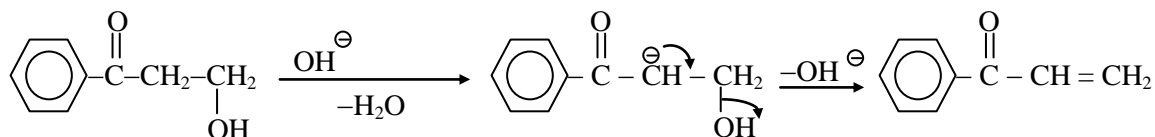
6.2   1,n-Elimination

When two atoms or groups are removed from non adjacent atoms, the elimination is called *1,n-elimination* (*also called cyclization*). Such eliminations result in the formation of cyclic compounds. These can result into formation of rings which can be 3 member or larger. Before discussing 1,n-Elimination we need to understand thermodynamic and kinetic aspect of ring formation.

Thermodynamic ease of ring formation

We know that the 6 member ring is strain free and most stable. Smaller rings have some strain in the ring which is very large in 3 member ring, large in 4 member ring and negligible in 5 member ring. Therefore, thermodynamic ease of ring formation is in the following order:

| | very large strain | large strain | negligible strain | no strain |
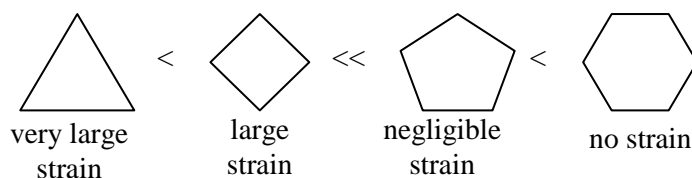
Kinetic ease of ring formation

Based on collision theory, we know that the reaction occurs only if the reacting molecules are in proper orientation. First and third atoms in every molecule (no sp hybrid atom) of a sample are close to each other (in proper orientation) and can form a bond with each other most easily. Therefore, 3 member ring formation is kinetically highly favoured.

First and fourth atoms in every molecule (due to rotation of bond between 2nd and 3rd atom) of a sample are not close to each other (not in proper orientation) and can not form a bond with each other easily. Therefore, 4 member ring formation is not kinetically favoured.

Similarly, larger the size of the ring, fewer will be the molecules in proper orientation (due to rotation of several bonds) and lesser it will be kinetically favoured.
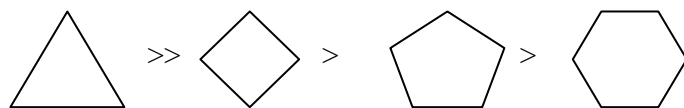
Conclusions from kinetic and thermodynamic study

(i)   3 member ring formation takes place readily as its formation is kinetically favoured.

(ii)   4 member ring formation takes place rarely as its formation is favoured neither kinetically nor thermodynamically.

(iii)   5,6,7,…. member rings are formed easily as their formation is favoured thermodynamically.

(iv)   When 4 member ring formation competes with other ring formation, formation of other rings dominate.

(v)   When 5 member ring formation competes with larger than 6 member ring formation, formation of 5 member ring generally dominates as it is kinetically favoured and the stability of 5 member ring is comparable to larger rings.

(vi)   When 6 member ring formation competes with other larger ring formation, formation of 6 member ring generally dominates because it is favoured kinetically as well as thermodynamically.

(vii)   When 5 member ring formation competes with 6 member ring formation, it is very difficult to get a general answer because 5 member ring is slightly more favoured kinetically and 6 member ring formation is slightly more favoured thermodynamically). However, thermodynamically favoured product generally dominates at high temperature,

Examples of 1,n-Elimination

(i)   1,n-Dehydrohalogenation of alkyl halide in basic medium when removal of H^+ from n^{th} atom is specially favoured (when n^{th} atom is highly electronegative like O, S, N etc. or when anion on n^{th} atom is resonance stabilized).
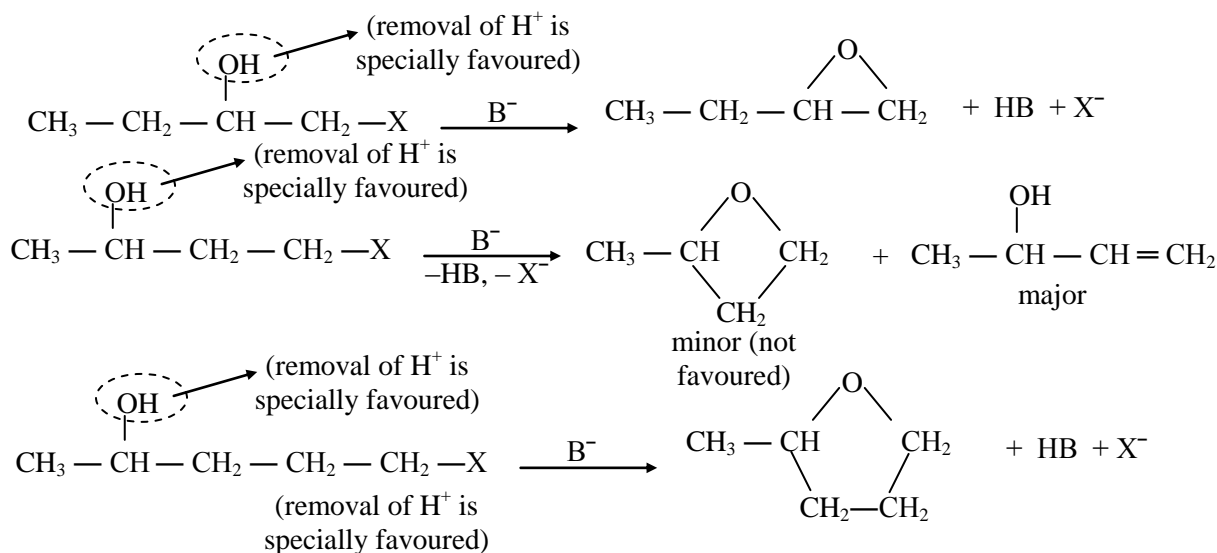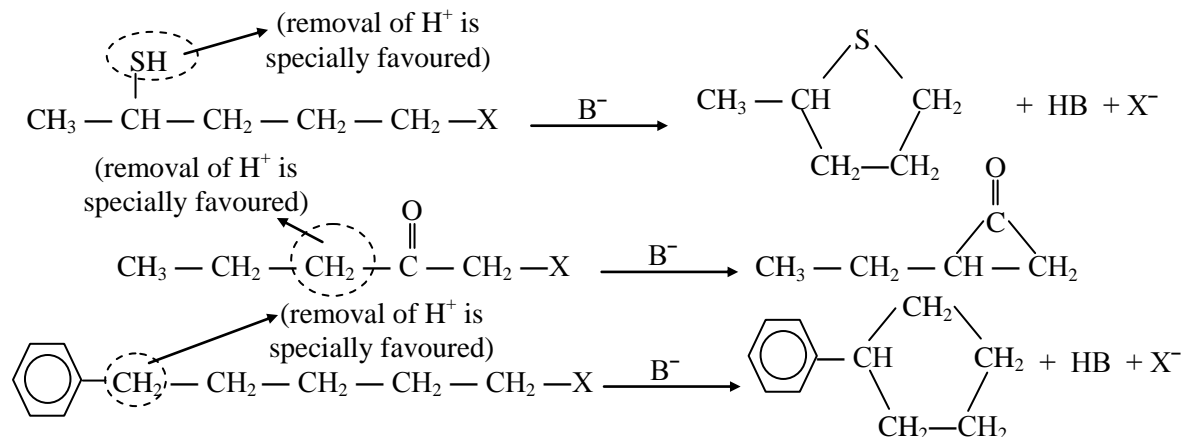
(ii)   1,n-Dehalogenation of 1,n-Dihaloalkane in presence of Magnesium or Zinc:
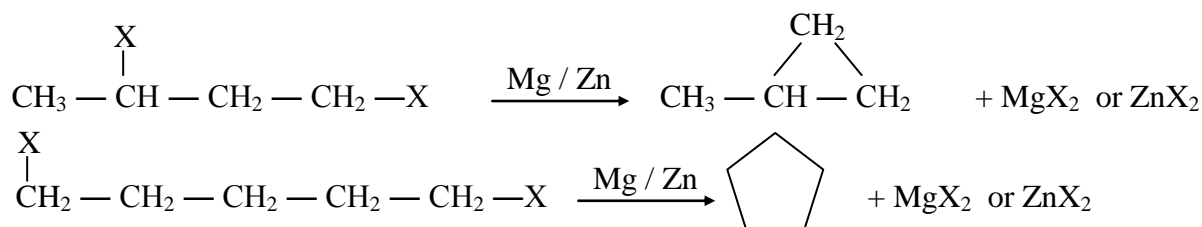
6.3   1, 1-Elimination (α-Elimination)

When two atoms or groups are removed from same atom, it is called 1,1- Elimination or α-Elimination. Such eliminations result in the formation of carbene or nitrene as we have already discussed during formation of intermediate. Such elimination occurs only when 1,n-Elimination reactions are not specially favoured and 1,2-elimination reactions are not possible. The carbene or nitrene intermediates formed in this way prefer to undergo rearrangements as discussed earlier.

Dehydrohalogenation of Alkyl halide using a base
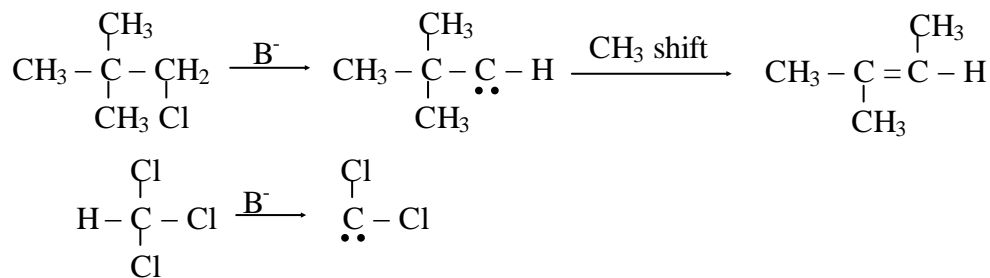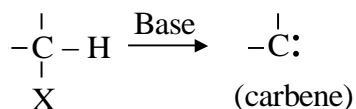
Dehalogenation of geminal dihalides using Mg or Zn

$$-\overset{|}{\underset{X}{C}}-X \quad \xrightarrow{2e^- Mg} \quad -\overset{|}{C}\!: \quad MgX_2$$

$$CH_3-\overset{Cl}{\underset{|}{C}H}-Cl \quad \xrightarrow{Mg} \quad CH_3\,\overset{..}{C}-H \quad \xrightarrow{\text{hydride shift}} \quad CH_2=CH_2$$

$$H-\overset{Cl}{\underset{\underset{Cl}{|}}{\overset{|}{C}}}-Cl \quad \xrightarrow{Mg} \quad H-\overset{Cl}{\underset{|}{C}}\!:$$
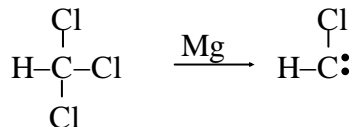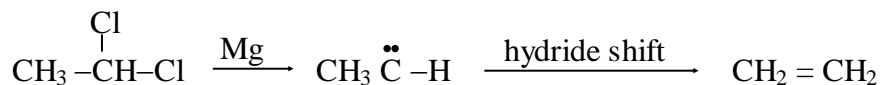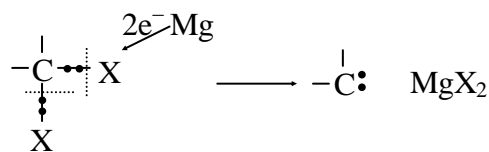
If 1,2-Dehalogenation is also possible, 1,2-Dehalogenation will dominate.

$$\overset{}{\underset{\underset{Cl}{|}}{C}H_2}-\overset{}{\underset{\underset{Cl}{|}}{C}H_2} \quad \xrightarrow{Mg} \quad CH_2=CH_2$$

$$\overset{}{\underset{\underset{Cl}{|}}{C}H_2}-\overset{Cl}{\underset{|}{C}H}-Cl \quad \xrightarrow{Mg} \quad CH_2=CHCl$$
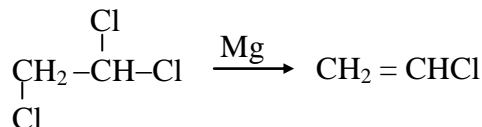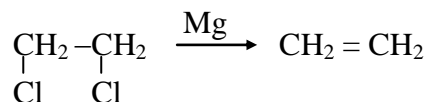
6.4 Other important examples of Elimination Reactions

It is observed that if two leaving groups are attached to one carbon, they are unstable provided at least one of the leaving groups has acidic hydrogen attached to directly linked atom. Such compounds are unstable even at room temperature and cannot be stored in pure form at room temperature because they undergo spontaneous elimination reactions even at room temperature. Although the reactions are endothermic but the increase in entropy favours the elimination reaction even at room temperature.

The following compounds are stable at room temperature inspite of more than one leaving group on same carbon. This is because the directly linked atom is not attached to acidic hydrogen.

$$\underset{Cl}{\overset{Cl}{C}} \qquad \underset{Cl}{\overset{OR}{C}} \qquad \underset{OR}{\overset{OR}{C}} \qquad \underset{Cl}{\overset{OCOR}{C}} \qquad \underset{OCOR}{\overset{OCOR}{C}} \qquad \underset{OR}{\overset{OCOR}{C}}$$
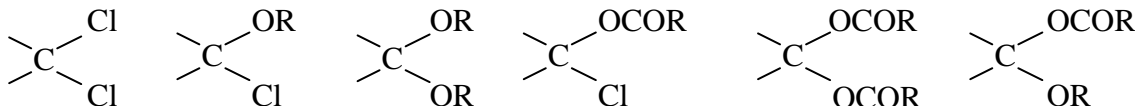
The following compounds are unstable at room temperature because of more than one leaving group on same carbon as well as acidic hydrogen attached to the directly linked atom.

GENERAL REACTION MECHANISM

$$\underset{Cl}{\overset{OH}{>}}C \xrightarrow{-HCl} >C=O$$

$$\underset{OOCR}{\overset{OH}{>}}C \xrightarrow{-RCOOH} >C=O$$

$$\underset{OH}{\overset{OH}{>}}C \xrightarrow{-H_2O} >C=O$$

$$\underset{OR}{\overset{OH}{>}}C \xrightarrow{-ROH} >C=O$$

$$\underset{Cl}{\overset{NH_2}{>}}C \xrightarrow{-HCl} >C=NH$$

$$\underset{OOCR}{\overset{NH_2}{>}}C \xrightarrow{-RCOOH} >C=NH$$

$$\underset{OR}{\overset{NH_2}{>}}C \xrightarrow{-ROH} >C=NH$$

$$\underset{NH_2}{\overset{NH_2}{>}}C \xrightarrow{-NH_3} >C=NH$$

$$\underset{OH}{\overset{NH_2}{>}}C \xrightarrow{-H_2O} >C=NH \qquad \xrightarrow{-NH_3} >C=O$$

Removal of H_2O is preferred over removal of NH_3 as H_2O is better leaving group.
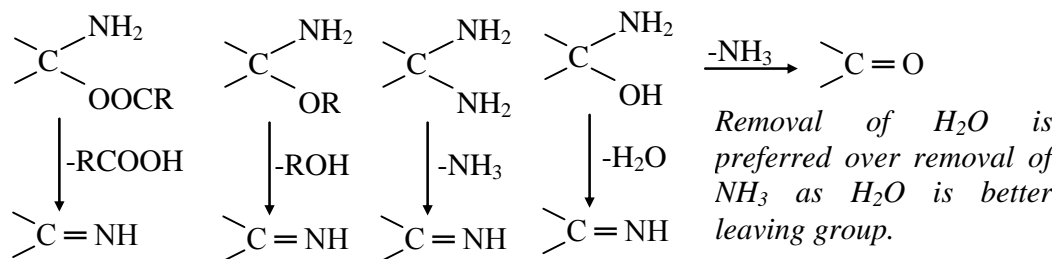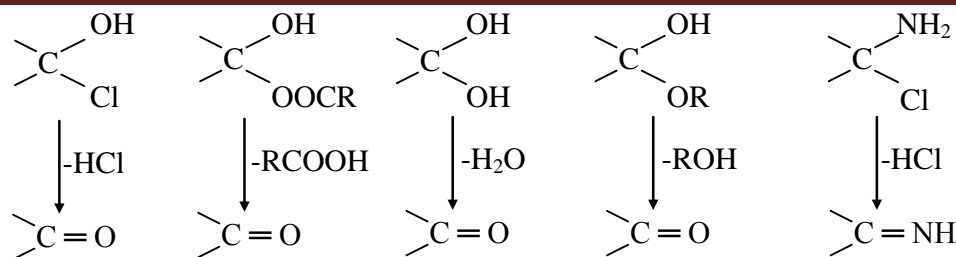
These reactions are catalyzed by acids as well as bases. The mechanism of the reaction is E_1 in acidic medium and E_{1CB} in basic medium. The mechanisms are shown here to have a clear view about the reaction. In E_1 mechanism, protonation is followed by removal of the leaving group which is then followed by loss of proton. In E_{1CB} mechanism, base first remove the proton and this step is followed by removal of leaving group from the conjugate base. Even strong bases like HO^-, RO^- and NH_2^- etc. can be removed from anions.
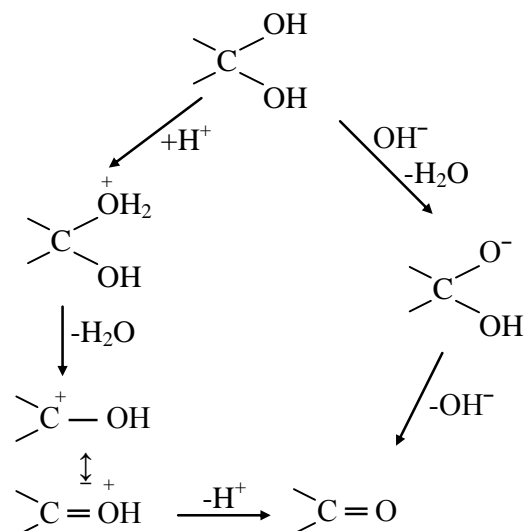
However, in special cases, such two leaving groups may be stable at room temperature and require heating to undergo elimination reactions. The stabilizing factors may be intramolecular hydrogen bonding, lesser strain etc. can increase their stability. This makes dissociation (elimination) more endothermic thus requiring higher temperature to make reaction spontaneous in forward direction.

Chloral hydrate
(Stable due to intramolecular hydrogen bonding) will lose H_2O on heating
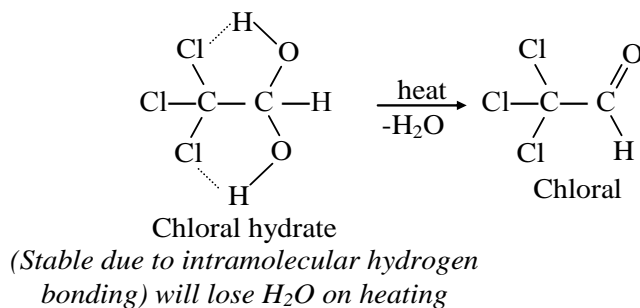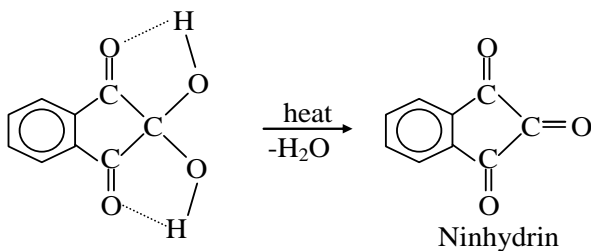
Ninhydrin hydrate
(Stable due to intramolecular hydrogen bonding) will lose H_2O on heating

Ninhydrin
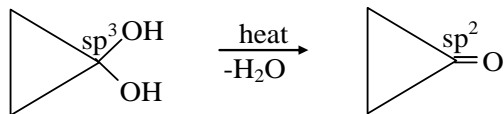
Cyclopropanone hydrate
(Stable due to lesser strain)
60° bond angle of sp^3 hybrid carbon

Cyclopropanone
(Unstable due to larger strain)
60° bond angle of sp^2 hybrid carbon

7. Nucleophilic Substitution Reactions

$$-\overset{|}{\underset{L}{C}}- \quad \xrightarrow[-:L^{\ominus}]{:Nu^{\ominus}} \quad -\overset{|}{\underset{Nu}{C}}-$$
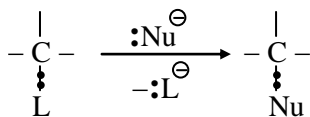
When a leaving group (which is also a nucleophile) is replaced by another nucleophile, the reaction is called nucleophilic substitution reaction. Nucleophilic substitution reaction can proceed through several mechanisms but 3 common mechanisms will be discussed here.

7.1 Unimolecular Nucleophilic Substitution (SN^1 or S$_N$1) Mechanism
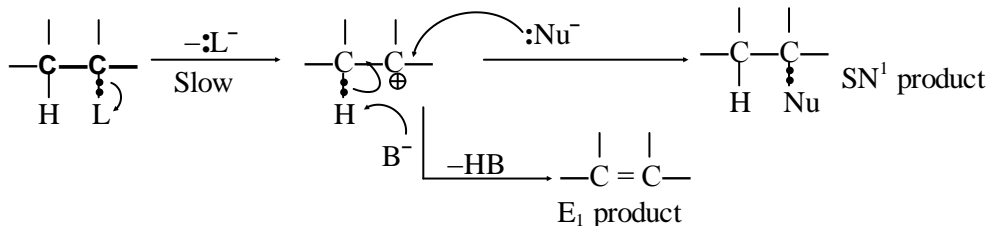
In unimolecular Nucleophilic substitution reaction, leaving group (a nucleophile) is first expelled in slow (rate determining) step followed by attack of another nucleophile. Some important characteristics of SN^1 mechanism are:

(i) *Better the leaving group, faster will be rate of SN^1 reaction* because leaving group is expelled in rate determining step.

$$R—I > R—Br > R—Cl \qquad (SN^1 \text{ reactivity})$$

(ii) As the product of rate determining step is carbocation, we can interpret that *more the stability of carbocation, more will be rate of SN^1 reaction*

$$3^o\ R—X > 2^o\ R—X > 1^o\ R—X$$

$$3^o\ R—OH > 2^o\ R—OH > 1^o\ R—OH$$
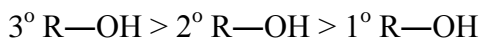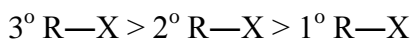
(iii) Polar aprotic solvents will solvate and stabilize cation only. Positively charged carbocation is solvated more than transition state while neutral reactant is not affected. This leads to decrease in activation energy and increase in SN^1 reactivity. Polar protic solvent can solvate cation as well as anion. Therefore, effect of solvation and decrease in activation energy is more (*as shown in energy profile of rate determining step*).
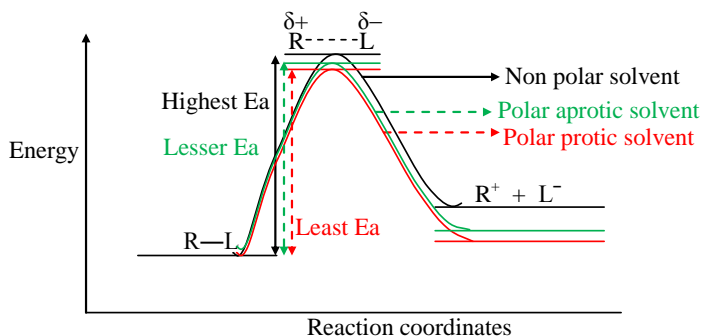
Therefore, order of SN^1 reactivity will be: Non polar < Polar aprotic < Polar protic.

Further increase in polarity will increase in SN^1 reactivity.

(iv) As a carbocation (containing six valence electrons and a vacant orbital) is formed, rearrangements are possible before the attack of nucleophile.

(v) Nu^- can be a weaker nucleophile than L^-. A strong Nu^- is not required for SN^1 reaction. Moreover, increase in nucleophilic strength of Nu^- or its concentration will not increase the rate of SN^1 reaction.

(vi)   As carbocation is planar, attack of Nu^- from both the sides of plane is equally favoured. Therefore, SN^1 reaction proceeds with 50% inversion of configuration (attack of nucleophile from opposite side of leaving group) and 50% retention of configuration (attack of nucleophile from the side of leaving group) i.e. SN^1 reaction proceeds with 100% racemization (racemization is the process of formation of racemic mixture which is the equilibrium mixture of two mirror images of each other).

formed due to attack of Nu^- from above the plane 50 % retention of configuration

formed due to attack of Nu^- from behind the plane 50 % inversion of configuration

100 % racemization
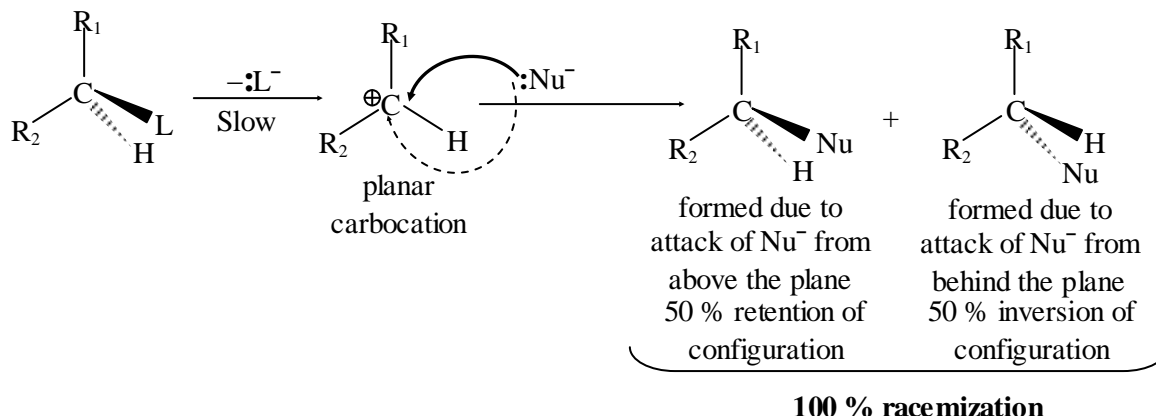
However, it must be remembered that even if solvent is highly polar (which is generally used for doing S_N1 reactions), the attractive force between the carbocation and L^- can not be completely destroyed. They will have some attractive force and will have some extent of ion pairing (although very small). Therefore, attack of nucleophile from opposite side of leaving group will be more favoured (though very slightly). In other words, inversion of configuration will be slightly more than retention of configuration i.e. S_N1 reaction leads to almost 100% racemization with little inversion.

(vii)   Unimolecular elimination (E_1) will be the competing reaction.

Examples of SN^1 Mechanism

(i) Acid catalyzed nucleophilic substitution on most alcohols except smaller primary alcohols.
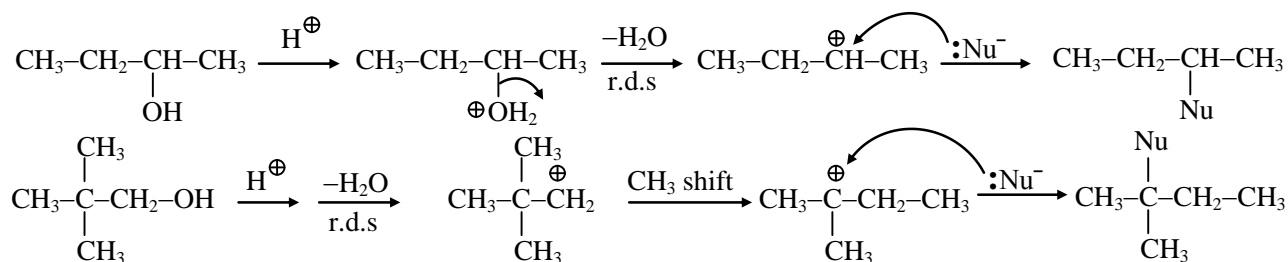
(ii) Solvolysis (hydrolysis & alcoholysis) of most Alkyl halides except smaller 1° Alkyl halides.
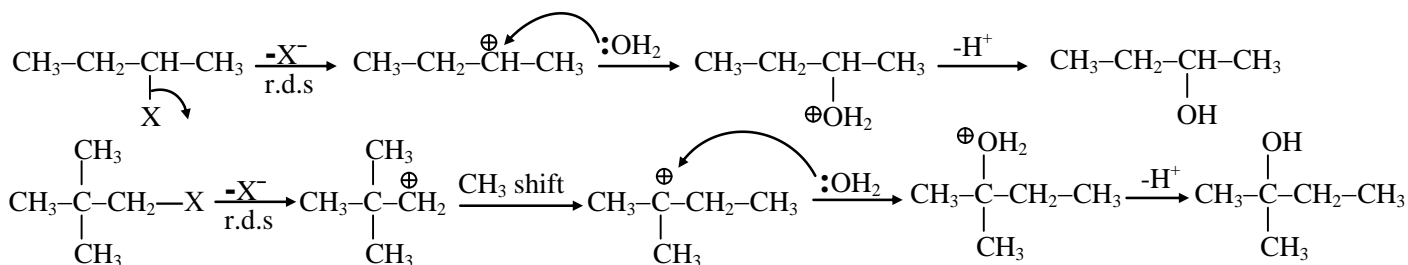
(iii) Reaction of nucleophile with protonated ether that can give stable (3°) carbocation
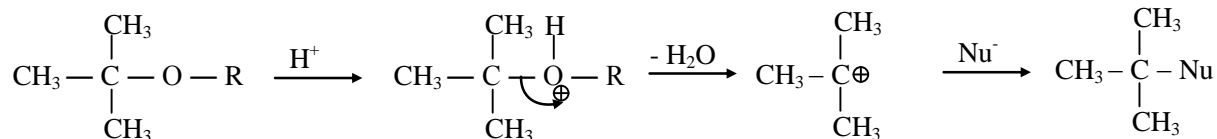
## 7.2 Bimolecular Elimination (SN^2 or S_N2)
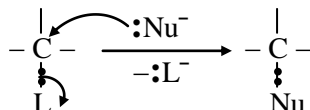
In bimolecular elimination, the attack of nucleophile as well as removal of leaving group occurs simultaneously in a single step. Some important characteristics of S_N2 mechanism are:

(i)   *Better the leaving group, faster will be rate of S_N2 reaction* because leaving group is expelled in rate determining step.

R—I > R—Br > R—Cl

(ii)   As the product of S_N2 reaction is saturated, stability of the product (highly stable) is of little importance. However, the transition state is highly crowded (five groups attached to carbon), steric hindrance is of large importance. More the steric hindrance, lesser will be the rate of S_N2 reaction.
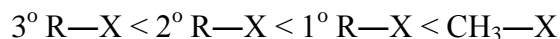
3° R—X < 2° R—X < 1° R—X < CH_3—X

(iii) In non-polar solvent and polar aprotic solvent, anions are not solvated. However, when polar protic solvent is used, negative reactants and products will be solvated considerably while partial negative transition state will be solvated only slightly. Therefore, energy of negatively charged reactants and products will decrease considerable while energy of transition state will decrease slightly. This results in increase of activation energy in polar protic solvent (*as shown in energy profile of rate determining step*).
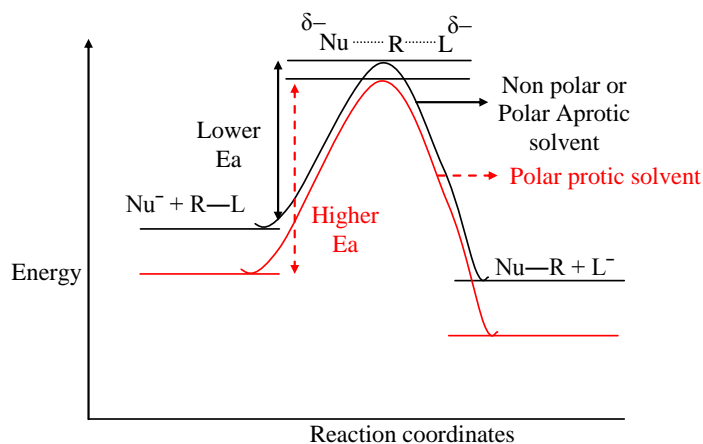
Therefore, rate of SN^2 reaction will be lesser in polar protic solvent. Similarly, increase in polarity of polar protic solvent will further increase activation energy and decrease rate of SN^2 reaction.

SN^2 reactivity : Non Polar ≈ Polar Aprotic > Polar Protic (Less Polar) > Polar Protic (More Polar)

(iv)   No rearrangements are observed during S_N2 reaction.

(v)   As Nu^- has to remove L^-, Nu^- has to be a stronger nucleophile than L^-. Moreover, increase in the nucleophilic strength or its concentration will increase rate of S_N2 reaction.

(vi) Nucleophile attacks from the opposite side of leaving group due to which S_N2 reaction proceeds with 100% inversion of configuration (it is called Walden inversion).


Transition State
Trigonal bipyramidal
(sp² hybrid)

formed due to attack of Nu^-
from opposite side of L
100 % inversion of configuration
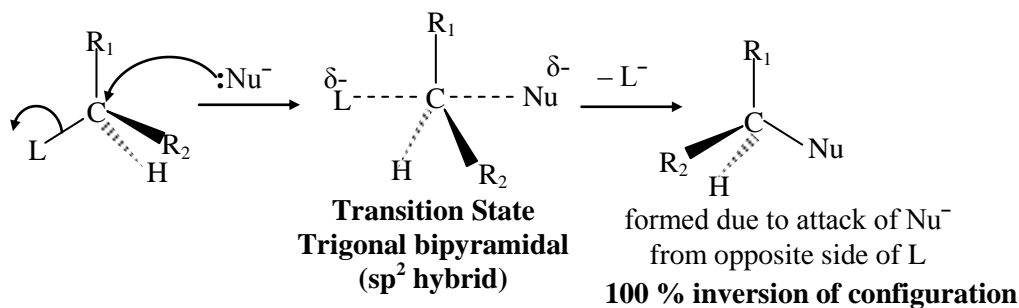
(vii) S_N1 and elimination reactions are the competing reactions because strong nucleophiles are generally strong bases also.
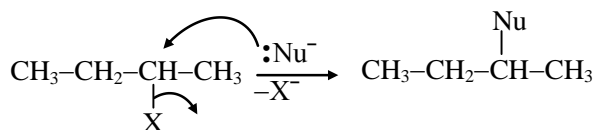
Examples of S_N2 Mechanism

(i) Nucleophilic substitution in lower 1° alcohol (CH₃OH, EtOH, C₃H₇OH etc) in acidic medium.
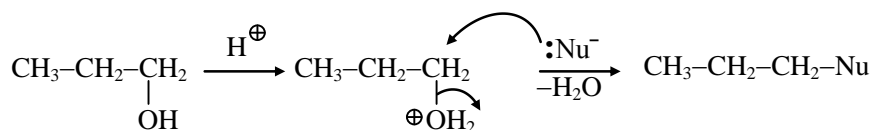
(ii) Solvolysis (hydrolysis & alcoholysis) of smaller 1° Alkyl halides like CH₃X, C₂H₅X, C₃H₇X etc.
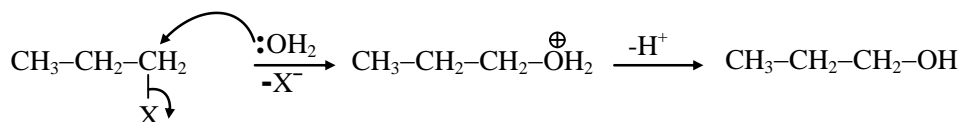
(iii) Most nucleophilic substitution reactions of alkyl halides except 3° alkyl halides.

(iv) Reaction of nucleophile with protonated ether that cannot give stable (3°) carbocation
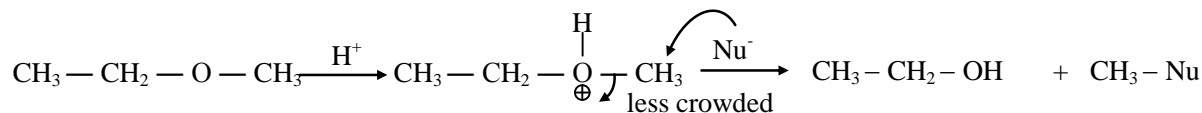

(v) Reaction of nucleophile with non-protonated strained cyclic ether
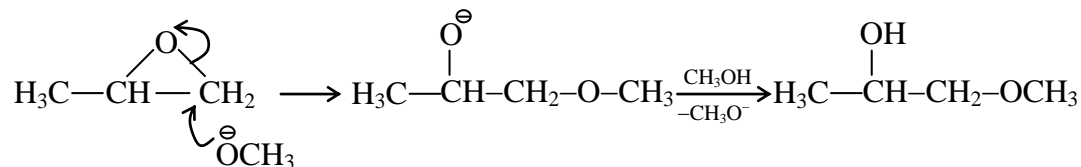
# GENERAL REACTION MECHANISM

7.3   AN+DN Mechanism (Attack of Nucleophile followed by Departure of Nucleophile)

This type of mechanism is observed when leaving group is attached to an unsaturated carbon having small amount of positive charge (to facilitate the attack of nucleophile on π electron rich system).
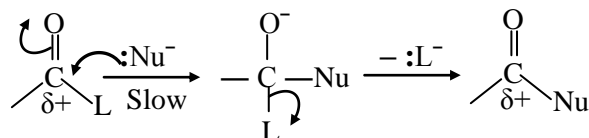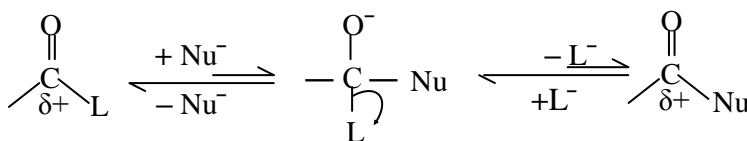

Some important aspects of AN+DN reaction

(i) Nu^- can be a weaker nucleophile than L^- because Nu^- has not expelled L^-. However, Nu^- must be a strong base (bad leaving group) than L^- so that removal of L^- can occur in preference to Nu^-.
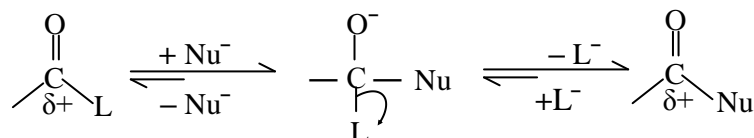

If Nu^- is stronger base than L^- reaction is more favoured in forward direction
(Almost complete if basic difference is large)

If L^- is stronger base than Nu^- reaction is less favoured in forward direction
(Almost negligible if basic difference is large)

Moreover, as nucleophile is involved in r.d.s., higher the nucleophilic strength or concentration of Nu^- higher will be rate of AN+DN reaction.

(ii)   Higher the amount of positive charge on the carbon faster will be attack of nucleophile i.e. r.d.s and faster will be AN+DN reaction.
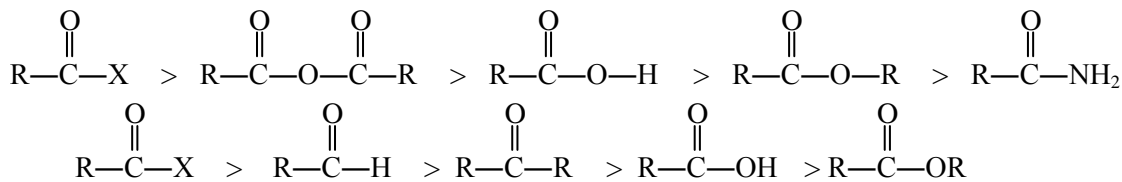
(iii)   Nucleophilic addition will be the competing reaction.

Here it can be generalized that if L is even a bad leaving group like NH₂, it can be removed from anions. However, removal of H⁻, R⁻ and Ar⁻ is almost impossible (almost a last option) even from anions. Therefore, AN+DN reaction will mainly occur if L is X, OCOR, OH, OR or NH₂ but Nucleophilic addition will dominate if L is H, R, Ar (i.e. in aldehydes and ketones).
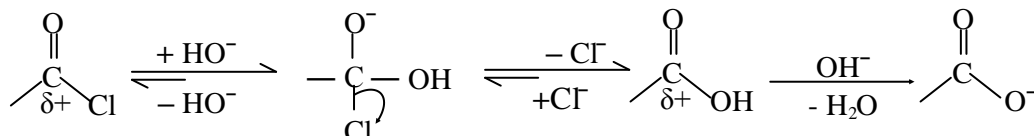

order of basic strength
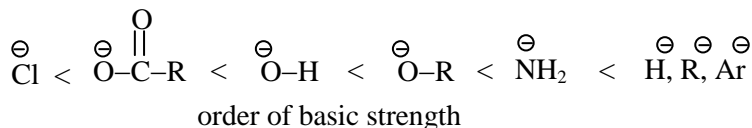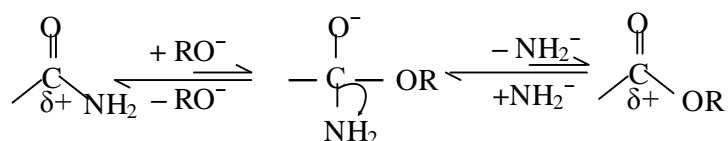
Examples of AN+DN Reactions

(i) **Nucleophilic substitutions in Acid halides, acid anhydrides, esters and amides etc.**
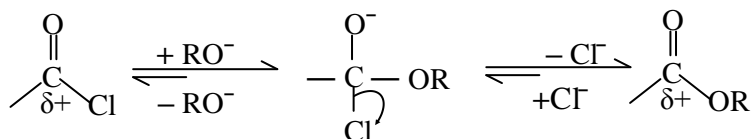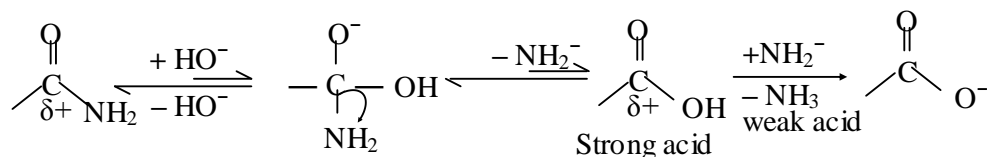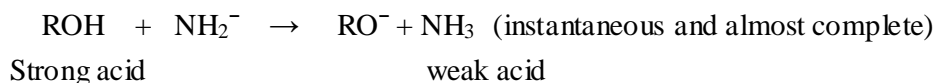

RO^- is very strong base than Cl^- & reaction is more favoured (almost complete) in forward direction.

HO^- is very strong base than Cl^- & reaction is more favoured (almost complete) in forward direction. Proton exchange reaction of $RCOOH$ with HO^- is instantaneous and complete and further shift the equilibrium in forward direction.
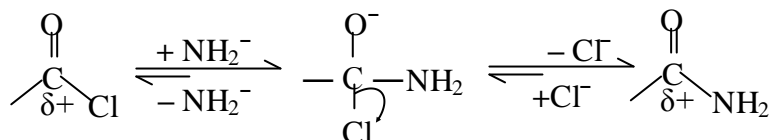

RO^- is very weak base than NH_2^- & reaction is almost negligible in forward direction. Still the reaction can be done almost completely if done in ROH solvent. Because the following proton exchange reaction will be almost complete and will shift AN+DN equilibrium as NH_2^- is completely consumed by ROH.

$$ROH \ + \ NH_2^- \ \rightarrow \ RO^- + NH_3 \ \text{(instantaneous and almost complete)}$$

Strong acid   weak acid

(instantaneous and complete) proton exchange reaction

HO^- is very weak base than NH_2^- & reaction is almost negligible in forward direction. Still the reaction can be done almost completely. Because the above reaction will be complete due to shift in equilibrium as $RCOOH$ is completely consumed by NH_2^-.

NH_2^- is very strong base than Cl^- & reaction is more favoured (almost complete) in forward direction.
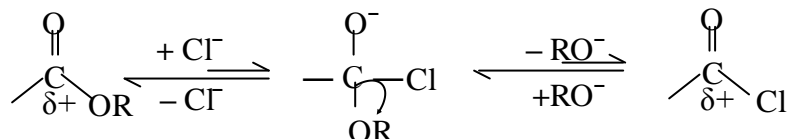
Cl^- is much weaker base than RO^- & reaction is very less favoured (almost negligible) in forward direction.

$$\underset{\delta+}{C}\overset{O}{\underset{OR}{\parallel}} \quad \xrightleftharpoons[-NH_2^-]{+NH_2^-} \quad -\underset{OR}{\overset{O^-}{\underset{|}{C}}}-NH_2 \quad \xrightleftharpoons[+RO^-]{-RO^-} \quad \underset{\delta+}{\overset{O}{\underset{NH_2}{\parallel}}}C$$

NH_2^- is very strong base than RO^- & reaction is more favoured (almost complete) in forward direction.

$$\underset{\delta+}{\overset{O}{\underset{OH}{\parallel}}}C \quad \xrightleftharpoons[-RO^-]{+RO^-} \quad -\underset{OH}{\overset{O^-}{\underset{|}{C}}}-OR \quad \xrightleftharpoons[+HO^-]{-HO^-} \quad \underset{\delta+}{\overset{O}{\underset{OR}{\parallel}}}C$$

RO^- is much stronger base than HO^- & reaction is much more favoured in forward direction, still AN+DN reaction is not observed. This is because acid base reaction (proton exchange) is instantaneous & complete.

$\Big| \begin{matrix} +RO^- \\ \text{instantaneous} \\ \text{and complete} \end{matrix}$

$$\overset{O}{\underset{O^-}{\parallel}}C \quad + ROH$$

$$\underset{\delta+}{\overset{O}{\underset{OR}{\parallel}}}C \quad \xrightleftharpoons[-HO^-]{+HO^-} \quad -\underset{OR}{\overset{O^-}{\underset{|}{C}}}-OH \quad \xrightleftharpoons[+RO^-]{-RO^-} \quad \underset{\delta+}{\overset{O}{\underset{OH}{\parallel}}}C \quad \xrightarrow{+RO^-} \quad \overset{O}{\underset{O^-}{\parallel}}C \quad + ROH$$

$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ instantaneous and complete

HO^- is much weaker base than RO^- & reaction is negligible in forward direction, still reaction is almost complete. This is because acid base reaction (proton exchange) is instantaneous & complete that will shift AN+DN equilibrium.

$$\underset{\delta+}{\overset{O}{\underset{NH_2}{\parallel}}}C \quad \xrightleftharpoons[-RO^-]{+RO^-} \quad -\underset{NH_2}{\overset{O^-}{\underset{|}{C}}}-OR \quad \xrightleftharpoons[+NH_2^-]{-NH_2^-} \quad \underset{\delta+}{\overset{O}{\underset{OR}{\parallel}}}C$$

RO^- is very weak base than NH_2^- & reaction is almost negligible in forward direction. Still the reaction can be done almost completely if done in ROH solvent. Because the following proton exchange reaction will be almost complete and will shift AN+DN equilibrium as NH_2^- is completely consumed by ROH.
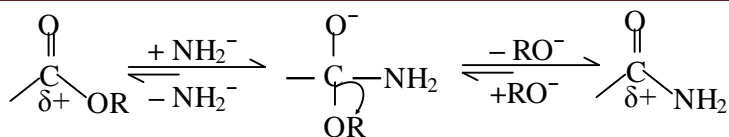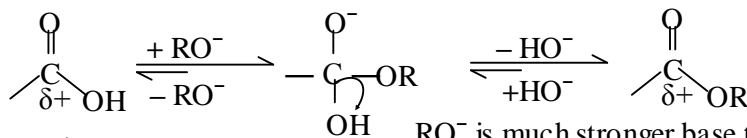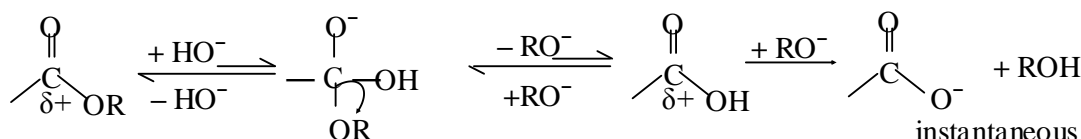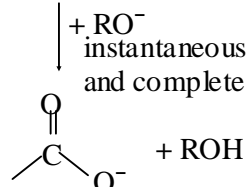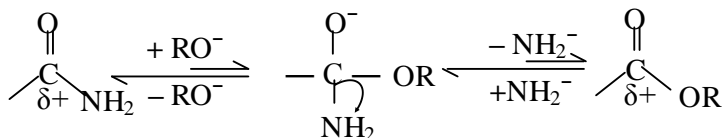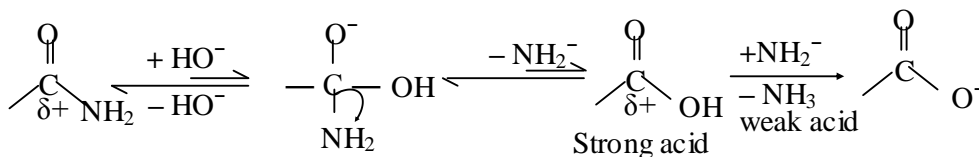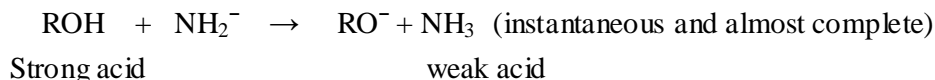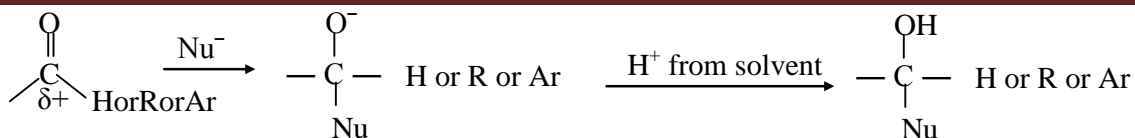
$$ROH \quad + \quad NH_2^- \quad \rightarrow \quad RO^- + NH_3 \text{ (instantaneous and almost complete)}$$

Strong acid $\qquad\qquad\qquad\qquad\qquad\qquad$ weak acid

$$\underset{\delta+}{\overset{O}{\underset{NH_2}{\parallel}}}C \quad \xrightleftharpoons[-HO^-]{+HO^-} \quad -\underset{NH_2}{\overset{O^-}{\underset{|}{C}}}-OH \quad \xleftharpoons[+NH_2^-]{-NH_2^-} \quad \underset{\delta+}{\overset{O}{\underset{OH}{\parallel}}}C \quad \xrightarrow[-NH_3]{+NH_2^-} \quad \overset{O}{\underset{O^-}{\parallel}}C$$

$\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ Strong acid $\quad$ weak acid

$\qquad\qquad\qquad\qquad\qquad\qquad$ (instantaneous and complete) proton exchange reaction

HO^- is very weak base than NH_2^- & reaction is almost negligible in forward direction. Still the reaction can be done almost completely. Because the above reaction will be complete due to shift in equilibrium as RCOOH is completely consumed by NH_2^-.

In aldehydes and ketones, nucleophilic substitution will not occur as removal of H^-, R^-, Ar^- is almost impossible even from anions. You can try addition of CN^- (in HCN, RMgX or RLi taken in ether followed by treatment with H_2O, Hydride like $NaBH_4$; $LiAlH_4$ followed by treatment with H_2O)

(ii) **AN+DN mechanism is also observed when leaving group is attached to an atom having vacant orbital.**

However, in such examples attack of nucleophile is not rate determining step because it does not involve any bond cleavage and only bond formation is never a slow i.e. rate determining step.

Trigonal bipyramidal
(sp^3d hybrid)