

FUNDAMENTALS OF ORGANIC CHEMISTRY

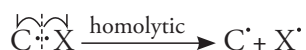
19.1 Introduction

Organic chemistry is defined as the study of compounds of carbon or the chemistry of hydrocabons and its derivatives. The term 'organic' is misleading. Earlier the term **organic chemistry** was used to describe the study of compounds obtained from living organisms, while the term inorganic chemistry was used for the study of compounds obtained from non-living sources. With the synthesis of urea, the first organic compound synthesised in the laboratory, it was proved that organic compounds can also be prepared artificially. Urea was synthesised from an inorganic compound, that is, from ammonium cyanate (NH_4CNO). Later on Kolbe (1845) succeeded in preparing acetic acid, the first organic compound synthesised in laboratory from its elements. Today most of the organic compounds can be synthesized. The division between organic and inorganic is retained till date. Presently, the term organic is used to describe the compounds of carbon. Carbon atoms have a unique property of attaching themselves to one another to an extent not possible for atoms of any other element. This property is called 'catenation'. The carbon atoms can form long chains (linear, branched and cross link) or rings of all sizes. Organic molecules have 'covalent bonds' formed by the sharing of electrons between the bonded atoms. Covalent bonding imparts properties to organic compounds which are quite different from those of inorganic compounds. The general concepts and principles underlined in the forthcoming sections will give a better understanding of the organic compounds, their mechanism of bond cleavage and organic reaction mechanisms.

19.2 Cleavage of Covalent Bonds

Organic reactions involve breaking and formation of covalent bonds. It is essential to understand the ways in which a covalent bond can break. A covalent bond generally breaks in two ways depending on the nature of organic compound, nature of attacking reagent and the reaction conditions. The different possibilities are illustrated below:

- (i) **Homolytic cleavage** As we know, a covalent bond is formed by sharing of electrons between the two atoms. In a homolytic cleavage, the bond breaks symmetrically in such a way that each species retains one electron of the shared pair.



where C represents carbon atom, X represents side group and \curvearrowright represents single electron transfer.

Homolytic cleavage thus results in the formation of highly reactive neutral species containing odd or unpaired electrons. Such species are known as free radicals. The reactions which proceed by the formation free radicals are known as free radical reactions. Homolytic cleavage occurs when the electronegativity of the bonded atoms is the same, that is, both the bonded atoms have equal attraction for the shared electron pair.

- (ii) **Heterolytic cleavage** When the electronegativities of the bonded atoms is different, one atom has greater attraction for the electron pair than the other; unsymmetrical bond cleavage occurs. This can take place in two different ways.

- (a) If X is more electronegative than carbon, then X retains the electron pair, leaving C positively charged.



where the curved arrow \curvearrowright represents the transfer of both electrons.

This carbon bearing a positive charge is called the carbonium ion or carbocation.

- (b) If X is less electronegative than carbon then the carbon atom retains the electron pair.

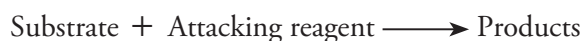


The carbon atom bearing the negative charge is called the carbanion.

Reactions which proceed by the formation of carbocations or carbanions are called ionic reactions.

19.3 Attacking Reagents

When a chemical reaction takes place between two substances, one of them is treated as the substrate and the other is the attacking reagent. The substrate forms the product in the presence of the attacking reagent.



Substrate and attacking reagent are relative terms. A substance can be attacking reagent in one reaction and substrate in the other. The substance due to whose presence the substrate undergoes a change is the attacking reagent.

There are generally two types of attacking reagents

- (i) Electrophilic reagents or electrophiles
- (ii) Nucleophilic reagents or nucleophiles
- (i) **Electrophiles or Electrophilic Reagents** (*electro*: electron; *philic*: loving). Electrophiles are electron-loving species which have an incomplete octet and attack electron-rich species. Such reagents can accept an electron pair and hence they are also known as lewis acids.

An electrophile can be either a positively charged species or a electrically neutral species having an incomplete octet.

- (a) **Positive electrophiles** They are electron-deficient species which carry a positive charge.

Some common examples of positive reagents are H^+ , H_3O^+ , Cl^+ , NO_2^+ , NO^+ , R^+ , etc.

- (b) **Neutral electrophiles** They are those species which have six electrons in their outermost orbit. They require an electron pair to complete their octet and acquire a stable configuration. Hence they are also electron loving and attack electron-rich species. Some common examples are BF_3 , FeCl_3 , AlCl_3 , ZnCl_2 , carbenes, nitrenes, etc.

- (ii) **Nucleophiles or Nucleophilic Reagents** (*nucleo*: nucleus; *philic*: loving). Nucleophiles are electron-rich species having an unshared pair of valence electrons. They attack electron-deficient sites. Being electron pair donors, they can also be termed as lewis bases.

A nucleophile can be either neutral or negatively charged species.

- (a) **Negative nucleophiles** These are electron-rich species carrying a negative charge. Some common examples are Cl^- , Br^- , I^- , $\bar{\text{O}}\text{H}$, $\bar{\text{O}}\text{R}$, $\bar{\text{N}}\text{H}_2$, $\bar{\text{C}}\text{N}$, COO^- , HSO_3^- , R^- (carbanion), RCOO^- , etc.
- (b) **Neutral nucleophiles** They are electron-rich species having a lone pair of electrons, but they carry no charge. Examples include $\text{H}-\ddot{\text{O}}-\text{H}$, $\text{R}-\ddot{\text{O}}-\text{H}$, $\text{R}-\ddot{\text{S}}-\text{H}$, $\text{R}-\ddot{\text{O}}-\text{R}$, etc.

The electron-rich species O, S, etc., donate electrons and attack the electron-deficient centres.

Table 19.1 Difference between electrophiles and nucleophiles

Electrophiles	Nucleophiles
1. They are electron-deficient species which can accept an electron pair.	They are electron-rich species which donate an electron pair.
2. Electro: electron; philic: loving. They are electron loving species and attack electron-rich centre.	Nucleo: nucleus; philic: loving. They are nucleus loving species and attack areas of low electron density.
3. They can be positively charged or neutral species having six electrons in their valence shell.	They can be negatively charged or neutral species with a lone pair of electrons.
4. They are lewis acids and can accept an electron pair	They are lewis bases and donate an electron pair
5. Example: BF_3 , AlCl_3 , H_3O^+ , Cl^+ , NO^+ , R^+ , etc.	Example: $\text{H}\ddot{\text{O}}\text{H}$, $\text{R}\ddot{\text{O}}\text{H}$, Cl^- , Br^- , $\bar{\text{O}}\text{H}$, $\bar{\text{C}}\text{N}$, etc.

Practice problems

- Classify the following into electrophilic and nucleophilic reagents
 (a) H^+ (b) Cl^- (c) NO_2^+ (d) OH^-
- Which of the following molecules or ions is electrophilic
 CH_4 , H_2O , Br^+ , $\text{CH}_2=\text{CH}_2$, BF_3 , NO_2^+ , NH_3
- Which of the following molecules and ions are nucleophilic
 CH_4 , H_2O , BH_3 , OH^- , Br^+ , NH_3 , AlCl_3

19.4 Electron Displacements in Covalent Bonds

Organic compounds mainly consist of covalent bonds. The electron pair of these covalent bonds may undergo displacement either due to different substituents attached in the molecule or under the influence of the attacking reagents (nucleophile or electrophile). The displacement of electrons develops polarity in the molecule. These electron displacements can be temporary or permanent. Temporary electron displacements occur under the influence of attacking reagents and disappear as soon as the attacking reagent is removed. These effects are known as **polarisability effects**. Permanent electron displacements occur under the influence of substituents within the molecules. They are known as **polarisation effects**.

Permanent and temporary effects are also denoted as static and dynamic effects respectively. Some important displacement effects are-

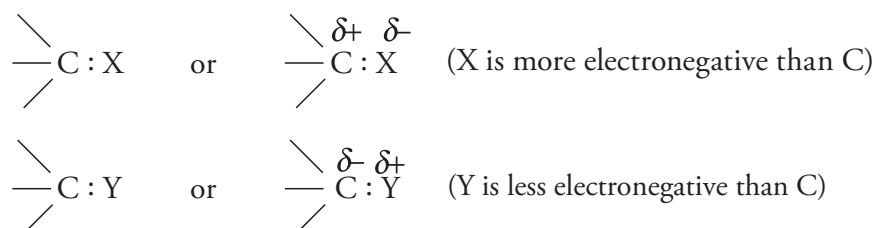
- Inductive effect
- Mesomeric effect
- Electromeric effect
- Inductomeric effect
- Hyperconjugation

Let us now discuss these static (permanent) and dynamic (temporary) effects one by one.

Inductive effect A covalent bond is formed by the sharing of electrons between the two bonded atoms. If the electronegativities of the two atoms is similar the electron pair will occupy a central position between the two nuclei of the concerned atoms. Such a covalent bond is termed as non-polar covalent bond. For example



On the other hand, if a covalent bond is formed between two dissimilar atoms having different electronegativities, then the electron pair will be attracted towards the more electronegative atom. Consequently a partial negative charge (denoted by δ^-) will develop on the more electronegative atom, and a partial positive charge (denoted by δ^+) will develop on the less electronegative atom. Consequently there is polarisation of the molecule. This polarisation is of a permanent nature.



Here, it is important to note that although the electron pair is permanently displaced, it remains in the valence shell.

This permanent creation of a dipole between a carbon atom and the atom or group to which it is attached is called the inductive effect or simply I effect.

If the substituent group is more electronegative than carbon atom and attracts the electron pair towards itself, it is said to exert $-I$ effect or negative inductive effect.

On the other hand if the substituent is electron releasing it is said to exert $+I$ effect or positive inductive effect.



Inductive effect is represented by the symbol \longrightarrow , the arrow pointing towards the more electronegative element or group.

Some groups in the order of decreasing inductive effects are

- (i) $-I$ effect groups (electron attracting or electron withdrawing)



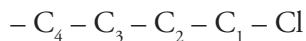
- (ii) $+I$ effect groups (electron repelling or electron releasing)



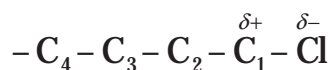
The values of dipole moments are a measure of the degree of inductive effect.

Inductive effect is transmitted along the chain of carbon atoms and its effect decreases rapidly with the length of the carbon chain. This can be understood with the help of the following example.

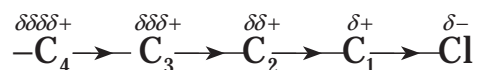
Consider a carbon chain with chlorine atom attached to the terminal carbon atom.



Being more electronegative than carbon, the chlorine atom pulls the bonded electron pair towards itself. As a result, chlorine develops a partial negative charge and the carbon atom C_1 acquires a small positive charge.



As C_1 is positively charged, it attracts the electron pair between C_1 and C_2 towards itself. As a result, C_2 acquires a small positive charge whose magnitude is smaller than the charge on C_1 . C_2 will further attract the electron pair between C_2 and C_3 towards itself, as a result of which C_3 will acquire a small positive charge. The magnitude of positive charge decreases from C_1 to C_2 to C_3 and it is denoted by δ^+ , $\delta\delta^+$ and $\delta\delta\delta^+$.



Inductive effect is transmitted along the sigma bonded carbon chain. It is a permanent effect and vanishes after C_3 for all practical purposes.

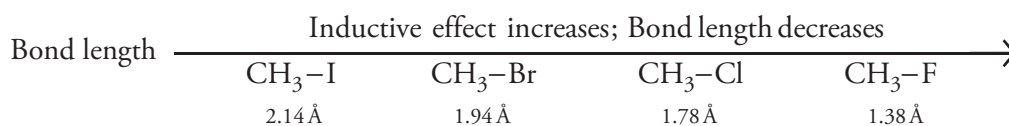
The effect will be reversed if an electron donating group (+I effect) is attached to the carbon atom.



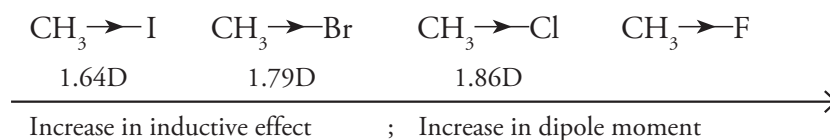
The electron attraction and repulsion are compared with hydrogen as a reference in the molecule CR_3-H as standard.

Inductive effect is a very important effect in organic chemistry and plays a significant role in understanding several reactions. Some common applications of inductive effect are discussed below

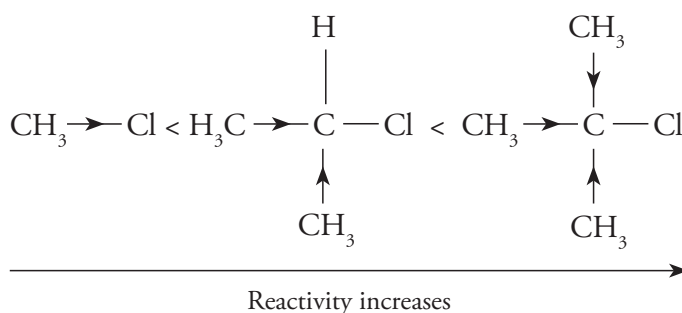
1. **Effect on bond length** Due to inductive effect, the covalent bond develops partial ionic character. Greater the inductive effect greater will be the ionic character and lesser will be the bond length. For example, the bond length of alkyl halides is found to increase with the decrease in inductive effect.



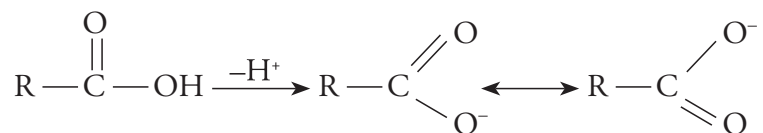
2. **Dipole moment** Molecule develops polar character due to inductive effect. Dipole moment is found to increase with the increase in inductive effect.



3. **Reactivity of alkyl halides** Alkyl halides are more reactive than the corresponding alkanes. They undergo nucleophilic substitution reactions. The formation of stable carbonium ion is facilitated due to +I effect of the methyl groups. Greater the number of methyl groups, more is the inductive effect (+I effect) facilitating the replacement of halogen atom and hence faster is the reaction.

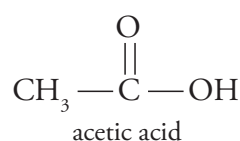
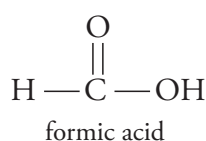


4. **Strength of carboxylic acids** The strength of a carboxylic acid depends on the ease with which it donates a proton. Carboxylic acids release a proton and change into carboxylate ion.

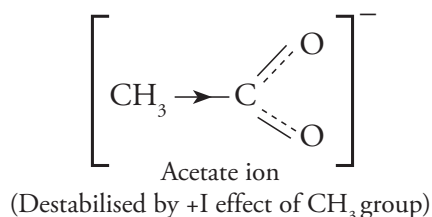
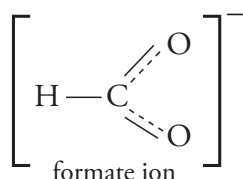


Any factor which stabilises the carboxylate ion increases the strength of the carboxylic acid. Lesser the stability of carboxylate ion weaker will be the carboxylic acid. Inductive effect influences the strength of carboxylic acids as follows.

- (i) **Effect of +I groups** Consider the example of formic acid (HCOOH) and acetic acid (CH_3COOH)



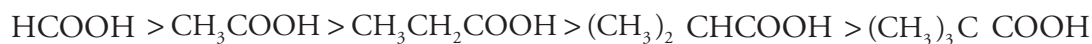
CH_3 group in acetic acid has +I effect (electron donating effect). Hence it will intensify the negative charge on oxygen and destabilise the carboxylate ion. There is no such destabilisation in formic acid. Hence its carboxylate ion is more stable. Hence formic acid is stronger than acetic acid.



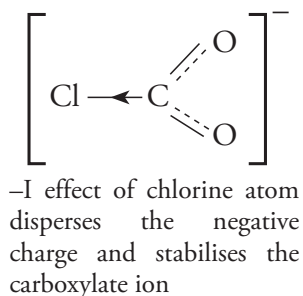
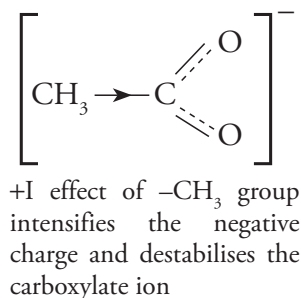
As the +I effect of alkyl groups increases in the order:



Hence the acidic strength decreases in the same order:



- (ii) **Effect of -I groups** The groups having -I effect will stabilise the carboxylate ion by dispersing the -ve charge on it. For example-



Therefore chloroacetic acid is stronger than acetic acid. The acid strength of halogenated acids is as follows:



–I effect of $\text{F} > \text{Cl} > \text{Br} > \text{I}$



More the number of halogens on the α – carbon atom stronger is the acid.



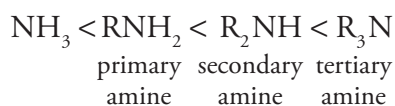
Since the –I effect decreases along the length of the carbon chain, acidic strength reduces.

5. **Basic nature of amines** A base is an electron pair donor. Greater the tendency of a compound to donate electron pair, greater will be its basic character. Amines have a lone pair of electron on nitrogen atom and therefore have a strong tendency to donate an electron pair. Inductive effect influences the basic nature of amines as described below-

- (a) **+I effect** Electron donating groups increase the density of electrons on the nitrogen atom and hence increase the basic strength of the amines.



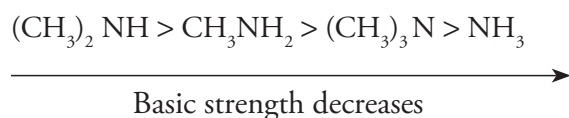
On the basis of the above description one would conclude that more the number of alkyl groups attached to nitrogen greater will be the basic strength. Hence on the basis of inductive effect, the strength of amines should follow the order



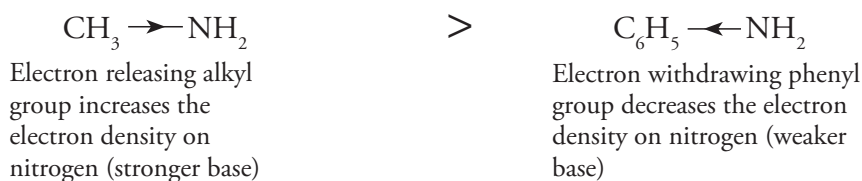
However, the *actual order* of basicity in aqueous solution is

secondary amine > primary amine > tertiary amine > ammonia

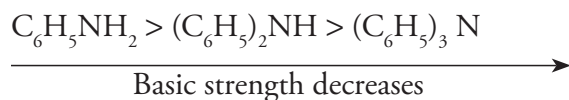
This is because apart from inductive effect, steric factor plays a vital role in determining the basic strength of amines. It has been found



- (a) **–I effect** The electron withdrawing groups present on the nitrogen atom in amines decrease the electron density on nitrogen making the electron release difficult. Hence –I groups decrease the basic strength of the amines.



Similarly the basic strength of aromatic amines follows the order

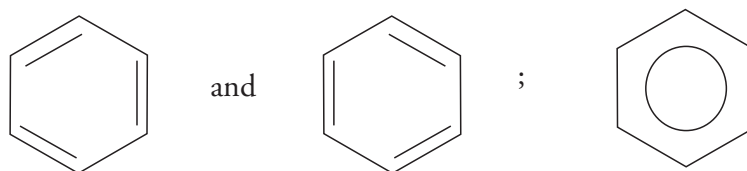


Mesomeric or Resonance Effect

It is a permanent effect in which the π electrons are transferred from a multiple bond to an atom or from a multiple bond to a single covalent bond or from atoms with lone pair of electrons to the adjacent single covalent bond.

To illustrate the above effect let us consider the example of benzene.

The structure of benzene shows that there are three carbon-carbon double bonds and three carbon-carbon single bonds. The bond lengths of the double-bonded carbons should be 1.33 Å and single-bonded carbon atoms should be 1.54 Å. X-ray diffraction studies show that all the six carbon-carbon bonds in benzene are equal and have a bond length of 1.39 Å, which is intermediate between the bond length of single and double bonds. Hence, the structure is symmetrical. This can be explained considering that benzene molecule is a hybrid of the following contributing structures.

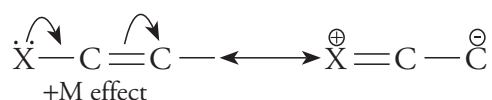


The molecule in such cases is said to be in a state of resonance (Heisenberg, 1926) or mesomerism (Ingold 1933)

The structures contributing to the resonance hybrid are indicated by double-headed arrows (\longleftrightarrow) and the contributing structures are called the canonical structures.

Like the inductive effect, mesomeric effect may be + or – and is generally denoted by +M or –M.

+ M Effect or +R Effect A group or atom is said to have +M or +R effect if the direction of displacement of electrons is away from it. This effect is generally exhibited by groups having lone pair of electrons.



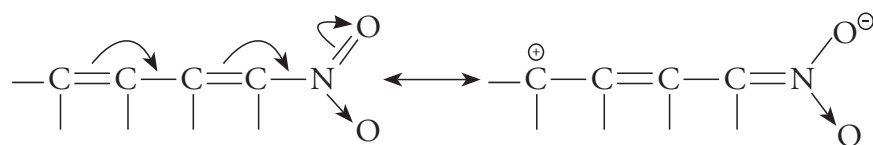
Groups showing + M or + R effect are

Halogens, $\ddot{\text{O}}\text{R}$, $-\ddot{\text{O}}\text{H}$, $-\ddot{\text{N}}\text{H}_2$, $-\ddot{\text{N}}\text{R}_2$ and $-\ddot{\text{S}}\text{R}$

–M Effect or –R Effect A group or atom is said to have a –M or –R effect if the direction of displacement of electrons is towards it. This effect is shown by groups having highly electronegative atoms attached to them.

$> \text{C}=\text{O}$, $-\text{NO}_2$, $-\text{CN}$ groups show –M effect

–M effect of nitro group can be depicted as follows:



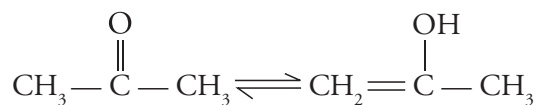
Conditions for Resonance

1. The position of atoms in each of the canonical structures must be the same as in the actual molecule (resonance hybrid). The arrangement of electrons can differ.

For example, vinyl chloride has the following resonating structures

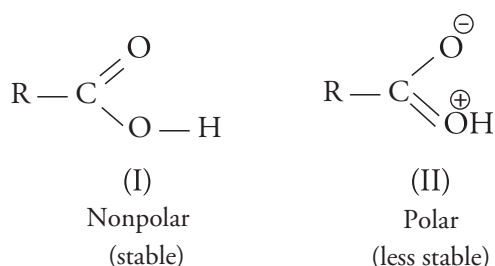


The following structures of acetone are no longer resonating structures because the position of hydrogen has shifted.



They instead represent two different molecules: the *keto* and *enol* forms.

2. The contributing structures are of comparable energy.
3. It is essential that the resonating structures must be planar.
4. There is delocalisation of π electrons.
5. Non-polar structures are more stable than dipolar structures. For example, in the resonating structures of carboxylic acids, structure (I) is more stable than structure (II) although both of them have the same number of bonds.



Resonance Energy

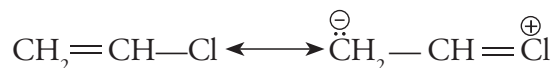
A resonance hybrid is characterised by (i) intermediate bond length, (ii) dispersal of charge and (iii) increased stability.

A resonance hybrid is more stable than any of its contributing (canonical) structures because its energy is lesser than the energy of any of the contributing structures. *This difference in energy between the resonance hybrid and the most stable canonical structure is referred to as the resonance energy of the molecule.*

It has been observed that greater the resonance energy, greater is the stability of the hybrid.

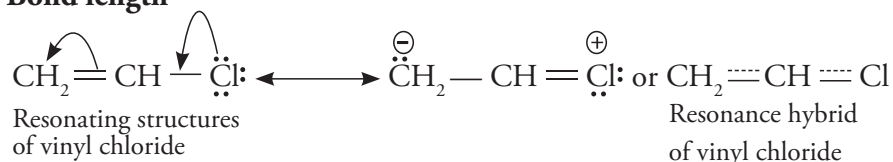
Effects of Resonance

- (a) **Dipole moments** The abnormal values of dipole moments of some molecules can be explained by resonance. The dipole moment value of vinyl chloride can be explained only if structure (II) contributes to the actual structure of the molecule.



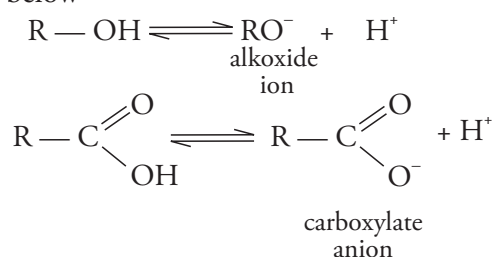
dipole moment $\mu = 1.44 \text{ D}$

- (b) **Bond length**

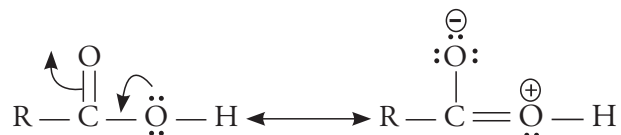


The C–Cl bond length (1.72 Å) in vinyl chloride is shorter than in ethyl chloride (1.78 Å). This can be explained by the concept of resonance. Resonance also explains the equal bond length of all the C–C bonds in benzene (discussed earlier)

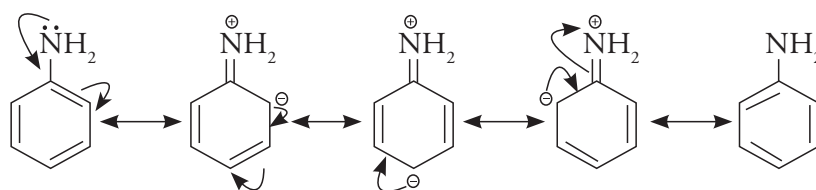
- (c) **Strength of acids and bases** The phenomenon of resonance explains why alcohols are neutral and carboxylic acids are strong acids. The ionisation of alcohols and acids is depicted below



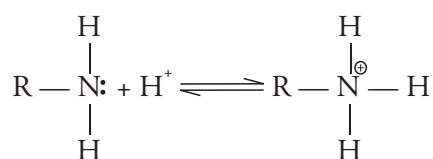
There is no resonance stabilisation in alkoxide ion, whereas carboxylate anion is stable as it is stabilised by resonance. Moreover the resonance stabilisation of carboxylate ion is more than that of the parent acid as in the latter it gets decreased due to charge separation.



Resonance also explains why aromatic amines are weaker bases than aliphatic amines. In aromatic amines the lone pair of electrons on the nitrogen atom is involved in resonance and hence is not easily available for protonation



Therefore, the lone pair of electrons is not available for protonation. In aliphatic amines the lone pair of electrons is very easily available for protonation as the phenomenon of resonance is not possible.



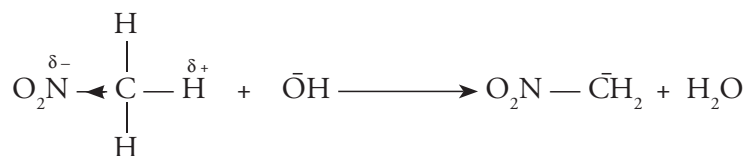
Resonance phenomenon also explains

- Acidic nature of phenols
- Acidity of acetylene

Inductomeric effect

It is a temporary effect and takes place in a sigma bonded system. It enhances the permanent inductive effect by the approach of a charged ion (attacking reagent). In the presence of the attacking reagent the transfer of σ electron cloud takes place readily.

For example, in nitromethane, the $-\text{NO}_2$ group has $-I$ effect. This $-I$ effect of nitro group is further enhanced by $\bar{\text{O}}\text{H}$ group of the base. In the presence of the base, the electron transfer takes place faster and hydrogen is removed as water.



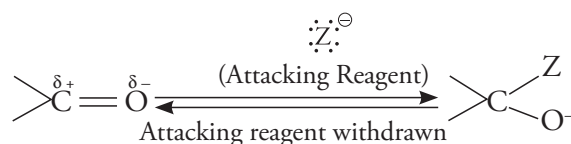
Inductomeric effect always aids a chemical reaction and never inhibits it. Except assisting in the displacement of electrons in inductive effect it does not find any other role in organic chemistry.

Electromeric Effect

Like inductomeric effect, this is also a temporary effect. But unlike inductomeric effect, this takes place between two atoms joined by a multiple bond (π bonded system), that is, double or triple bond ($C = C$, $C = O$, $C \equiv N$, etc.). It is represented by the symbol E and comes into play at the requirement of the attacking reagent. It involves complete transfer of the shared pair of electrons of the multiple bond instantaneously to one of the bonded atoms leading to the development of + and – centres within the molecule.

It is important to note that electromeric effect is temporary in nature and the molecule acquires its original electronic condition on removal of the attacking reagent.

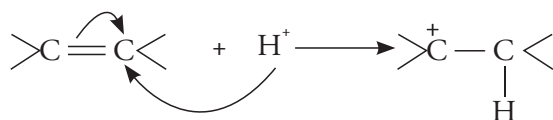
For example, when a negatively charged reagent say $:\ddot{Z}:^{\ominus}$ approaches an aldehyde or ketone, it causes instantaneous shift of electron pair of carbonyl group to oxygen (as it is more electronegative than carbon).



Electromeric effect can be of two types.

+E effect When the transfer of electrons takes place towards the attacking reagent, it is called +E effect

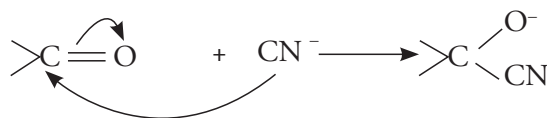
For example



In the above example, the electrons of the double bond are transferred to that atom to which the attacking reagent finally gets attached.

–E effect When the transfer of electrons takes place away from the attacking reagent it is called –E effect.

For example



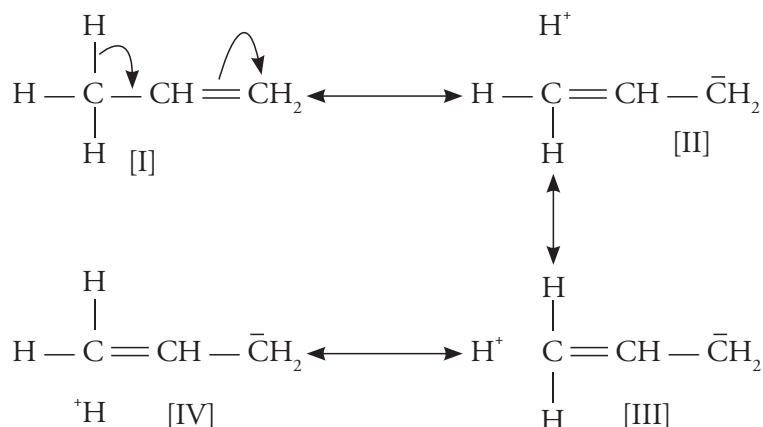
The electrons of the double bond are transferred to the atom other than the one to which the attacking reagent finally gets attached.

Like inductomeric effect, electromeric effect also affects the chemical reactivity of molecules. When both E and I effects operate in opposite directions, the electromeric effect overcomes the inductive effect.

Hyperconjugation

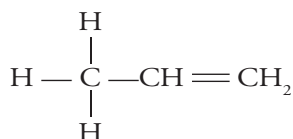
This was given by Baker and Nathan in 1935. It is also known as the **Baker–Nathan Effect**, which takes place in organic molecules in which an alkyl group is attached to the unsaturated system such as multiple bonds or benzene ring.

Baker and Nathan suggested that alkyl groups with at least one hydrogen on the α – carbon atom attached to an unsaturated carbon atom are able to release electrons by a mechanism similar to the electromeric effect, for example

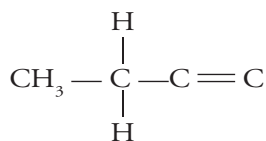


Structures II, III and IV are called the contributing hyperconjugative structures. Hyperconjugation is also termed as *no bond resonance* as there is no real bond between C and one of the hydrogens in these structures.

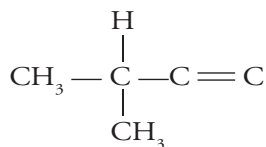
Moreover, greater the number of hydrogen atoms attached to α carbon atom greater will be the electron release by this mechanism.



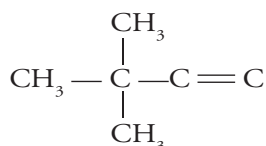
Three hydrogen atoms on the α - carbon atom; hence, three hyperconjugated structures



(2-H on a α carbon atom; hence two hyperconjugated structures)



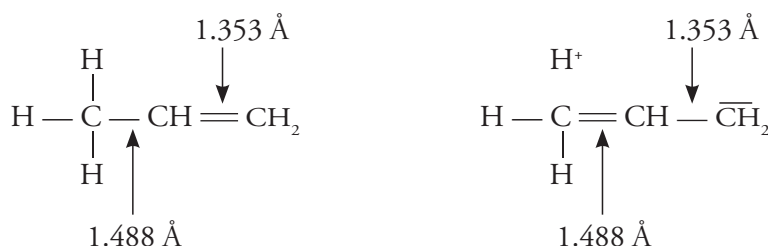
(1-H on a α carbon atom; hence one hyperconjugated structure)



(no hydrogen on α - carbon; hence does not show hyperconjugation)

Effects of hyperconjugation

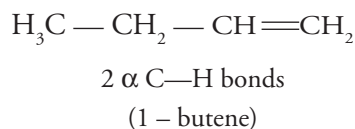
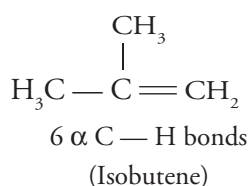
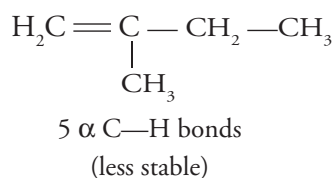
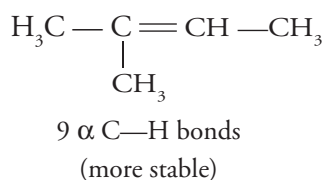
1. **Effect on bond length** The carbon–carbon single bond close to the multiple bond acquires some double bond character. Hence, the bond length reduces.



The $\text{C}-\text{C}$ bond length is 1.488 \AA in contrast to the normal value of 1.54 \AA in ethane and the $\text{C}=\text{C}$ bond length is 1.353 \AA as compared to 1.334 \AA in ethylene.

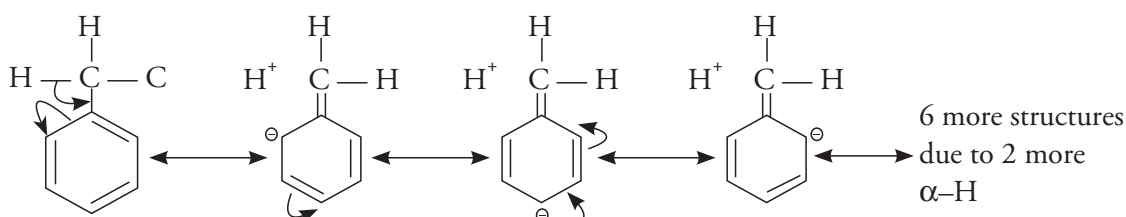
2. **Stability of alkenes** Stability of certain alkenes over others can be explained with the help of hyperconjugation.

For example, 2-methyl-2-butene is more stable than 2-methyl-1-butene as the former has nine $\alpha-\text{C}-\text{H}$ bonds hence has nine hyperconjugative structures whereas the latter has only five $\alpha-\text{C}-\text{H}$ bonds and hence only five hyperconjugative structures.

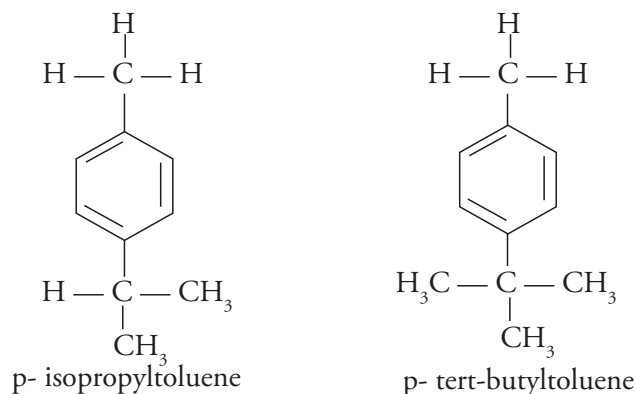


3. **Directive influence of alkyl benzene**

In electrophilic substitution reactions, the methyl group of methyl benzene is *o*, *p* directing. This has been ascribed to +I and hyperconjugative effect.



All the structures show maximum electron density at *o*- and *p*- positions, and hence the electrophilic substitution reaction occurs at the *o*- and *p*- positions.



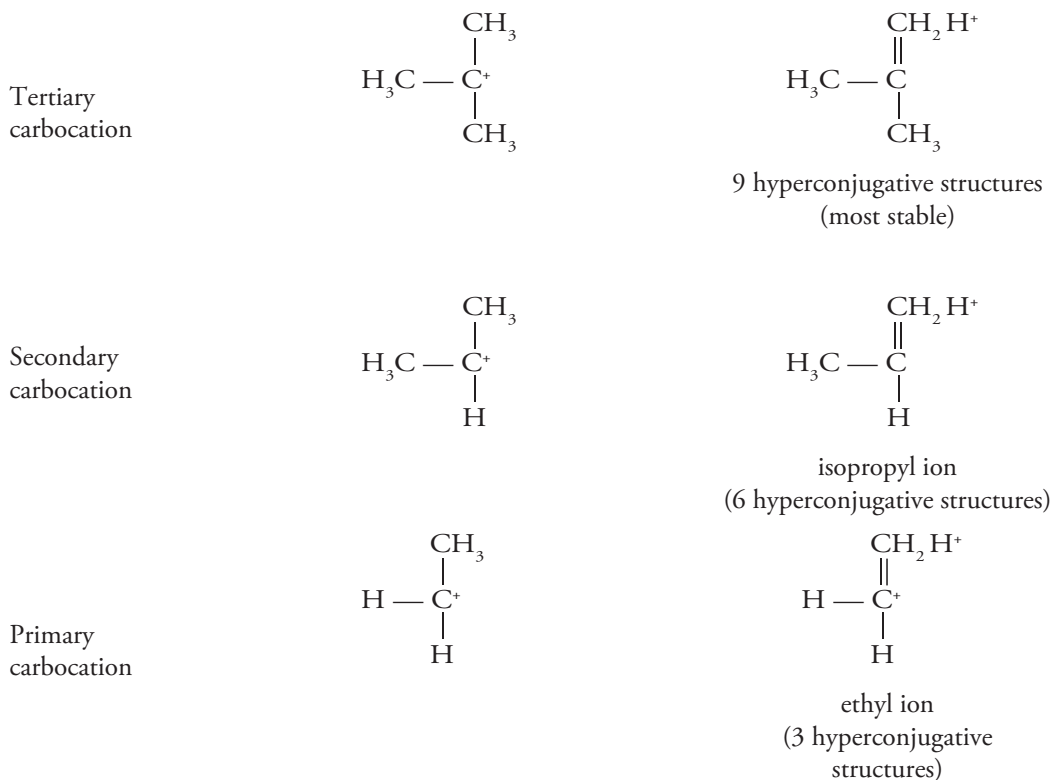
Nitration of p-isopropyltoluene and p-tert butyltoluene yields products with $-\text{NO}_2$ groups attached at position ortho to $-\text{CH}_3$ groups. Hence, in the above cases hyperconjugation effect dominates the +I effect of isopropyl and tert butyl group.

4. Stability of carbocations

The stability of carbocations is in the order

Tertiary > Secondary > primary

The above stability can be explained on the basis of +I effect as well as hyperconjugative effect.



Practice problems

- Give reasons why
 - Methyl amine is more basic than ammonia.
 - Chloroacetic acid is more acidic than acetic acid.
 - Carbon-carbon bond distance in benzene is intermediate between C — C bond distance in ethylene and C — C bond distance in ethanes.
 - CHCl_3 is more acidic than CHF_3 .
 - Formic acid is stronger than acetic acid.
 - Acidic strength decreases in the order.

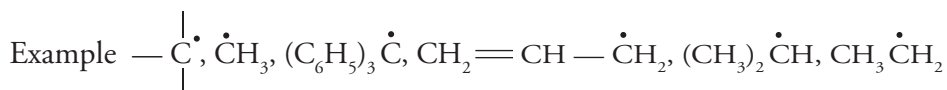
$$\text{CH}_3\text{CH}_2\text{CHClCOOH} > \text{CH}_3\text{CHClCH}_2\text{COOH} > \text{CH}_2\text{ClCH}_2\text{CH}_2\text{COOH} > \text{CH}_3\text{CH}_2\text{CH}_2\text{COOH}$$
 - Phenol is more acidic than alcohols (ethylalcohol).
- Which among the following undergoes nucleophilic substitution by $\text{S}_{\text{N}}2$ mechanism
 $\text{C}_6\text{H}_5\text{CH}_2\text{Br}$, $(\text{CH}_3)_2\text{CHBr}$, $(\text{CH}_3)_3\text{CBr}$, CH_3Br
- Aniline is a weaker base than aliphatic amines.

19.5 Reaction Intermediates

As an organic reaction proceeds, homolytic or heterolytic bond cleavage takes place leading to the formation of highly reactive intermediate species. These transient intermediates are known as reaction intermediates. These intermediates have varying stabilities and their half lives range from fraction of a second to several minutes. Their existence has been proved by spectroscopic studies. They may be neutral or charged species, all of them are short lived and very reactive. Some common reaction intermediates are free radicals, carbocations, carbanions, carbenes, nitrenes, benzyne, etc.

The different types of reaction intermediates are discussed below:

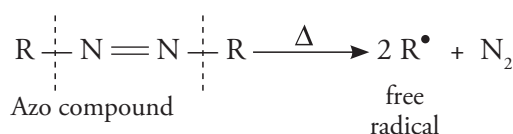
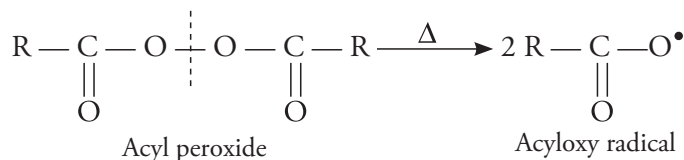
Free radicals A free radical is a neutral species containing an unpaired electron in its valence shell. It shows paramagnetism.



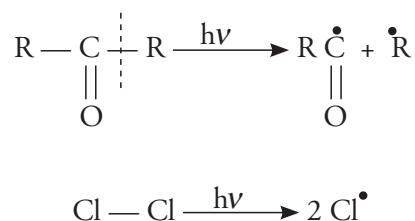
Free radicals are highly reactive species. They have a tendency to pair up and complete their octet.

Generation Free radicals are generally formed in non-polar solvents. They are produced by homolytic cleavage of bonds generally in the presence of high temperature or under the influence high energy radiation.

- **Thermolysis** (bond cleavage at high temperature) of peroxides and azo-compounds produces free radicals.



- **Photolysis** It is the process of formation of free radicals in the presence of sunlight or ultraviolet radiation.



Geometry of free radicals

Free radicals can have both pyramidal (sp^3 hybridised) and planar (sp^2 hybridised) geometries (Fig. 19.1).

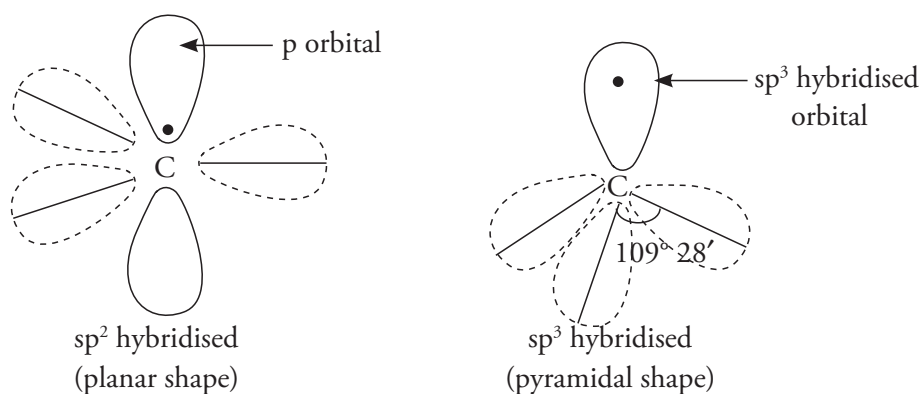


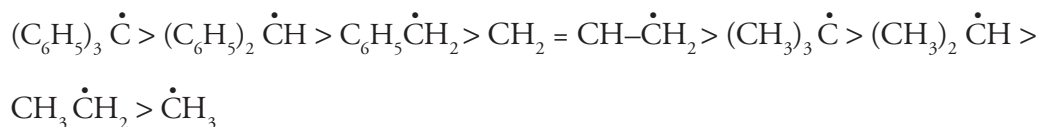
Figure 19.1 Hybridisation and geometry of free radicals

When the free radical is sp^2 hybridised, the three bonds are directed towards the three corners of planar trigonal geometry. The unhybridised p orbital lies perpendicular to the plane and contains the odd electron. For example, $\text{CH}_2=\dot{\text{C}}-\text{CH}_3$ free radical is sp^2 hybridised.

sp^3 hybridised free radical contains the odd electron in the sp^3 hybridised orbital and acquires a pyramidal geometry.

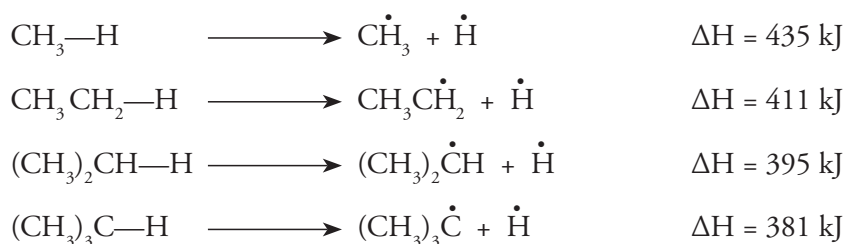
Example $(\text{CH}_3)_3\dot{\text{C}}$, $(\text{C}_6\text{H}_5)_3\dot{\text{C}}$ free radical have pyramidal shape

It has been observed that the stability of free radicals is in the order.

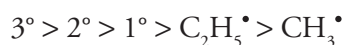


The above order can be explained on the basis of ease of formation, hyperconjugation, resonance and steric factors.

- (i) **Ease of formation** It is easier to break weak bonds. Hence lesser the bond dissociation energy greater is the ease with which the free radical is formed and greater its stability.

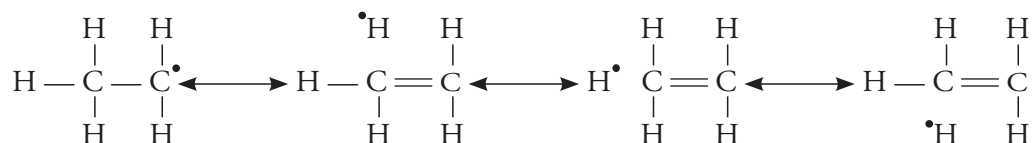


Therefore, the ease of formation of free radicals follows the order.

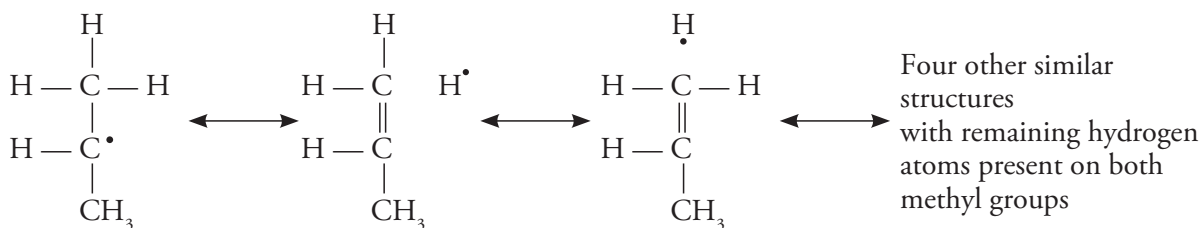


More stable is the radical, the more rapidly it is formed. Hence, the stability of alkyl radicals follows the same order.

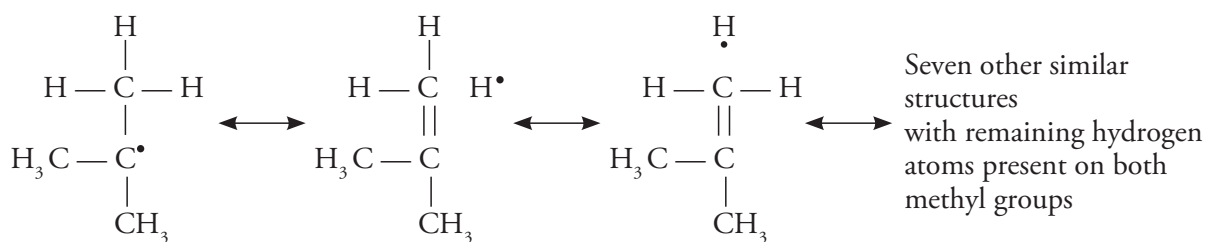
- (b) **Hyperconjugation** The relative stability of 3° , 2° , 1° alkyl radical can be explained on the basis of hyperconjugation. The greater the number of hyperconjugative structures the more stable will be the free radical.



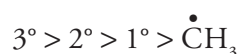
Four canonical structures for primary ethyl free radical.



Seven canonical structures for secondary isopropyl radical.



Ten canonical structures for tertiary butyl radical. Therefore, the order of stability of alkyl free radical is

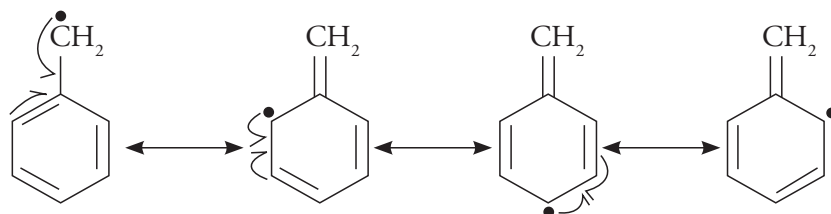


Steric factor also plays a vital role in deciding the stability of free radical. In isobutane there is more steric repulsion hence removal of hydrogen is easier. Moreover, removal of hydrogen relieves the molecule as its bond angle increases from 109° to 120° .

Resonance Allylic and benzylic free radicals are stabilised by resonance; hence, they are more stable than simple alkyl radicals.

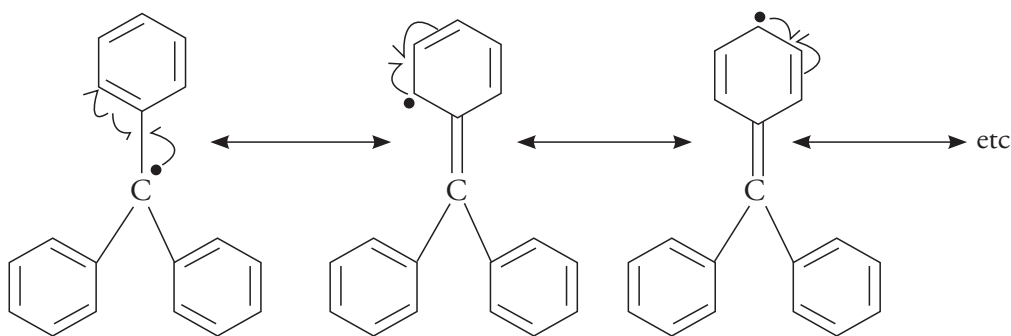


Resonance stabilisation of allyl free radical



Resonance stabilisation of benzyl radical

Diphenylmethyl and triphenylmethyl free radicals are even more stable due to greater resonance stabilisation of these structures.

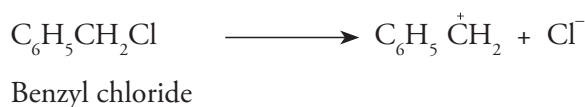
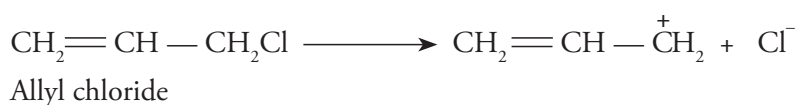
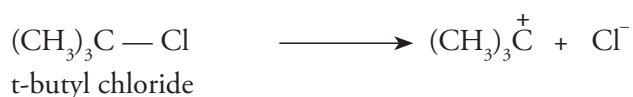


Carbonium ions (carbocations)

The term carbonium ion is widely used in organic chemistry; however, IUPAC recommends the use of the term carbocation and we shall follow the latter. Carbocations is a cation in which the carbon atom bears a positive charge with six electrons in its valence shell. A carbocations is formed due to heterolytic cleavage of the bond in which the leaving group is more electronegative and takes the electron pair with it leaving the carbon electron-deficient.

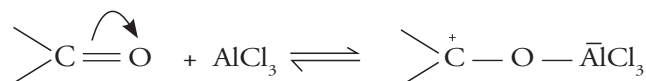
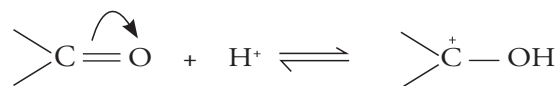
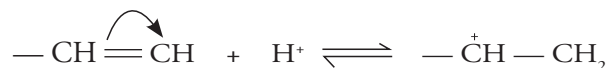
Generation Carbocations can be produced in several ways.

- (i) **Direct ionisation** Organic halides form carbocations in the presence of polar medium.

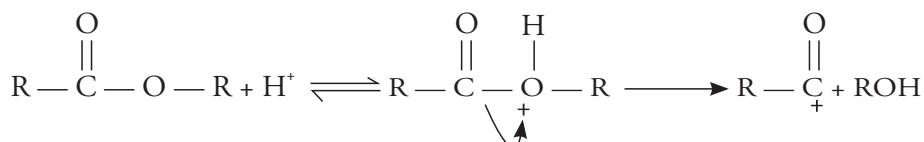
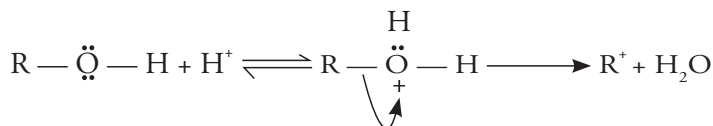


- (ii) **Protonation of unsaturated compounds**

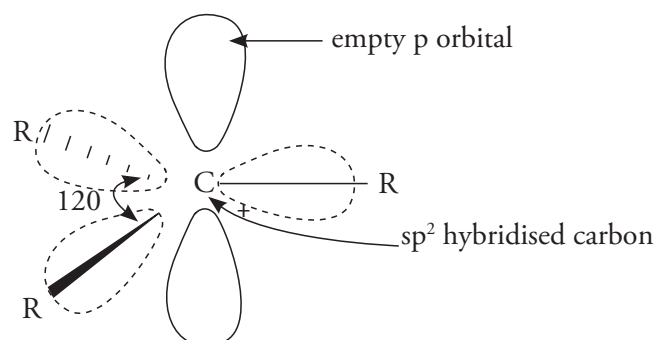
Olefins and carbonyl compounds on being treated with lewis acids or proton-donating solvents yield carbocations.



- (iii) **Protonation of atoms having lone pair of electrons**

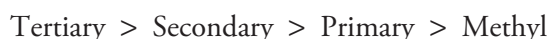
**Geometry of carbocations**

The central carbon atom of the carbocations is sp^2 hybridised. The three bonds attached to it are planar and the bond angles are 120° . The unhybridised p orbital lying perpendicular to the plane of hybridised orbitals is empty Figure 19.2.

**Figure 19.2** Geometry of carbocation

Stability of carbocation Greater the dispersal of positive charge greater is the stability of the carbocation. If the charge is localised, then the stability of the carbocation will decrease.

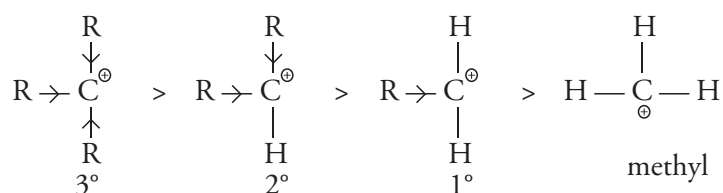
Stability of simple carbocation is as follows:



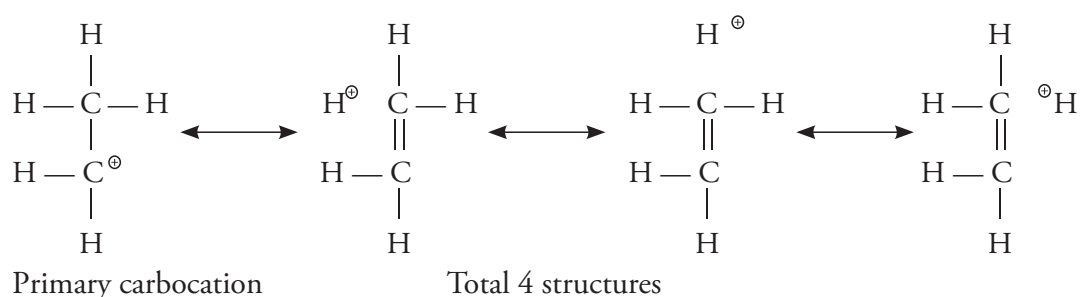
The above order of stability can be explained by two factors: inductive effect and hyperconjugation.

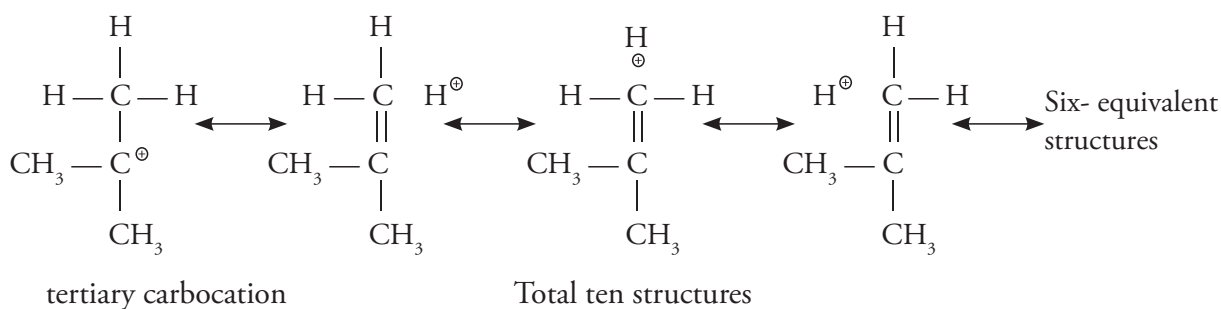
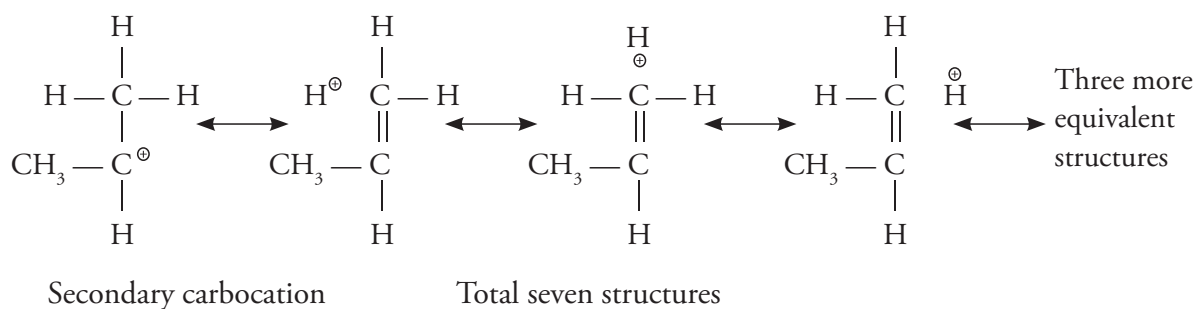
- (a) **Inductive effect** As we know that the alkyl groups have + I inductive effect, that is, electron releasing effect. The alkyl groups attached to the positively charged carbon atom tend to release electrons towards carbon. As a result, the positive charge on the carbon atom decreases but the alkyl group becomes somewhat positive. As a result, the positive charge on the carbon atom gets dispersed. The dispersal of charge leads to increased stability. Therefore, more the alkyl groups, greater will be the charge dispersal and more stable will be the carbocation.

Thus, tertiary carbocations with three alkyl groups attached to positive carbon is more stable than secondary carbocation with two alkyl groups which in turn is more stable than primary carbocation. The primary carbocation is more stable than the methyl carbocation with no charge dispersal.

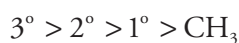


- (b) **Hyperconjugation** The greater stability of alkyl substituted carbocations can be partly attributed to the phenomenon of hyperconjugation in which there is delocalisation of σ electrons.

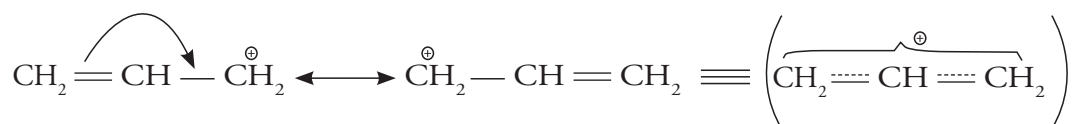




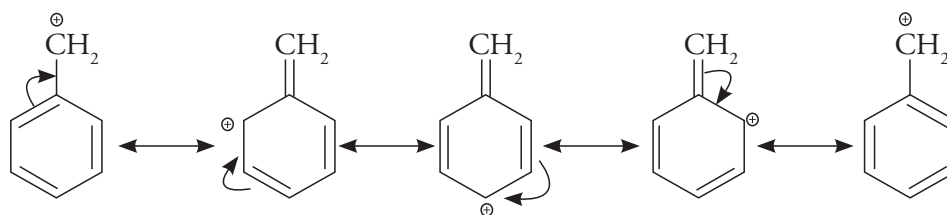
Tertiary carbocation has ten, secondary has seven and primary has four hyperconjugative structures. Greater the number hyperconjugative structures, greater is the stability. Hence, the order stability is



(c) **Resonance** Stability of benzyl and allyl carbocations is explained on the basis of resonance.

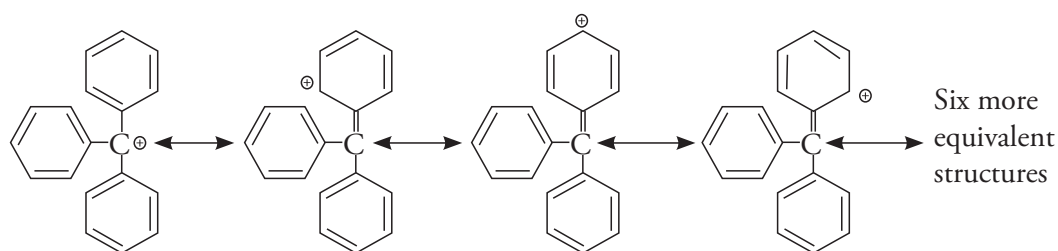


Resonance stabilisation of allyl cation

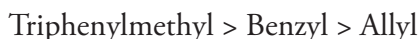


Resonance stabilisation of benzyl cation

The triphenylmethyl carbocation is extremely stable. It is regarded as the most stable carbocation. Its remarkable stability is due to extensive dispersal of positive charge as shown below.

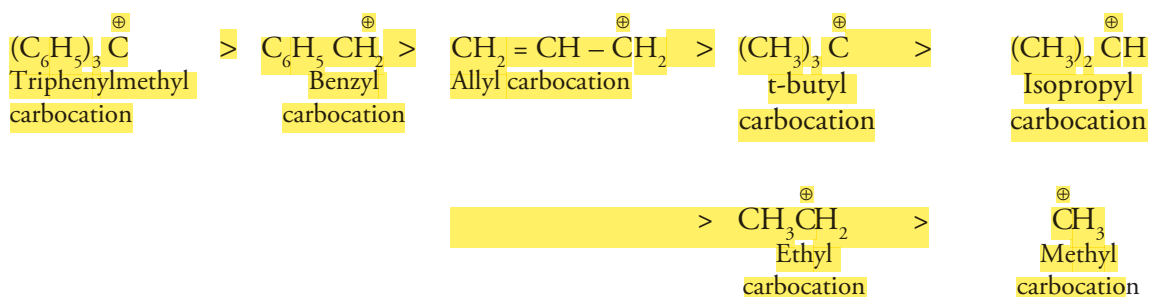


The order of stability is



These carbocations are more stable than the alkyl carbocations.

The overall order of stability of the carbocations is



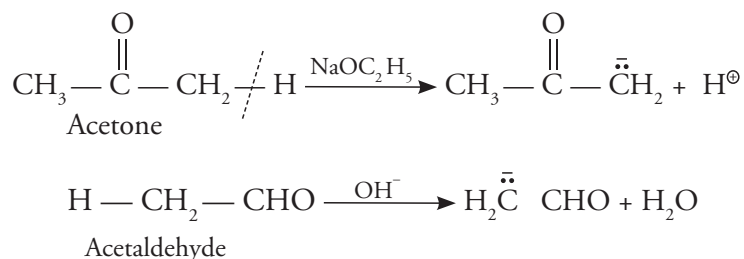
Carbanions A carbanion is defined as an organic species containing negatively charged carbon atom. The carbon atom in a carbanion is trivalent and has two extra electrons which are not bonded.

Generation

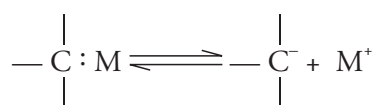
- (i) A carbanion is formed by the heterolytic fission of a bond attached to the carbon atom in such a way that the carbon retains the electron pair. Hence, carbon acquires a negative charge.

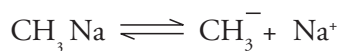
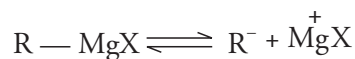


The reaction generally occurs in the presence of a base.

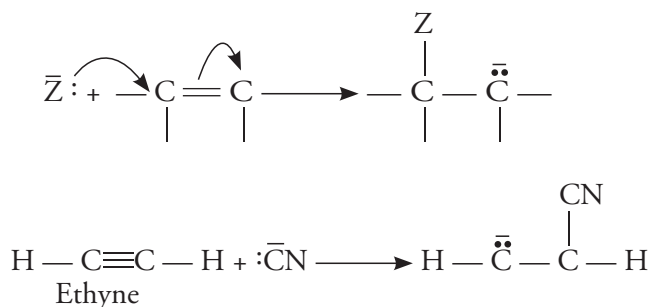


- (ii) Carbanions can also be formed by breaking of carbon metal bonds of organometallic compounds





(iii) By nucleophilic attack on a carbon–carbon multiple bond



Structure of carbanion

The carbon atom of the carbanion is sp^3 hybridised. Three of the four sp^3 hybrid orbitals form sigma bonds with the other groups whereas the fourth sp^3 hybrid orbital contains the lone pair of electrons. Hence, it has a pyramidal shape similar to that of ammonia (Fig. 19.3).

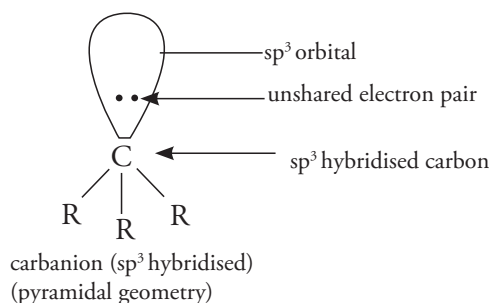
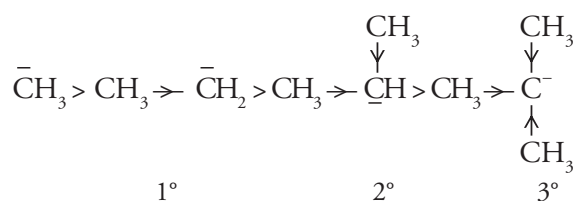


Figure 19.3 Geometry of carbanion

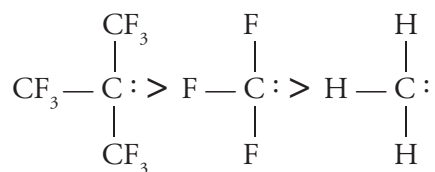
Stability of carbanion

- (i) Presence of electron releasing groups (+I effect) intensifies the negative charge on the carbon making the anion less stable. Greater the number of alkyl groups, greater will be the negative charge density at the central atom and less will be the stability of the carbanion.

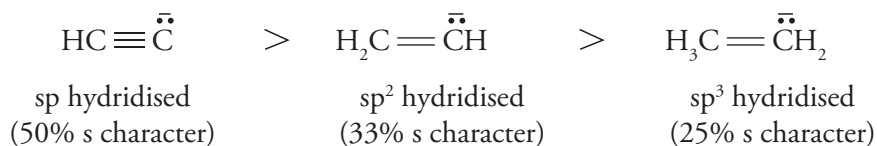


$\bar{\text{C}}\text{H}_3$ is the most stable followed by primary, secondary and tertiary carbanion.

If electron withdrawing groups (–I effect) are introduced the stability of the carbanion greatly increases.

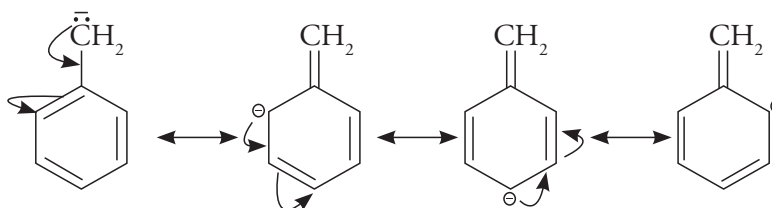


- (ii) **s-character** Greater the s-character of the carbon atom having negative charge, greater will be its stability.



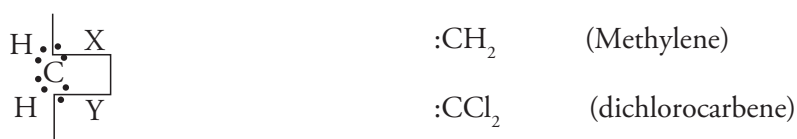
Higher the s character, closer are the electrons to the nucleus and more is the stability.

- (iii) **Resonance** The carbanion is stabilised by resonance due to delocalisation of the negative charge which is distributed over other carbon atoms in the resonating structures. For example:

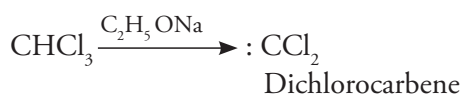
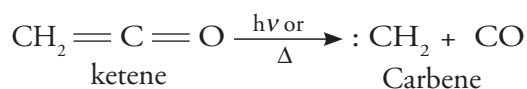
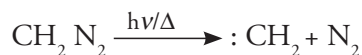


Carbenes

It is a short lived, neutral, divalent carbon with two unpaired electrons. It has six electrons in its valence shell and is formed by homolytic fission:



The simplest carbene is methylene which is generated by the decomposition of diazomethane:



Structure of carbene

Methylene can exist in two forms-singlet and triplet. In singlet state the two non-bonded electrons are in the same orbital and paired and it is sp^2 hybridised (Fig. 19.4 a). Triplet methylene (carbene) is sp of sp^2 hybridised. sp hybridised methylene has two electrons are placed in p_y and p_z orbital and it is linear (Fig. 19.4 b) whereas sp^2 hybridised methylene is bent (bond angle 140° – 150°).

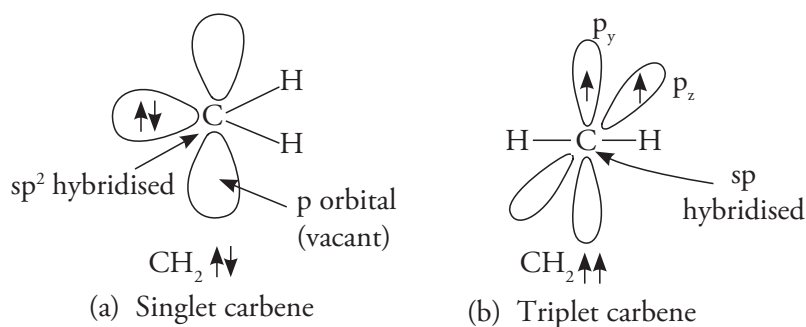


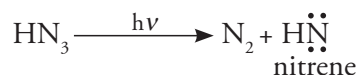
Figure 19.4 Structure of carbenes

Nitrenes

Nitrenes are intermediate species containing nitrogen atom having one bond pair and two lone pairs. It is an electron-deficient nitrogen and is analogous to carbenes.



It is also called imidogen, azene or imene. They can be present in both singlet and triplet states and can be generated by the hydrolysis of hydrazoic acid in aromatic solvents.



Hofmanns rearrangement reaction occurs by the formation of intermediate nitrene (refer to Section 19.10).

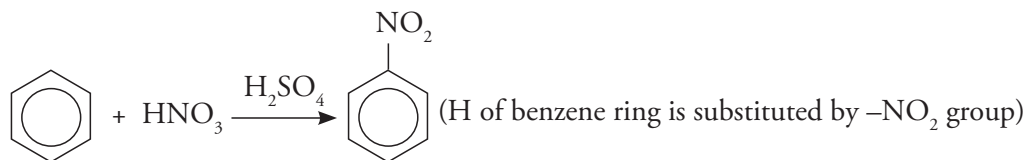
19.6 Types of Organic Reactions

Organic reactions are broadly classified as

- (i) Substitution reactions
- (ii) Addition reactions
- (iii) Elimination reactions
- (iv) Rearrangement reactions

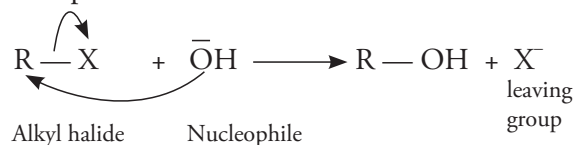
Let us discuss these reactions one by one.

Substitution Reactions A substitution reaction is one in which an atom or group of atoms in a molecule is replaced or substituted by different atom or group of atoms. They can also be termed as displacement reactions. For example:



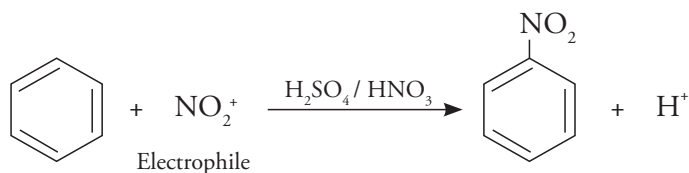
The attacking species in substitution reactions can be nucleophile, electrophile or a free radical. Depending on the nature of the attacking species the substitution reactions are of three types.

- (a) **Nucleophilic Substitution Reactions** Reactions in which substitutions are brought about by nucleophiles are called nucleophilic substitution reactions. They are denoted by SN (S = substitution, N = nucleophilic). These reactions are characteristic of alkyl halides. For example:



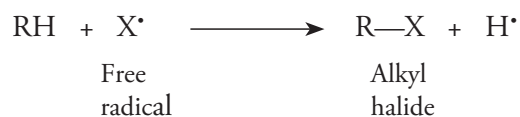
The mechanism of nucleophilic substitution is discussed later in Section 19.7.

- (b) **Electrophilic Substitution Reactions** These reactions are characteristic of aromatic compounds like benzene and are brought about by electrophiles which attack the high electron density of the aromatic system. For example, nitration of benzene ring.



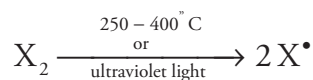
The detailed mechanism is discussed in Section 19.8.

- (c) **Free Radical Substitutions Reactions** In this type of reactions, the substitution is brought about by free radicals. Example: Halogenation of alkanes in the presence of sunlight.



The reaction occurs in three steps:

- (i) **Initiation** Free radicals are generated in this step. Halogens in the presence of sunlight form free radicals.



(ii) **Propagation** The free radicals formed in the initiation step attack the alkane.



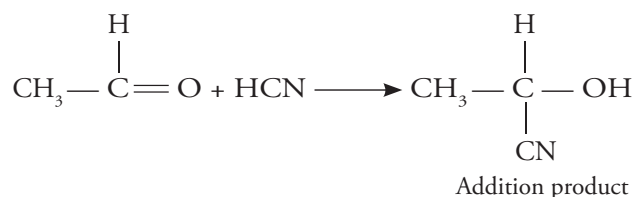
The reaction continues till finally the chain is terminated.

(iii) **Termination** The free radicals combine to terminate the chain. The following reactions can occur.



Addition Reactions An addition reaction is one in which the attacking reagent adds up to the reactant molecule to form a single product. Addition reactions occur in compounds containing double or triple bonds.

For example



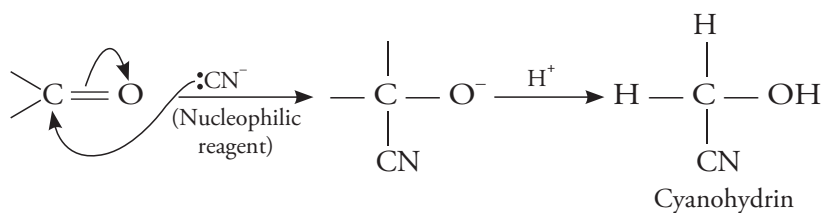
Like substitution reactions, addition reactions can also be nucleophilic, electrophilic or free radical addition reactions depending on the type of attacking reagent.

(a) **Nucleophilic Addition Reactions** Addition reactions which are brought about by nucleophiles are called nucleophilic addition reactions. Common examples of compounds undergoing nucleophilic addition reactions are aldehydes, ketones, esters, etc.

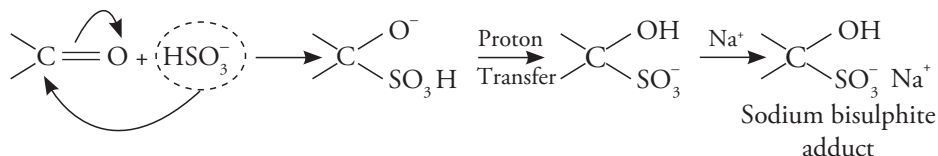
In aldehydes, ketones and esters, the π electrons are pulled towards oxygen (as it is more electronegative than carbon) making the carbonyl carbon electron-deficient and the carbonyl oxygen electron-rich.



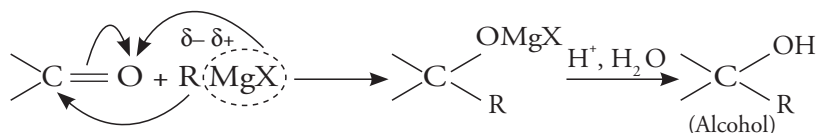
The nucleophile uses its electron pair and forms a bond with the carbon atom of carbonyl group. The electrophile then associates itself with the oxygen atom and the final addition product is formed. The above mechanism can be explained by considering the addition of HCN to a ketone to form cyanohydrin. In the addition reaction the strongly basic cyanide ion attacks the carbonyl carbon; subsequently (or possibly simultaneously) the oxygen accepts hydrogen ion to form the cyanohydrin product.



Similarly, addition of sodium bisulphite takes place as follows:

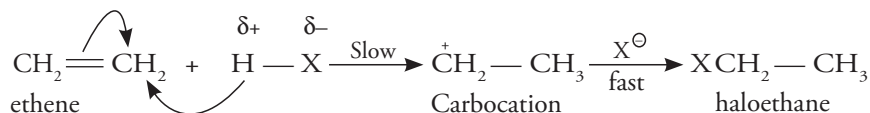


Consider the addition of Grignards reagents:



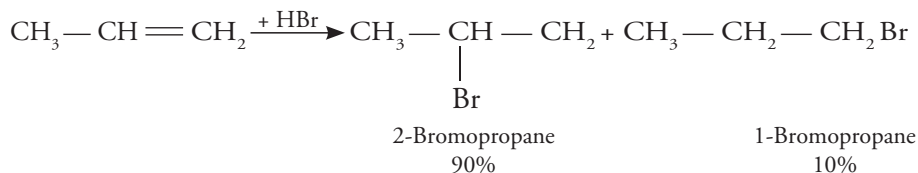
- (b) **Electrophilic Addition Reactions** Addition reactions brought about by electrophiles are called electrophilic addition reactions. They are characteristic of alkenes, alkynes and occur by the formation carbocations as intermediates.

Consider the addition of hydrogen halides to alkenes:

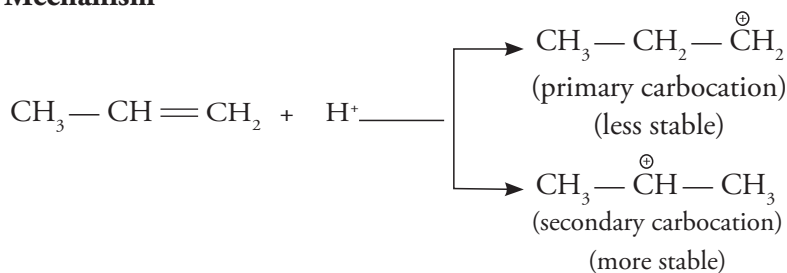


Electrophilic addition to asymmetrical alkenes takes place in accordance to the 'Markownikoffs rule'.

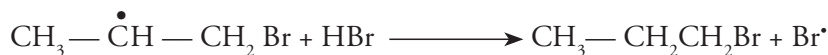
According to this rule, *during addition across unsymmetrical double bond, the negative part of the attacking reagent attaches itself to the carbon atom carrying lesser number of hydrogen atoms while positive part goes to the carbon atom with more number of hydrogen atoms.*



Mechanism



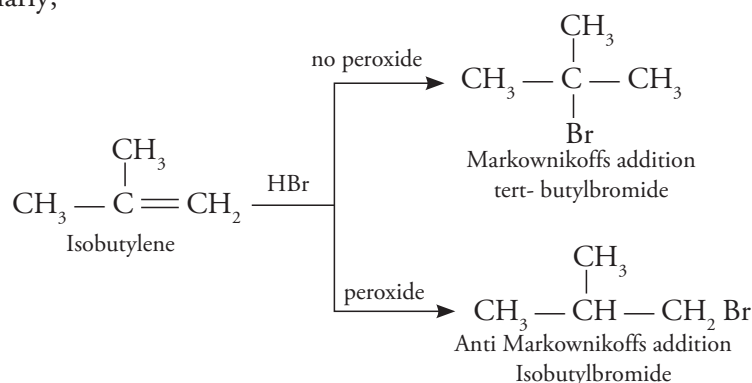
The free radical formed above is attacked by HBr to form the product. Since secondary free radical is more stable than primary free radical, hence the final product is obtained from the secondary free radical.



Chain termination



Similarly,

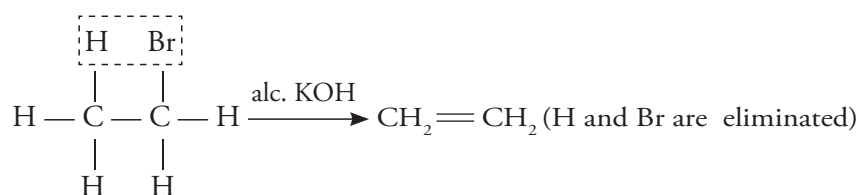


Elimination Reactions

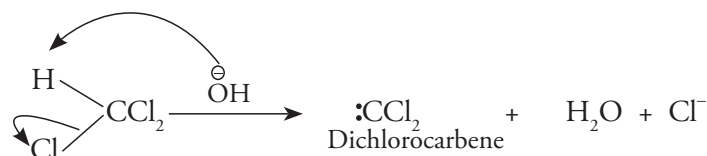
The term 'eliminate' means 'to remove'. Elimination reactions are those reactions in which a molecule loses atoms or groups without being replaced by other atom or group. These reactions are of two types.

- (i) **β - Elimination** If the two atoms or groups are lost from the vicinal (adjacent) carbon atoms, it is called β -elimination. β -elimination leads to the formation of double and triple bonds

For example:



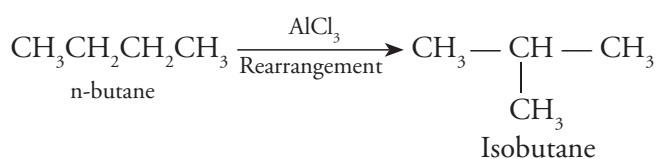
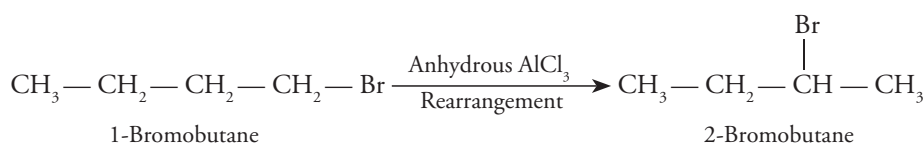
- (ii) **α -Elimination** If the two atoms or groups are lost from the same carbon atom, it is called an α -elimination or 1, 1 elimination. The most common example of α -elimination reaction is the generation of dichlorocarbene from chloroform in the presence of a base.



The carbene thus formed is unstable and reacts quickly to form products.

β - elimination reactions are more common than α -elimination reactions. Brief mechanism of elimination reactions is discussed in Section 19.9.

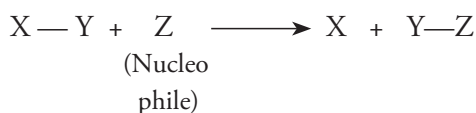
Rearrangement Reactions These reactions involve the migration of an atom or group of atoms to another position within the molecule under suitable conditions. For example:



Beckmann's rearrangement (discussed in Section 19.10)

19.7 Mechanism of Nucleophilic Substitution Reactions

These reactions constitute the most important class of organic reactions and involve the substitution or replacement of one group or atom by the other to form a new compound.



In the above example, the atom X is replaced by Z to form the new product. Nucleophilic substitution reactions are represented as S_N reactions. The carbon compound on which the substitution occurs is called the substrate. The group which is replaced by the attacking reagent (nucleophile) is called the leaving group. The leaving group leaves the substrate carrying its electron pair with it.

Substitution reaction involves:

- Bond breaking to release the leaving group
- Bond formation with the nucleophile

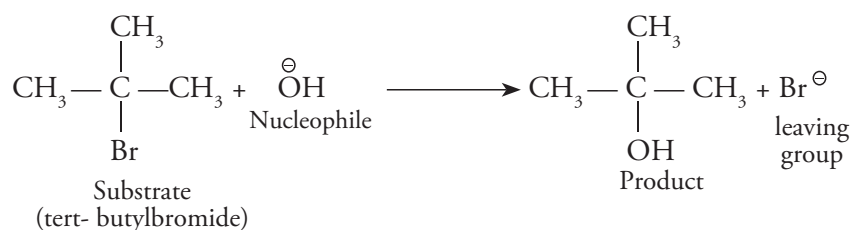
Two types of mechanisms have been proposed for substitution reaction.

- (i) S_N1 Mechanism (Substitution nucleophilic unimolecular)
- (ii) S_N2 Mechanism (Substitution nucleophilic bimolecular)

S_N1 Mechanism (Substitution Nucleophilic Unimolecular)

This type of substitution reaction takes place in two steps through the formation of intermediate carbocation.

Consider the example

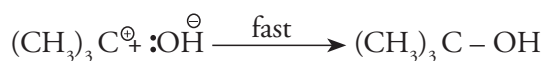


The above reaction is considered to be taking place in two steps

- (i) The first step is slow and reversible. It involves the ionisation of C–Br bond to form a carbocation, $(\text{CH}_3)_3\text{C}^+$ and a bromide ion Br^- .



- (ii) The second step is fast and involves the reaction of the carbocation and hydroxyl ion (nucleophile) to yield an alcohol.

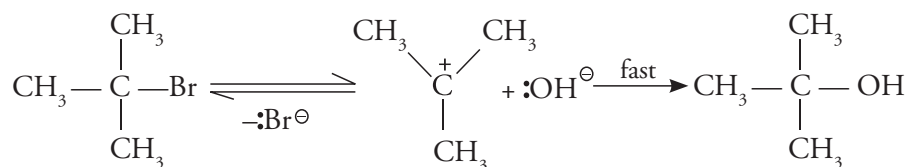


As the rate of a reaction is determined by the slow step (called rate determining step), the rate law expression for the above reaction can be written as

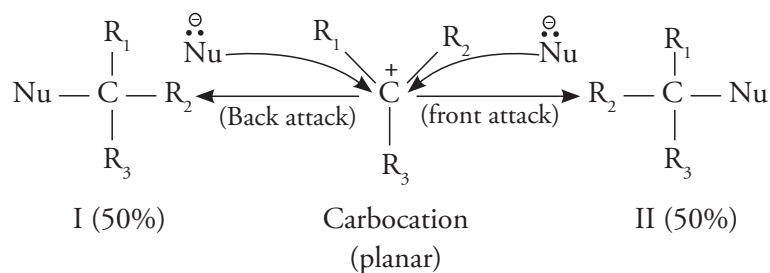
$$\text{Rate} = k [(\text{CH}_3)_3\text{C}-\text{Br}]$$

Hence the reaction follows first order kinetics and since only one molecule takes part in the rate determining step it is termed as unimolecular.

The carbon atom in the carbocation is sp^2 hybridised, it is planar and the overall reaction can be written as



Stereochemistry of $\text{S}_\text{N}1$ Reaction As discussed above, the intermediate carbocation formed in $\text{S}_\text{N}1$ mechanism is sp^2 hybridised and is planar. Hence the nucleophile can attack from either face of the cation. Hence, if the carbocation has been derived from an asymmetric (optically active) alkyl halide, then the product will be a racemic mixture.



Structures I and II are enantiomers.

Energy Changes in S_N1 Reaction The energy changes occurring during an S_N1 reaction can be represented by an energy profile diagram (Fig. 19.5). Every step of the S_N1 reaction has its transition state.

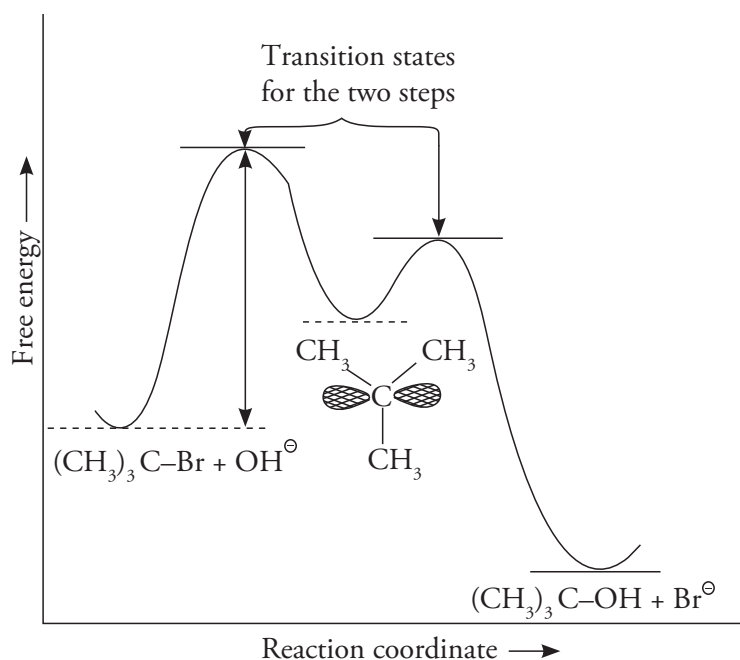
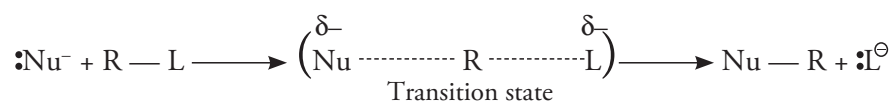
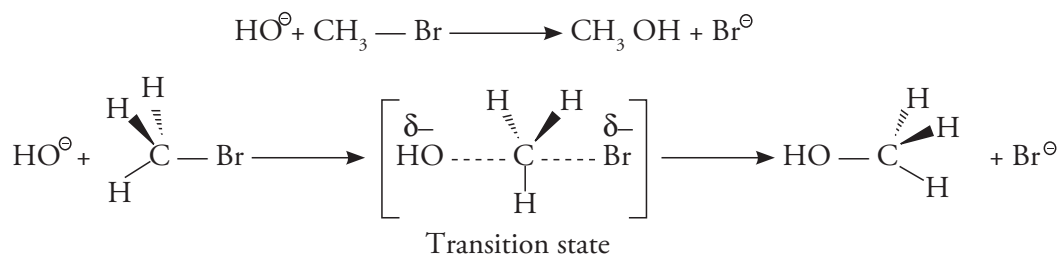


Figure 19.5 Energy changes in S_N1 reaction

S_N2 Mechanism (Substitution Nucleophilic Bimolecular) This type of substitution reaction takes place in a single step. In this mechanism, bond making and bond breaking take place simultaneously and there is direct displacement of the leaving group with the attacking nucleophile.



Consider the reaction of methylbromide with sodium hydroxide to yield methanol.

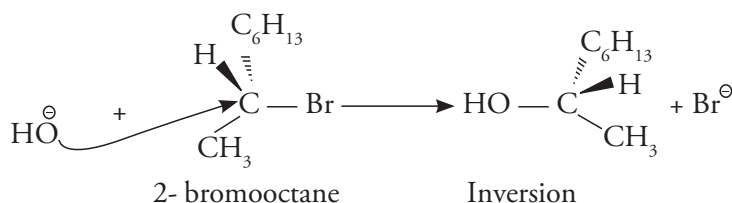


The rate of the reaction depends on the concentration of both the reactants.

$$\text{Rate} = k [\text{CH}_3\text{Br}] [\text{OH}^-]$$

Since both the reactants take part in the rate determining step, it is a bimolecular reaction and the mechanism is called $\text{S}_\text{N}2$ mechanism (Ingold).

Stereochemistry of $\text{S}_\text{N}2$ Mechanism In the $\text{S}_\text{N}2$ mechanism, the nucleophile attacks the side of the carbon atom opposite to that of the leaving group. Hence, in $\text{S}_\text{N}2$ mechanism the stereochemistry of the product is opposite to that of the substrate. In other words $\text{S}_\text{N}2$ mechanism proceeds with stereochemical inversion, commonly referred to as Walden inversion. It can be illustrated by the hydrolysis of asymmetric halide 2-bromooctane.



Energy Changes in $\text{S}_\text{N}2$ Mechanism The energy changes can be described by the energy profile diagram as shown in Figure 19.6.

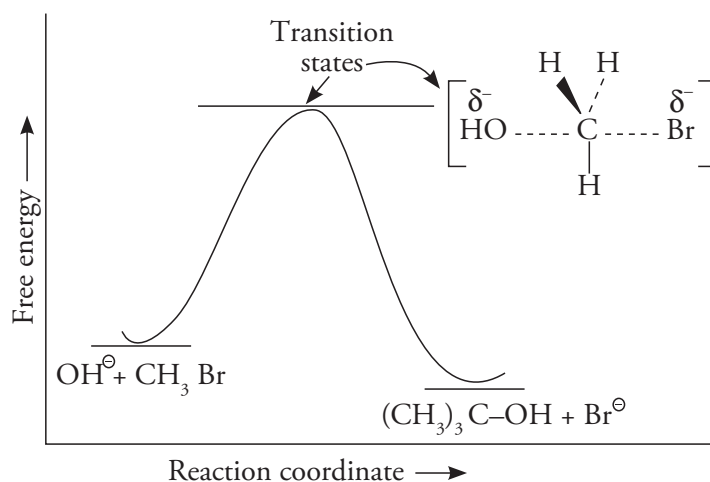
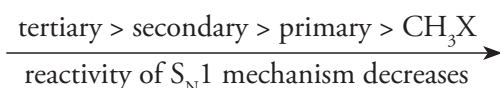


Figure 19.6 Energy profile diagram for $\text{S}_\text{N}2$ reactions

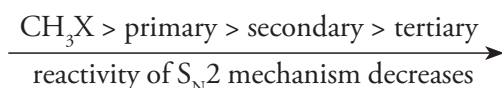
Factors Affecting the Reactivity and Mechanism of Nucleophilic Substitution Reactions

A nucleophilic substitution reaction can proceed by S_N1 or S_N2 mechanism. Which mechanism is to be followed depends upon various factors. The reactivity and rate of reaction is also influenced by several factors like nature of substrate, nature of solvent, nature of nucleophile, nature of leaving group, etc. Let us discuss these factors one by one.

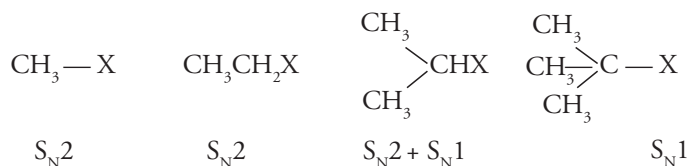
- Nature of substrate** S_N1 reactions proceed by the formation of intermediate carbocation whereas in S_N2 reactions the nucleophile attacks from the rear end and the transition state having partially bonded leaving group and partially bonded attacking reagent (nucleophile) is formed. Factors like inductive effect, hyperconjugation and resonance which stabilise the intermediate carbocation favor S_N1 reactions whereas steric factors which assist or hinder the bond formation of nucleophile and bond cleavage of leaving group will play a decisive role in determining the reactivity of S_N2 mechanism. The sequence of reactivity of alkyl halides to S_N1 reactions is in the following order:



The reactivity of alkyl halides to S_N2 reactions is in the following sequence:

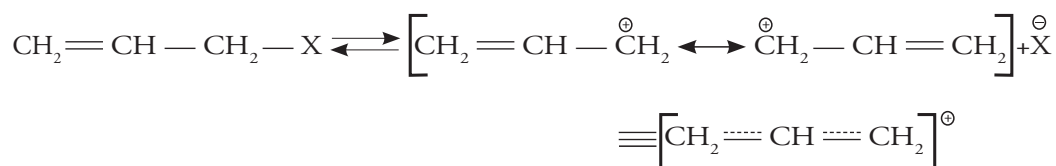


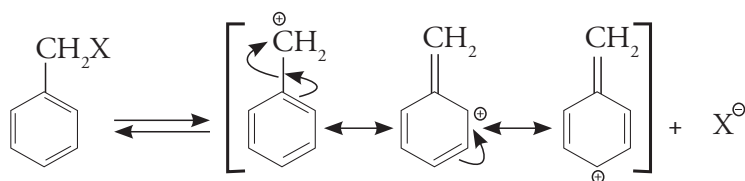
It can be seen from the above order that tertiary alkyl halides are substituted by S_N1 mechanism whereas the primary alkyl halides follow S_N2 substitution reactions. Secondary alkyl halides can undergo substitution by both S_N1 and S_N2 mechanisms:



We can see that the introduction of methyl groups changes the mechanism from S_N2 to S_N1 . This change in mechanism can be explained by the following factors.

- Inductive, hyperconjugation effects** S_N1 reactions proceed by the formation of carbocations. +I effect of methyl groups and hyperconjugation stabilise the carbocations (Refer to Section 19.4 inductive effect and hyperconjugation). This effect is maximum in tertiary carbocations, and hence they react exclusively by S_N1 mechanism.
- Resonance effect** Allylic and benzylic substrates readily undergo S_N1 reaction because the intermediate carbocation is resonance-stabilised.

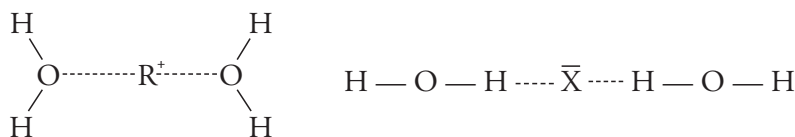




- (iii) **Steric hindrance** In S_N2 mechanism, the nucleophile attacks from the backside on the alkyl halides leading to a transition state. In primary halides it is easier for the nucleophile to push itself between the hydrogen atoms, and hence primary halides undergo substitution by S_N2 mechanism. As the hydrogen atoms are replaced by alkyl groups, the nucleophile finds it difficult to approach the carbon site. Hence, S_N2 mechanism becomes difficult in secondary alkyl halides and tertiary alkyl halides react exclusively by S_N1 mechanism.

2. Nature of solvents As S_N1 reactions proceed by the initial ionisation of the molecule producing carbocation hence polar solvents are found to increase the rate of S_N1 reaction because

- They facilitate the ionisation of the molecule.
- They stabilise the liberated ions by solvation.



The cations are solvated by the solvent molecules through coordination with electron pair, whereas the anions are solvated by solvent molecules through hydrogen bonding.

The above observation is supported by experimental results. The rate of hydrolysis of *t*-butylchloride in 50% aqueous ethanol is 30,000 times faster than 100% ethanol.

On the contrary the rate of S_N2 mechanism does not alter appreciably with the solvent.

3. Effect of nucleophile

S_N1 Reactions

Rate \propto [Substrate]

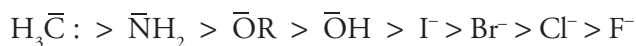
The rate equation shows that nucleophilic reagent does not take part in the rate-determining step. Hence, the entering group has no effect on the rate of S_N1 reactions.

S_N2 Reaction

Rate \propto [Substrate] [Nucleophile]

The rate of reaction depends on the nature of the nucleophile. The more strongly nucleophilic the reagent, that is, the greater the tendency of the reagent to donate electrons to the substrate molecule, the faster will be the reaction.

The decreasing order of basicity of few nucleophiles is given below:



The rate of reaction also decreases in the above order.

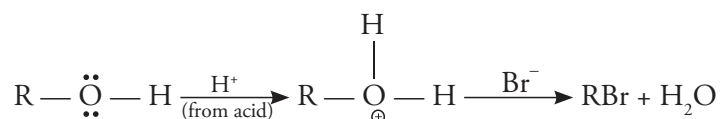
4. **Nature of leaving group** The less basic the leaving group, the more easily it is displaced by the solvent in S_N1 mechanism or by the attacking nucleophile in S_N2 reactions.

In alkyl halides, the ease of separation of halide ions is $I^- > Br^- > Cl^- > F^-$. This is the reverse of carbon halogen bond strength. The easily the leaving group is polarised the more reactive is the alkyl halide.

Here it is important to note that both the entering and leaving groups are bases. Hence strong nucleophilic reagents will displace the weaker base. For example, alkaline hydrolysis of alkyl halide.



If it is the reverse, that is, if the leaving group is more basic than the entering group then it will not be displaced in ordinary conditions but can be made to do so in acid solution which makes them less basic due to protonation. For example, conversion of alcohols to alkyl halides.



This is the reason why alcohols undergo substitution reactions in acidic conditions only.

Table 19.2 Comparison between S_N1 and S_N2 reaction

	S_N1	S_N2
1	They show first order kinetics	They follow second order kinetics. In the presence of excess of nucleophile they may follow first order kinetics, but still the reaction proceeds by S_N2 mechanism
2	Rate of reaction is mainly affected by electronic factors	Rate of reaction is determined by steric factors
3	Rearranged products can be formed. The intermediate carbocation formed can rearrange to form stable carbocations	Since carbocations are not formed rearrangement is not possible
4	Reactivities of halide $t > s > p > \text{methyl}$	Reactivities of halides $CH_3 > p > s > t$
5	Favoured by mild nucleophiles	Favoured by strong nucleophiles
6	Favoured by low concentration of nucleophiles	High concentration of nucleophiles is needed
7	Favoured by solvents of high polarity	Favoured by solvents of low polarity
8	Stereochemistry-partial racemization of products occurs	Complete inversion of products occurs

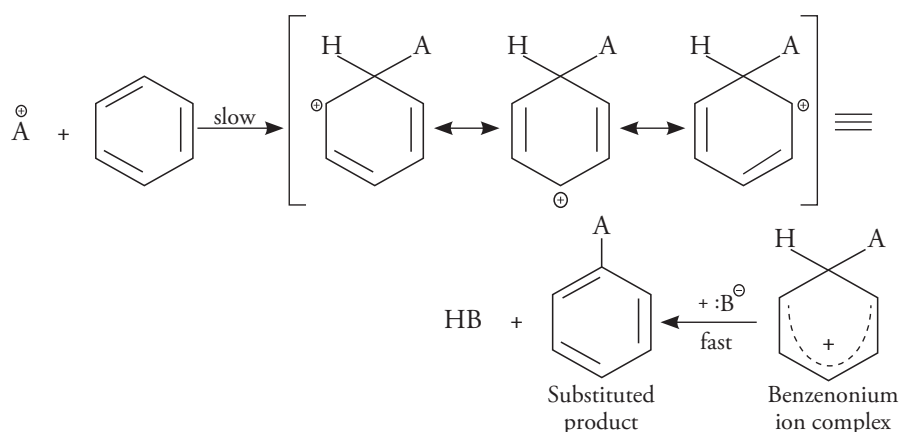
19.8 Mechanism of Electrophilic Substitution Reactions

As discussed in Section 19.6, reactions which are brought about by electrophiles are called electrophilic substitution reactions. These reactions are characteristic of aromatic compounds.

Although aromatic compounds have double bonds but they do not undergo addition reactions under normal conditions. The lack of reactivity to addition reactions is due to the greater stability of aromatic ring systems due to complete π electron delocalisation (resonance). The aromatic compounds react by electrophilic aromatic substitution reactions in which the aromaticity of the ring system is preserved.

Mechanism Electrophilic substitution reaction involves attack by an electrophile and liberation of a proton. This takes place in two steps:

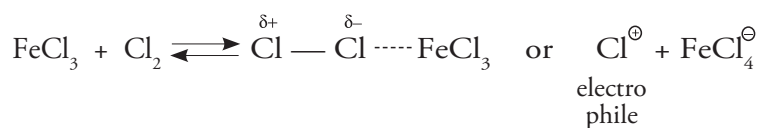
- In the first step the electrophile attacks the benzene ring to form an intermediate carbocation called the benzenonium ion. This step is slow and is the rate determining step.
- In the second step, which is fast, a proton is removed from this intermediate yielding the substituted product.



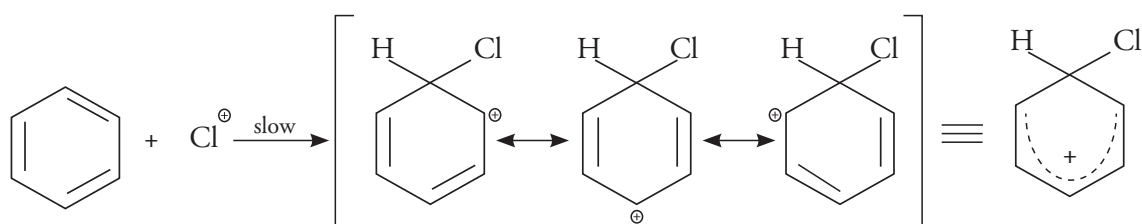
Some typical electrophilic substitution reactions of benzene are discussed below:

Halogenation

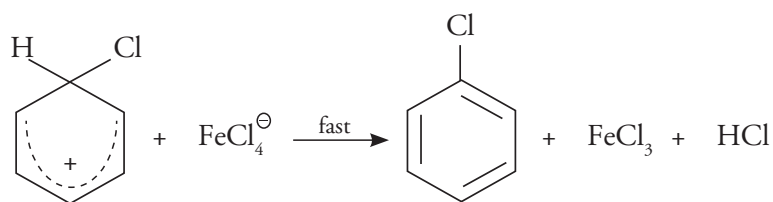
Halogenation is carried in the presence of a catalyst which acts as a halogen carrier. The commonly used catalysts are iron powder, FeCl_3 , ZnCl_2 , AlBr_3 , iodine, pyridine, etc. The main function of the halogen carrier is to polarise the halogen-halogen bond and generate the electrophile.



The electrophile then attacks the aromatic ring.



Finally the aromatic structure is restored by loss of proton to FeCl_4^- and the catalyst is regenerated.



Nitration

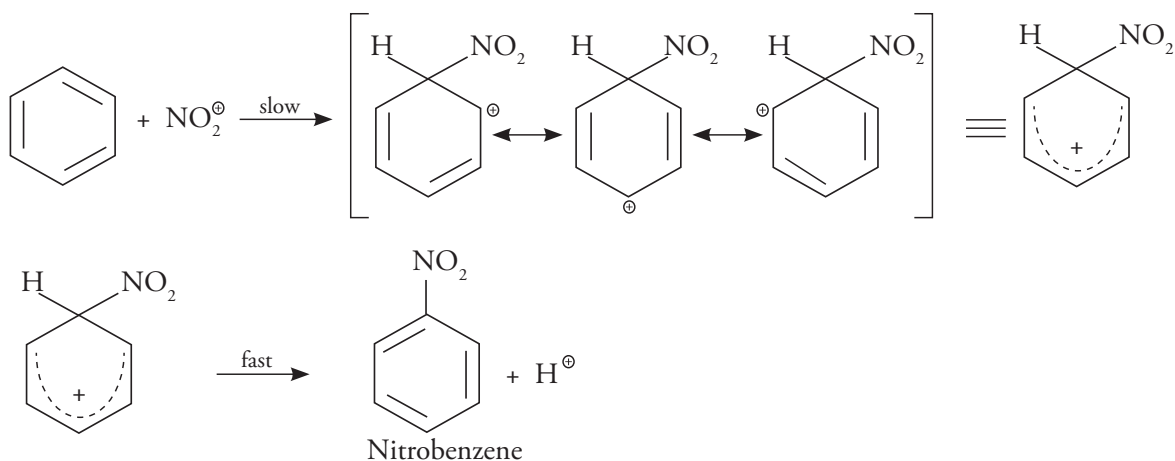
Nitration is brought about by treating benzene with a mixture of concentrated nitric acid and sulphuric acid. Nitronium ion (NO_2^+), which brings about the nitration, is generated in situ.



Nitronium ion can also be generated using BF_3 and HF as catalysts.

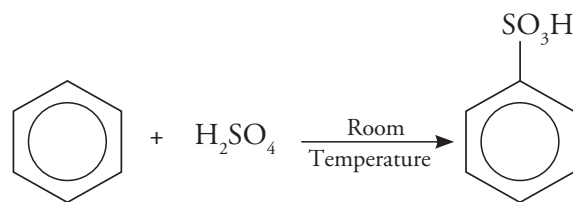


The nitronium ion thus produced attacks the benzene ring followed by the loss of proton to form nitrobenzene.

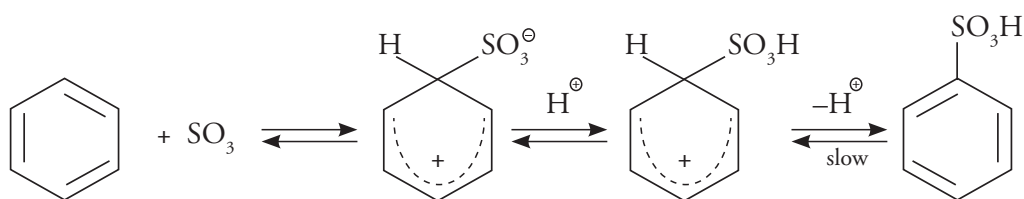


Sulphonation

Benzene reacts with concentrated sulphuric acid at room temperature to produce benzene sulphonic acid.



The electrophile involved is sulphur trioxide.

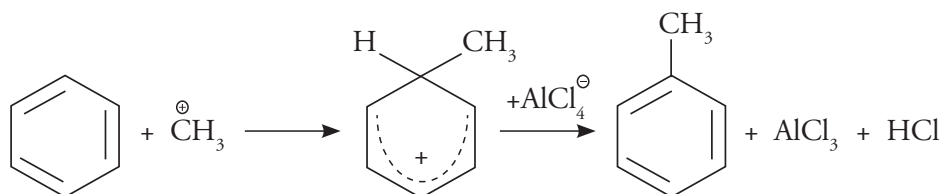


Here, it is important to note that the second step, removal of proton, is the rate-determining step.

Friedel Craft Alkylation

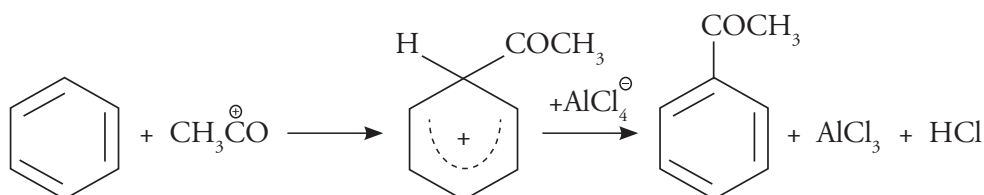
Benzene reacts with alkyl halides in the presence of a lewis acid (generally AlCl_3) to produce alkylated products. Other lewis acids like BF_3 , AlBr_3 , etc. can also be used.

The lewis acid assists in the generation of electrophile which attacks the benzene ring followed by abstraction of proton.



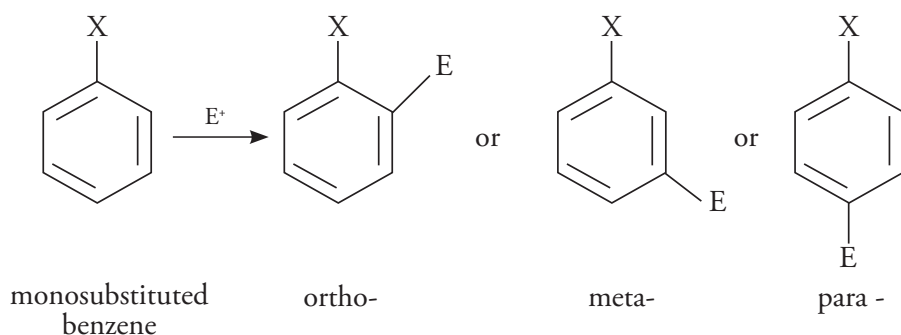
Friedel Craft Acylation

In friedel craft acylation, the acylating species is produced by the reaction of acid halides or anhydrides with a lewis acid.



Effects of Substituents

When benzene undergoes electrophilic substitution, initially a monosubstituted product is formed because all the six carbon atoms are the same. However, if a monosubstituted benzene further undergoes electrophilic substitution the new group can enter at ortho, meta or para position with respect to the group already present on the benzene ring.



The substituent X exerts two types of effects on the benzene ring for further substitution.

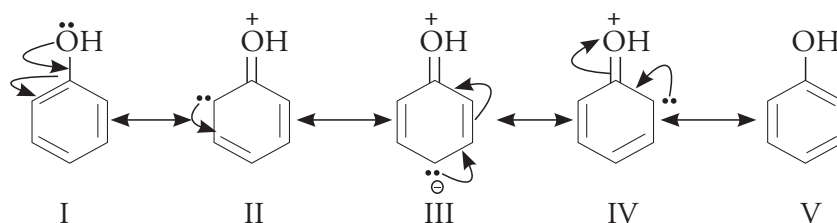
- (i) **Directive influence** The substituent X may direct the incoming group to *o*, *m* and *p* position depending on the nature of the substituent. The effect is also called the orientation effect.
- (ii) **Activity effect** The group already present may activate or deactivate the benzene ring towards further substitution.

On the basis these characteristics the substituents are divided into three categories.

- 1 Groups such as alkyl, OH, NH₂, NR₂, NHCOR, OR and OCOR are *o*, *p* directing and activate the benzene ring for further substitution.
- 2 Halogens which although *o*, *p* directing exert a deactivating effect on the benzene ring.
- 3 Groups such as –C = O, –C ≡ N, SO₂, –NO₂, –NR₃⁺ are *m* directing and deactivate the benzene ring.

Activating Groups : Ortho – Para Directors

All ortho and para directing groups have a lone pair of electrons except the methyl group. They donate the lone pair of electrons to benzene ring due to resonance and increase the electron density at *o*- and *p*- positions. Hence the substitution occurs at *o*- and *p*- positions.



It is clear from structures II, III and IV that the electron density at *o*- and *p*- position is high; hence, electrophilic substitution occurs at these positions.

On the other hand –OH groups also exerts –I effects (electron withdrawing effect); but the resonance effect is much powerful than the –I effect.

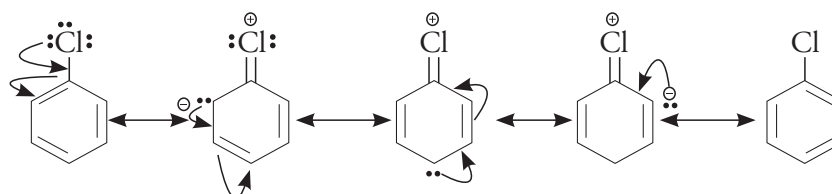
Effect of alkyl groups

Alkyl groups do not have a lone pair of electrons, and hence do not undergo mesomeric (resonance) effect. However, they have strong +I effect which increases the electron density at *o*- and *p*-position, directing the incoming groups to these position.

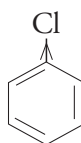
Deactivating groups: ortho-para directors

Halogens are *o*- and *p*- directing but deactivating. The lone pair of electron conjugates with the benzene ring and increases the electron density at *o*- and *p*- position (resonance effect), and directs the incoming group to ortho and para position. But on the other hand halogens exert a strong –I effect, which tends to remove electrons from ortho and para positions.

So the net result is that although halogen atoms are *o*, *p* directing due of +R effect, they deactivate the ring due to –I effect ($+R \geq -I$) and hence compared to benzene it is difficult to carry out the substitution in chlorobenzene.



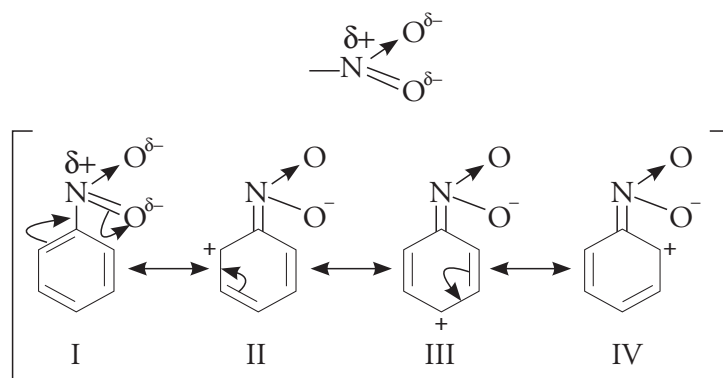
Resonance effect in chlorobenzene



(–I effect in chlorobenzene)

Deactivating groups: meta directors

The nitro group is a powerful electron withdrawing group. It withdraws electrons by both inductive effect (–I effect) and resonance effect. Let us consider the resonating structures of nitrobenzene.



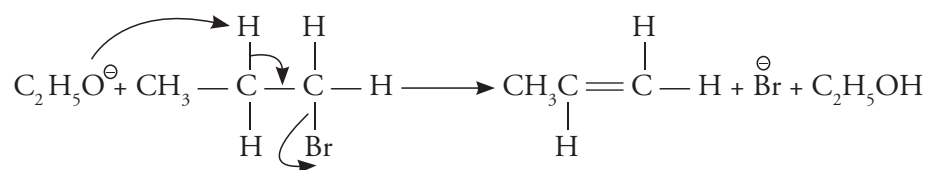
From the structures II, III and IV, it is clear that the electron density at *m* position is greater than at *o*- and *p*-position, hence the incoming groups attack the *m*- position. Owing to the –I effect of –NO₂ group, it exerts deactivating influence.

19.9 Mechanism of Elimination Reactions

β -elimination reactions may proceed either by bimolecular (E2) or by unimolecular (E1) mechanism.

- (a) **Bimolecular Mechanism (E2)** This is a one-step process which involves the attack of a nucleophilic base on the β carbon atom followed by the simultaneous loss of halide ion from α -carbon atom.

Consider the example of the action sodium ethoxide on 1-bromopropane when propene is formed.



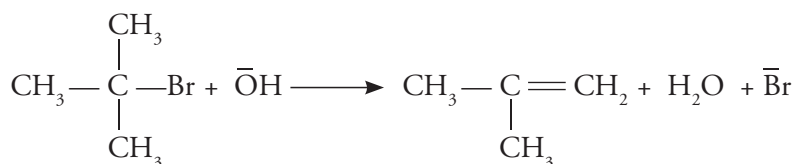
The rate of the reaction depends on the concentration of both the substrate and the base. The rate of reaction for the above reaction is

$$\text{Rate} = k [\text{CH}_3\text{CH}_2\text{CH}_2\text{Br}] [\text{C}_2\text{H}_5\text{O}^\ominus]$$

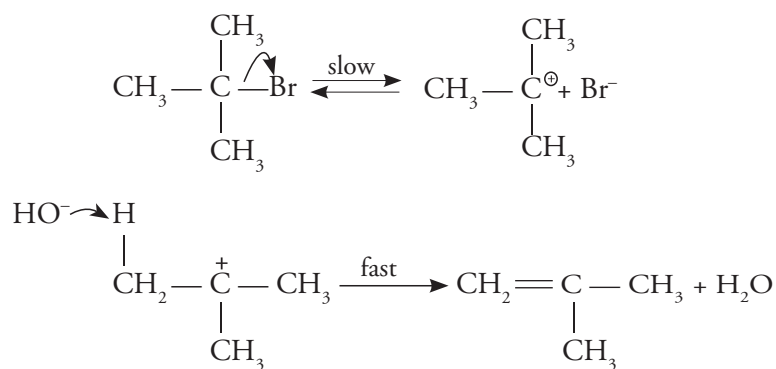
or for a general elimination reaction

$$\text{Rate} = k [\text{Substrate}] [\text{Base}]$$

- (b) **Unimolecular Mechanism (E1)** These elimination reactions occur in two steps. The first step which is the rate-determining step involves the formation of carbocation (analogous to $\text{S}_{\text{N}}1$ mechanism). The attack of base occurs in the second step. Let us consider the example of the action of strong solution of alcoholic alkali on 2-bromo-2-methylpropane (t-butylbromide).



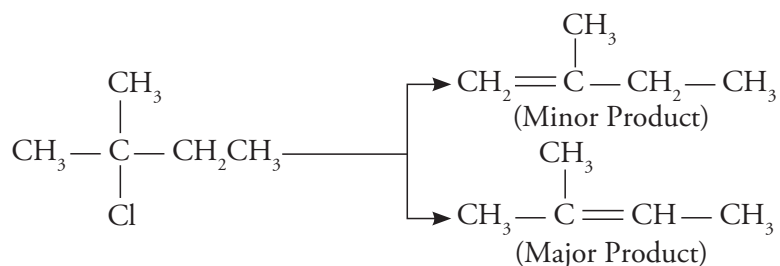
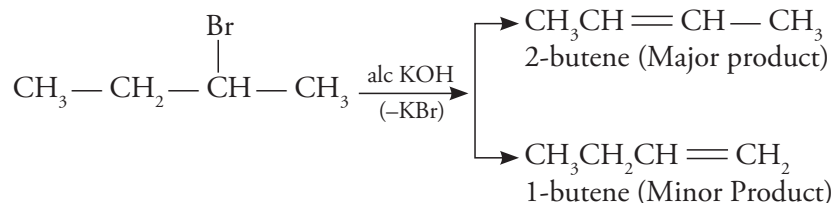
Mechanism



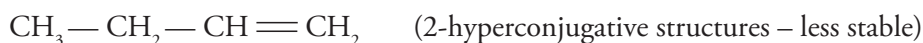
$$\text{Rate of reaction} = k [(\text{CH}_3)_3\text{C Br}]$$

Hence the reaction follows first order kinetics. The first step involves ionisation of the substrate forming carbocation. In the second step, the carbocation thus formed loses a β -proton with the help of the base forming the final elimination product.

Saytzeff Rule This rule states that during the elimination reaction that alkene is formed preferably which has greater number alkyl groups attached to the double bond.

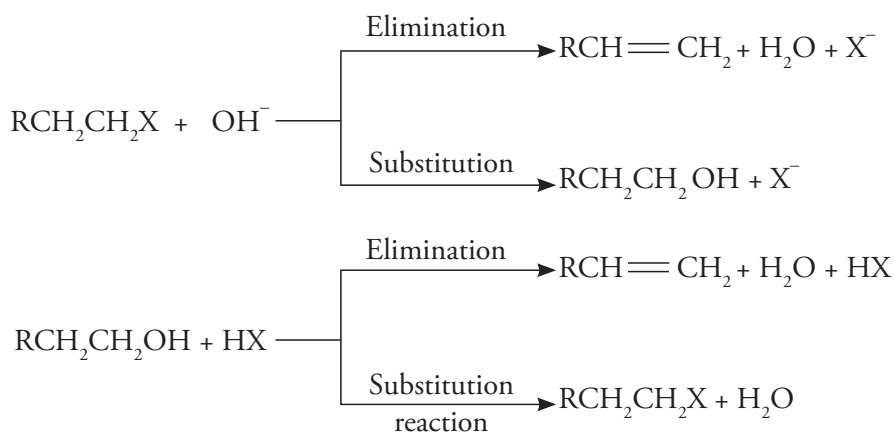


The preferential formation of more substituted alkenes in the above reactions can be correlated to the relative stabilities of various alkenes. The greater stability of more substituted alkenes can be explained on the basis of hyperconjugation.



Elimination versus Substitution

As discussed earlier both E1 and $\text{S}_{\text{N}}1$ reactions proceed with the formation of intermediate carbocation and both require a base or nucleophile. Hence, elimination reactions can be accompanied by substitution reactions or it can be better said that the two compete with each other or occur simultaneously, for example



The factors favouring elimination or substitution reactions are given below

- (i) **Basic strength of reagent** A base is an electron pair donor or a proton abstractor. Therefore stronger bases favour elimination reactions (removal of proton) whereas weaker bases will merely substitute the group and hence favour substitution reaction. The decreasing basic strength of some bases is

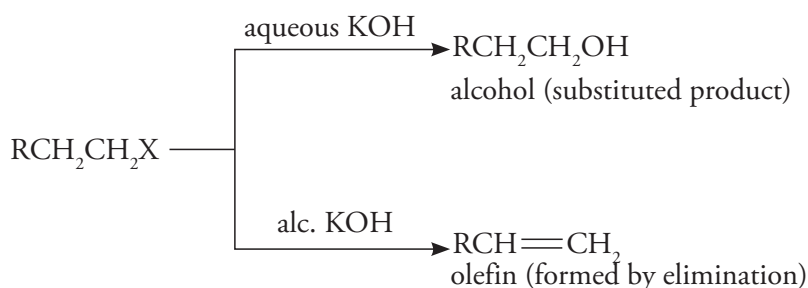


- (ii) **Ionising power of the solvent**

More ionising solvents favour substitution reactions and less ionising solvents favour elimination reactions. The ionising power of some solvents is



This has been proved by the fact that alkyl halides undergo substitution reactions in the presence aqueous KOH solution and elimination reaction in the presence of alcoholic KOH solution.



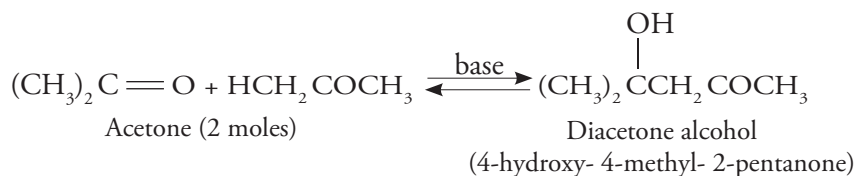
- (iii) **Concentration of the reagent** Higher concentration of base favours elimination reactions.
 (iv) **Effect of temperature** Elimination reactions are favoured by high temperatures.

Practice problems

Give reasons why

- Propene reacts with HBr to give isopropyl bromide and not n-propyl bromide.
- C_6H_6 although highly unsaturated, undergoes substitution reactions.
- Carbonyl compounds are reactive towards nucleophilic reagents, but alkenes are not reactive towards such reagents.
- Alkyl chloride reacts with aqueous KOH to form alcohols, whereas in the presence of alcoholic KOH alkenes are formed as major products.
 (Hint: aqueous KOH gives OH^- ions which act as nucleophile whereas alc KOH gives ethoxide ion $\text{C}_2\text{H}_5\text{O}^-$ which are more basic than OH^- ions and brings about elimination.)
- Haloalkanes are more reactive than haloarenes.

Aldehydes and ketones having one or more α -hydrogen atom when treated with a dilute base undergo addition reactions. This is known as aldol condensation. 'Aldol' is an abbreviation of aldehyde and alcohol as the β -hydroxy aldehyde or β -hydroxy ketone formed has both aldehyde and alcohol functional groups.


$$\text{CH}_3-\overset{\begin{array}{|c|c|} \hline \text{OH} & \text{H} \\ \hline \end{array}}{\underset{|}{\text{CH}}}-\underset{|}{\text{CH}}-\text{CHO} \xrightarrow[\text{warm}]{\text{H}^+} \text{CH}_3\text{CH}=\text{CHCHO} + \text{H}_2\text{O}$$

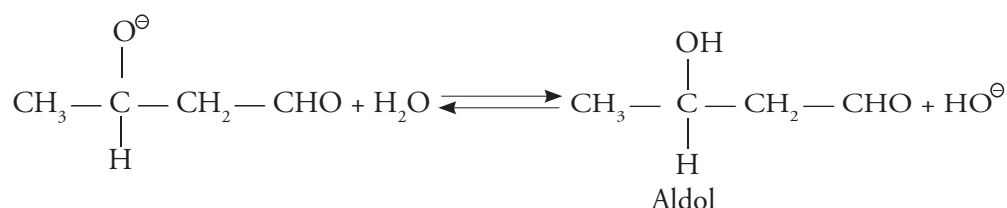
2-butenal



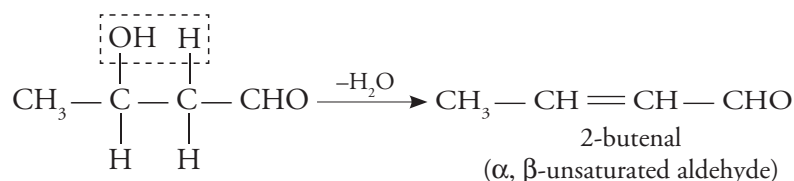
- $$\text{HO}^\ominus + \text{H}-\text{CH}_2-\overset{\text{O}}{\parallel}{\text{C}}-\text{H} \rightleftharpoons \left[\text{CH}_2^\ominus - \overset{\text{O}}{\parallel}{\text{C}}-\text{H} \longleftrightarrow \text{CH}_2=\overset{\text{O}^\ominus}{\text{C}}-\text{H} \right] + \text{H}_2\text{O}$$

- $$\text{CH}_3-\overset{\text{O}}{\underset{\text{H}}{\underset{|}{\text{C}}}} + \overset{\ominus}{\text{CH}_2}-\overset{\text{O}}{\underset{|}{\text{C}}}-\text{H} \longrightarrow \text{CH}_3-\overset{\text{O}^\ominus}{\underset{\text{H}}{\underset{|}{\text{C}}}}-\text{CH}_2-\text{CHO}$$

(iii) The anion so formed accepts hydrogen from the solvent molecule to form the product.

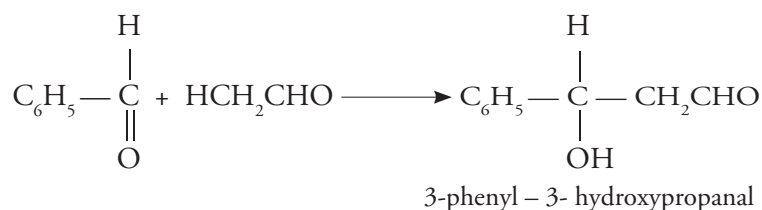
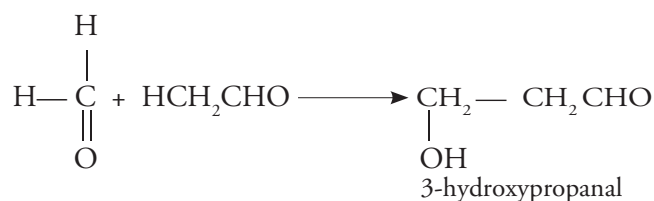


In the presence of dilute acids and bases the aldol may eliminate a water molecule to form α, β -unsaturated aldehyde.



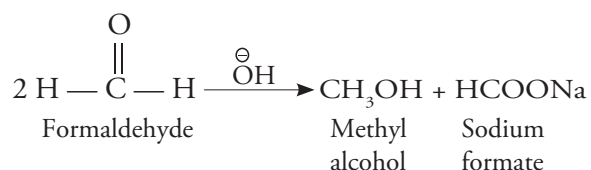
Crossed aldol condensation

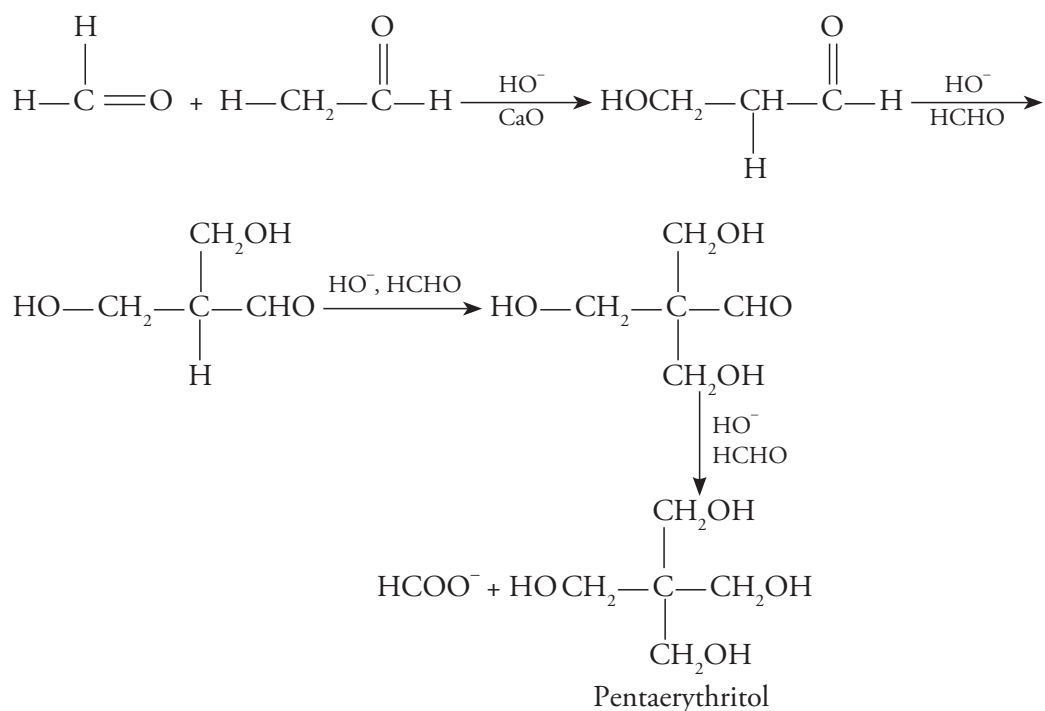
Crossed aldol condensation occurs between two different carbonyl groups. Different products can be formed. If both the aldehydes contain α -H atom, a mixture of four products is formed. These reactions are of little synthetic value. However, if one of the carbonyls does not possess α -hydrogen atom, then aldol condensation yields useful products.



Cannizaro's Reaction

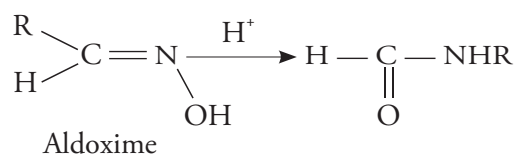
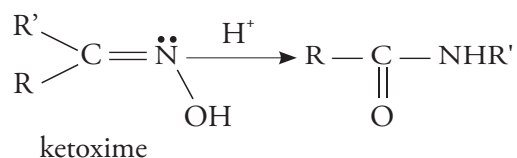
Aldehydes without α -H atoms, when treated with concentrated alkali undergo self oxidation and reduction to yield an alcohol and a salt of carboxylic acid. One molecule of an aldehyde is reduced to an alcohol at the cost of other, which is oxidised to a carboxylic acid.





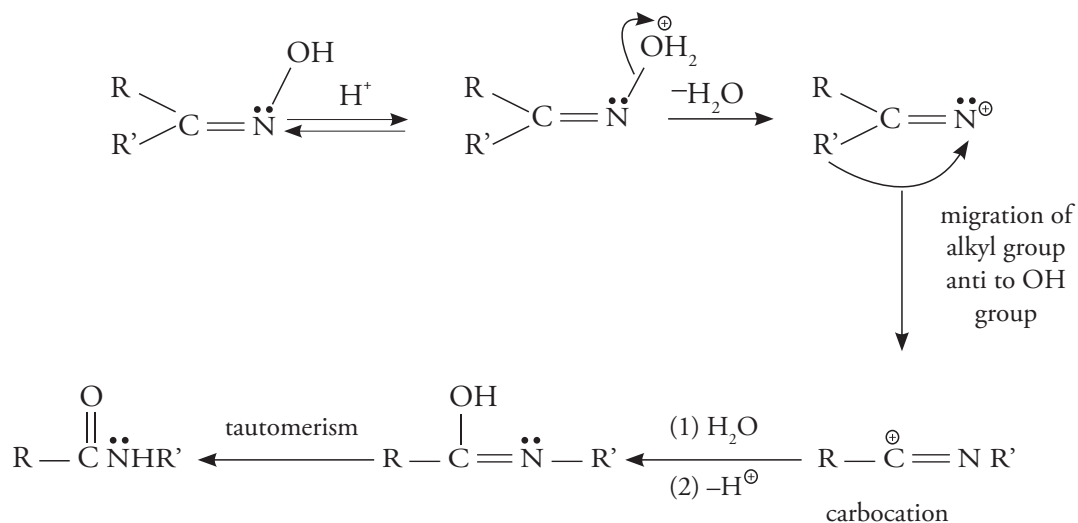
Beckmann Rearrangement

It involves the acid catalysed rearrangement of a ketoxime to N-substituted amide.

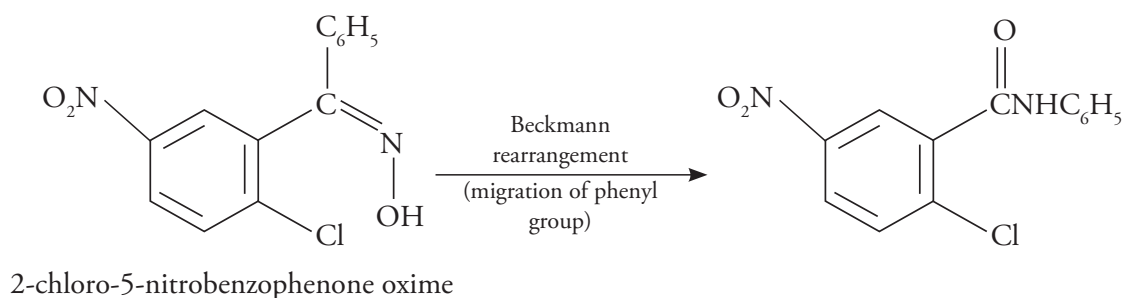


Mechanism

Acidic reagents like H_2PO_2 , H_2SO_4 , P_2O_5 , SOCl_2 , PCl_5 , etc. catalyse this rearrangement reaction. The mechanism is as follows.



The rearrangement is highly stereospecific in which the group anti to OH migrates. Migration of anti groups is proved further by the conversion of 2-chloro-5-nitrobenzophenone oxime to a chloronitrobenzanilide. It is found that the phenyl group, rather than the nitrated benzene ring, migrates to the nitrogen.

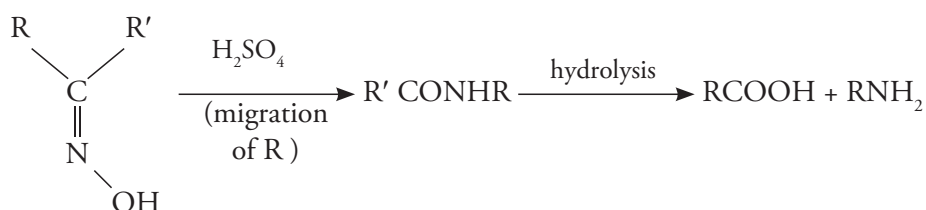


Applications

1. Determination of the configuration of ketoximes

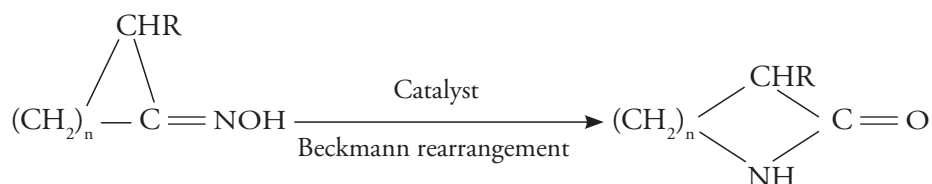
The *syn* and *anti* ketoximes yield different products. Hence the end products help in predicting the configuration of the ketoxime.

For example

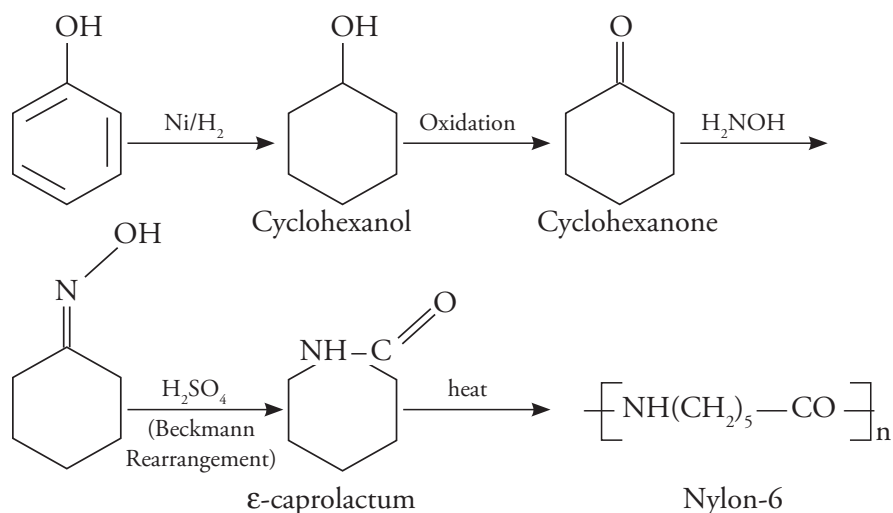




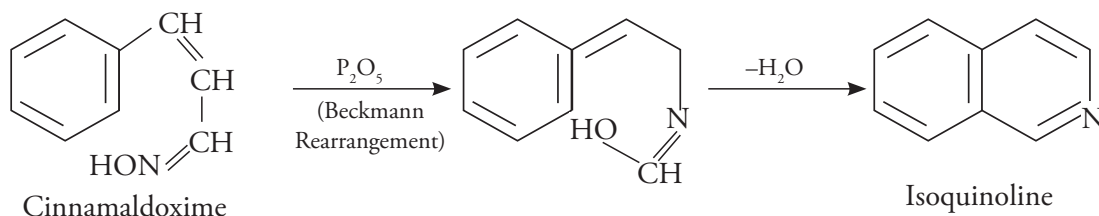
2. **Ring enlargement in cyclic ketoximes** Cyclic ketoximes undergo ring enlargement in the presence of a suitable catalyst.



This finds application in the synthesis of caprolactum by the Beckmann rearrangement of cyclohexanone oxime in the presence of concentrated sulphuric acid. ϵ -caprolactum on heating polymerises to give nylon-6



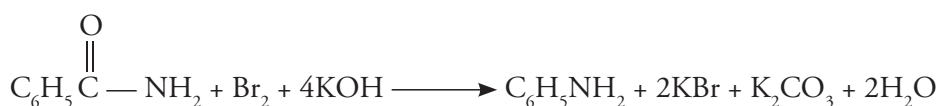
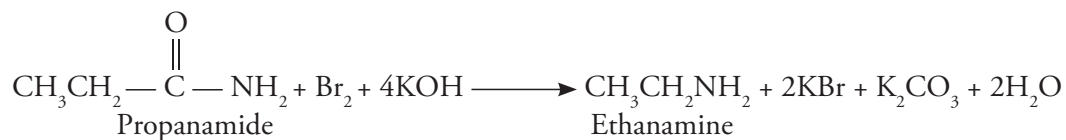
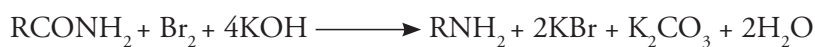
3. **Synthesis of Isoquinoline** Cinnamaldehyde oxime on Beckmanns rearrangement with acid yields isoquinoline.



Hoffmann Rearrangement or Hoffmann Degradation

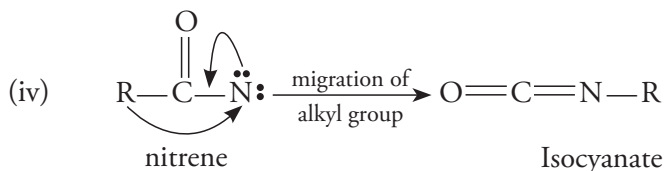
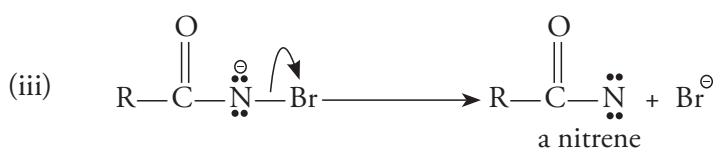
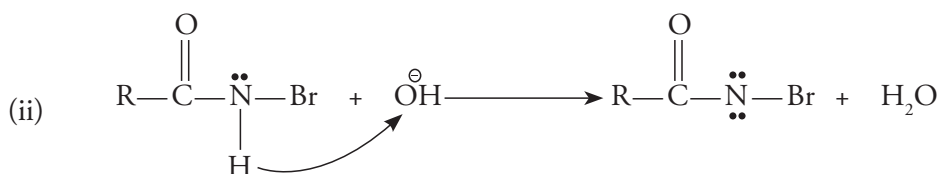
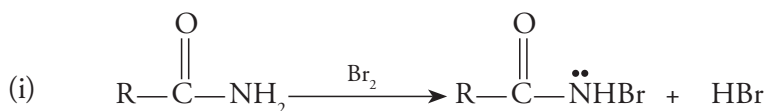
It is also known as Hofmann bromamide reaction. It involves the reaction of a primary amide with bromine in the presence of an alkali to yield primary amine with one carbon atom less than the parent amide.

This reaction is used for the preparation of primary amines.

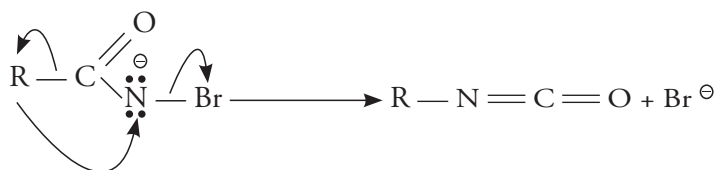


Mechanism

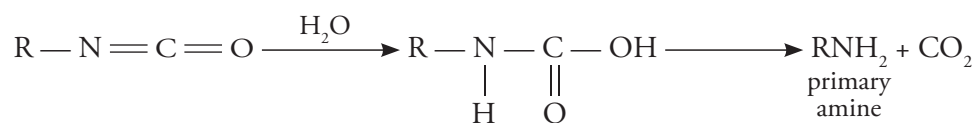
The reaction proceeds by the formation of intermediate nitrene followed by the migration alkyl group. Following steps are observed.



Steps (iii) and (iv) occur simultaneously, so that there occurs the loss of bromide ion and migration of alkyl group in the same step.

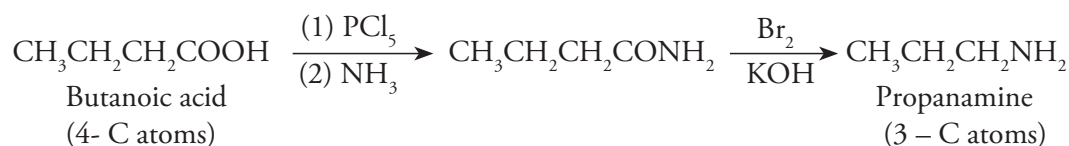


- (v) Hydrolysis of isocyanate takes place forming the primary amine.

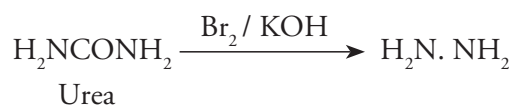
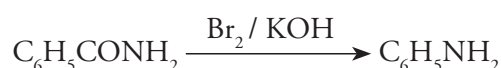
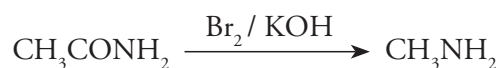


Applications

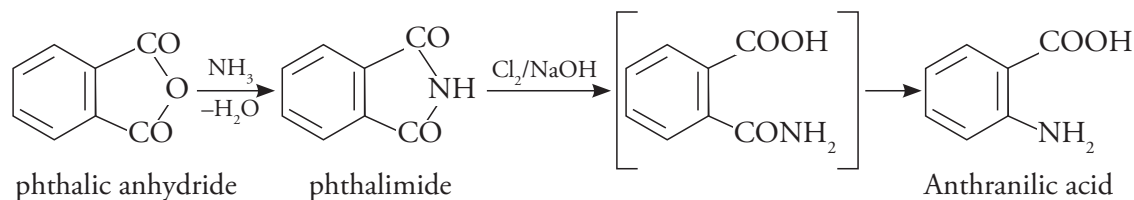
- (i) Hofmann reactions are used to step down the homologous series, that is, decrease the length of the carbon chain by one carbon atom.



- (ii) It is an important method for the preparation of primary amines.

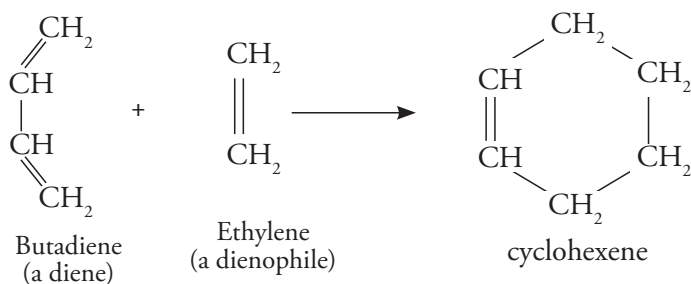


- (iii) **Preparation of aminoacids**

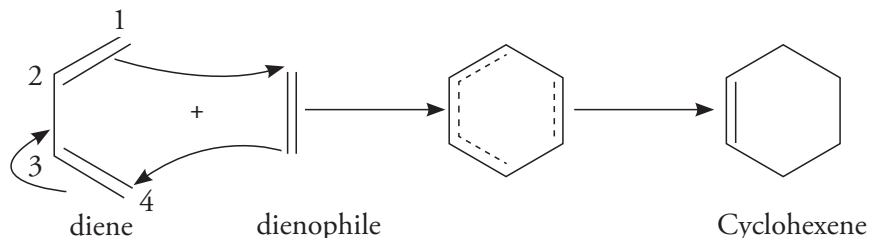


Diels–Alder Reaction

Diels–Alder reaction consists in addition of a conjugated diene to an unsaturated molecule called a dienophile, resulting in the formation of a six membered ring. The example is the reaction between butadiene and ethylene.



Diels–Alder reaction belongs to special class of reactions called pericyclic reactions, which are characterised by the making and breaking of two or more bonds in a single concerted step through cyclic transition states.

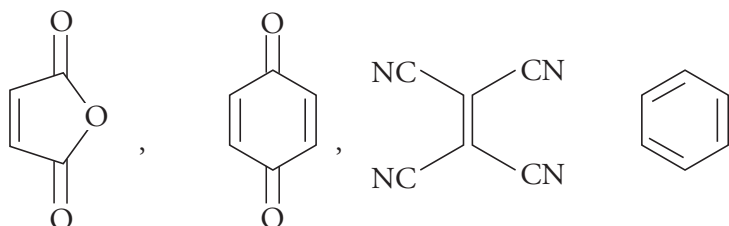


Since a cyclic product is formed via a cyclic transition state, these reactions are known as **cycloaddition reactions**. The above example involves addition between a 4π electron system (diene) and 2π electron system (dienophile), it is known as $[4 + 2]$ cycloaddition.

The rate of the above reaction is promoted by the presence of:

- Electron-donating groups in the diene (like $-\text{CH}_3$ groups).
- Electron-withdrawing groups on the dienophile or the alkene (like $-\text{CHO}$, $-\text{COOR}$, $-\text{NO}_2$, $-\text{CN}$, etc.)

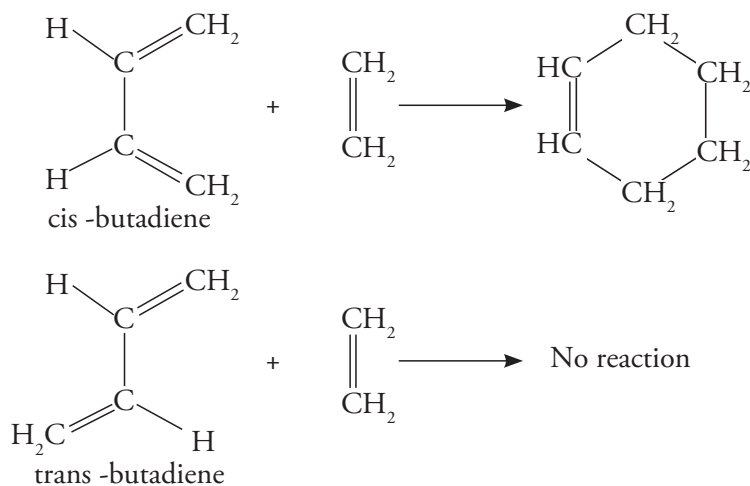
Reactive dienophiles are



Stereochemistry

The Diels–Alder reaction is stereospecific.

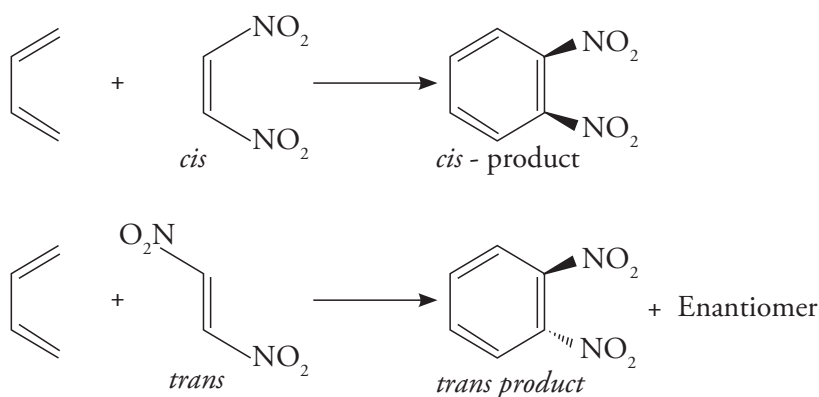
- The *cis* form of diene takes part in the reaction to form the adduct. The *trans* form cannot form the adduct.



Trans dienes where transformation to *cis* form is not possible do not undergo the reaction.



- (ii) The Diels Alder reaction is also *cis* with respect to the dienophile, that is, groups lying *cis* to each other in the dienophile also lie *cis* to each other in the adduct. If they are *trans* on the dienophile, they form the *trans* product.



19.11 Stereochemistry

Stereochemistry is defined as the part of chemistry which deals with the study of three dimensional arrangement of atoms in space. It also studies the influence of this arrangement on the physical and chemical properties of these compounds.

Compounds having similar structure and connectivity but differing in their three dimensional arrangement in space are called stereoisomers and the phenomenon is called stereoisomerism. There are three types of stereoisomerism.

- (i) Optical isomerism
- (ii) Geometrical isomerism
- (iii) Conformational isomerism

Optical Isomerism

It is a kind of stereoisomerism in which the isomers differ in the spatial arrangement of atoms or groups of atoms. Optical isomers have same physical properties but differ in their behaviour towards plane polarised light. Let us see what is plane polarised light?

Plane polarised light

A beam of ordinary light has waves vibrating in all planes at right angles to the line of propagation. When this light is passed through a nicol prism (a special type of prism made of crystalline calcium carbonate), the vibrations in all but one plane are cut off (Fig. 19.7). Hence, the nicol prism converts an ordinary light into a plane polarised light.