

Chapter 23

General Organic Chemistry

Carbon is an essential element of organic compounds, it has four electrons in its outer most shell.

According to the ground state electronic configuration of carbon, it is divalent. Tetravalency of carbon can be explained by promoting one of the $2s^2$ - electrons to the unoccupied $2p_{z,1}$ atomic orbital.

The four valencies of carbon atom are similar and they are symmetrically arranged around the carbon atom. According to **Le Bell and Van't Hoff** the four valencies of carbon do not lie in one plane. They are directed towards the corners of a regular tetrahedron with carbon atom at the centre and the angle between any two valencies is 109.28° .

Hybridisation in Organic Compounds

(i) The process of mixing atomic orbitals to form a set of new equivalent orbitals is termed as **hybridisation**. There are *three types* of hybridisation,

- (i) sp^3 **hybridisation** (involved in saturated organic compounds containing only single covalent bonds),
- (ii) sp^2 **hybridisation** (involved in organic compounds having carbon atoms linked by double bonds) and
- (iii) sp **hybridisation** (involved in organic compounds having carbon atoms linked by a triple bonds).

Table : 23.1

| Type of hybridisation | sp^3 | sp^2 | sp |
|-----------------------------|---------------|-----------------------------|---------------------------|
| Number of orbitals used | 1s and 3p | 1s and 2p | 1s and 1p |
| Number of unused p-orbitals | Nil | One | Two |
| Bond | Four σ | Three σ One π | Two σ Two π |
| Bond angle | 109.5° | 120° | 180° |
| Geometry | Tetrahedral | Trigonal planar | Linear |
| % s-character | 25 or 1/4 | 33.33 or 1/3 | 50 or 1/2 |

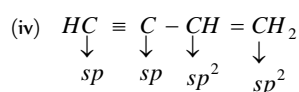
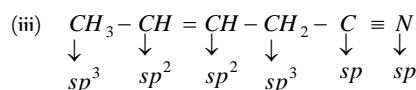
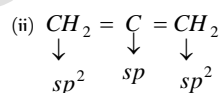
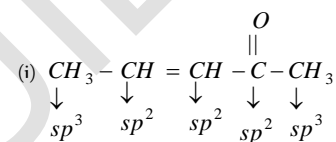
(2) **Determination of hybridisation at different carbon atoms** : It can be done by two methods,

(i) **First method** : In this method hybridisation can be know by the number of π - bonds present on that particular atom.

| Number of π - bond/s | 0 | 1 | 2 |
|--------------------------|---|---|---|
|--------------------------|---|---|---|

| Type of hybridisation | sp | sp | sp |
|-----------------------|------|------|------|
|-----------------------|------|------|------|

Examples :

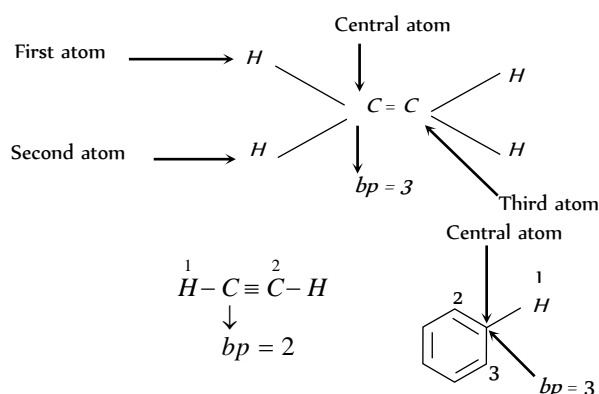


□ In diamond carbon is sp hybridised and in graphite carbon is sp^2 hybridised.

(ii) **Second method** : (Electron pair method)

$ep = bp + lp$; where ep = electron pair present in hybrid orbitals, bp = bond pair present in hybrid orbitals

Number of bp = Number of atoms attached to the central atom of the species



$$s > sp > sp^2 > sp^3 > p$$

% s-character and electronegativity in decreasing order.

(iii) **Bond length variation in hydrocarbons**

% of s orbital character

$$\propto \frac{1}{C-C \text{ bond length}} \propto \frac{1}{C-H \text{ bond length}}$$

Table : 23.2

| Bond type (C – H) | Bond length | Bond type (C – C) | Bond length |
|-------------------------|-------------|-------------------------|-------------|
| $sp^3 - s$ (alkanes) | 1.112 Å | $sp^3 - sp^3$ (alkanes) | 1.54 Å |
| $sp^2 - s$ (alkenes) | 1.103 Å | $sp^2 - sp^2$ (alkenes) | 1.34 Å |
| $sp - s$ (alkynes) | 1.08 Å | $sp - sp$ (alkynes) | 1.20 Å |

(iv) **Bond strength in hydrocarbons** : The shorter is the bond length, the greater is the compression between atomic nuclei and hence greater is the strength of that bond.

Table : 23.3

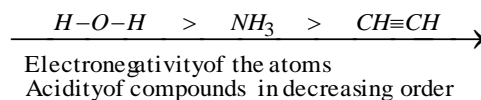
| Bond type (C – H) | Bond energy (kcal/mole) | Bond type (C – C) | Bond energy (kcal/mole) |
|----------------------------|-------------------------|-------------------------------|-------------------------|
| $sp^3 - s$ (in alkanes) | 104 | $sp^3 - sp^3$ (in alkanes) | 80 – 90 |
| $sp^2 - s$ (in alkenes) | 106 | $sp^2 - sp^2$ (in alkenes) | 122 – 164 |
| $sp - s$ (in alkynes) | 121 | $sp - sp$ (in alkynes) | 123 – 199 |

(v) **Acidity of hydrocarbons**

(a) Hydrogen present on electronegative carbon is acidic in nature.

(b) Acidity of hydrogen is directly proportional to the electronegativity of the atom on which hydrogen is present.

Thus



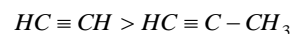
(c) Acidity of hydrocarbon \propto % of s-character

| | | | |
|---------------|----------------|---------------|---------------|
| | $CH \equiv CH$ | $CH_2 = CH_2$ | $CH_3 - CH_3$ |
| % s-character | 50 | 33.33 | 25 |
| pK_a | 25 | 44 | 50 |

s-character and acidity in decreasing order

$$\text{Acidity} \propto K_a \text{ and } \text{Acidity} \propto \frac{1}{pK_a} (pK_a = -\log K_a)$$

Order of acidic nature of alkynes is,



The relative acidic character follows the order;

Number of lp 's can be determined as follows,

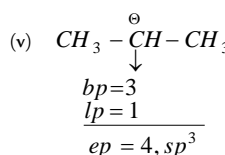
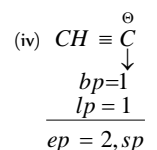
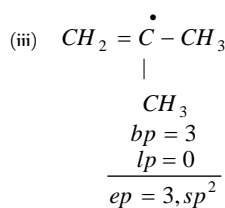
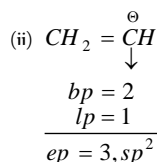
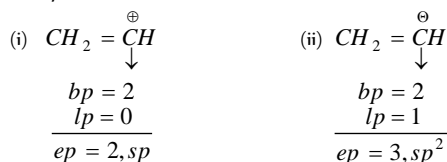
(a) If carbon has π - bonds or positive charge or odd electron, than lp on carbon will be zero.

(b) If carbon has negative charge, then lp will be equal to one.

Number of electron pairs (ep) tells us the type of hybridisation as follows,

| ep | 2 | 3 | 4 | 5 | 6 |
|-----------------------|------|--------|--------|---------|-----------|
| Type of hybridisation | sp | sp^2 | sp^3 | sp^3d | sp^3d^2 |

Example :



(3) **Applications of hybridisation**

(i) **Size of the hybrid orbitals** : Since s - orbitals are closer to the nucleus than p - orbitals, it is reasonable to expect that *greater the s character of an orbital the smaller it is*. Thus the decreasing order of the size of the three hybrid orbitals is opposite to that of the decreasing order of s orbital character in the three hybrid orbitals.

$$sp^3 > sp^2 > sp$$

(ii) **Electronegativity of different orbitals**

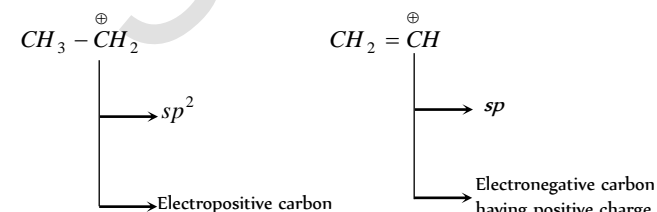
(a) Electronegativity of s -orbital is maximum.

(b) Electronegativity of hybrid orbital \propto % s -character in hybrid orbitals

| Orbital | sp | sp^2 | sp^3 |
|---------------|------|--------|--------|
| % s-character | 50 | 33.33 | 25 |

s-character in decreasing order and electronegativity in decreasing order

Thus sp -hybrid carbon is always electronegative in character and sp^3 - hybrid carbon is electropositive in character. sp^2 -hybrid carbon can behave as electropositive (in carbocation) as well as electronegative (in carbanion) in character.



(c) Electronegativities of different hybrid and unhybrid orbitals in decreasing order is as follows



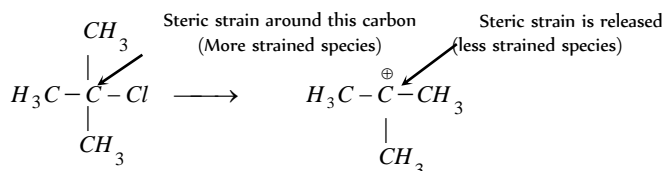
Obviously, the basic character of their conjugate bases follows the reverse order, i.e.,



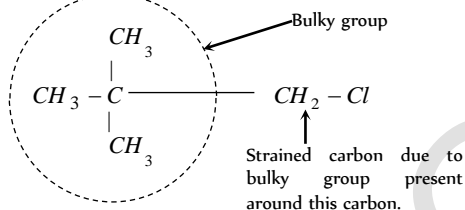
Steric effect

On account of the presence of bulkier groups at the reaction centre, they cause mechanical interference and with the result the attacking reagent finds it difficult to reach the reaction site and thus slows down the reaction. This phenomenon is called **steric hindrance** or **steric effect**.

(1) Tertiary alkyl halides having bulky groups form tertiary carbocation readily when hydrolysed because of the presence of the three bulky groups on the carbon having halogen.



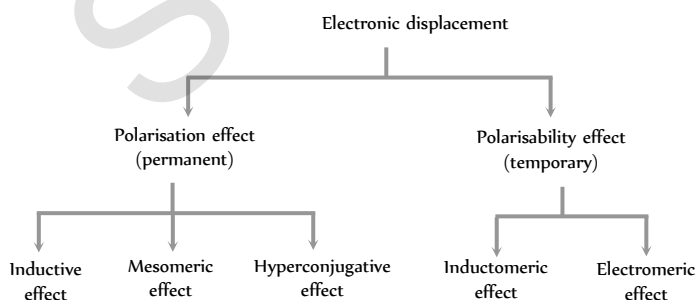
(2) Primary alkyl halide having quaternary β -carbon does not form transition state because of the steric strain around α -carbon by the β -carbon. To release the strain it converts into carbocation.



(3) Steric strain inhibits the resonance. This phenomenon is known as **steric inhibitions of resonance**.

Electronic displacement in covalent bonds

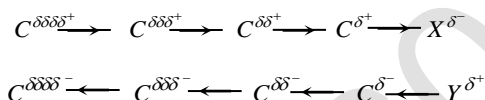
It is observed that most of the attacking reagents always possess either a positive or a negative charge, therefore for a reaction to take place on the covalent bond the latter must possess oppositely charged centres. This is made possible by displacement (partial or complete) of the bonding electrons. The electronic displacement in turn may be due to certain effects, some of which are **permanent** and others are **temporary**. The former effects are permanently operating in the molecule and are known as **polarisation effects**, while the latter are brought into play by the attacking reagent and as soon as the attacking reagent is removed, the electronic displacement disappears; such effects are known as the **polarisability effects**.



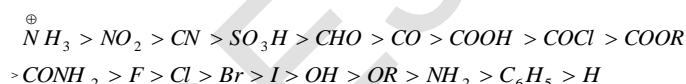
Inductive effect or Transmission effect

(1) When an electron withdrawing (X) or electron-releasing (Y) group is attached to a carbon chain, polarity is induced on the carbon atom and on the substituent attached to it. This permanent polarity is due to displacement of shared electron of a covalent bond towards a more electronegative atom. This is called **inductive effect** or simply as **I-effect**.

$C - C - C - C$ Non polar



(2) Carbon-hydrogen bond is taken as a standard of inductive effect. Zero effect is assumed for this bond. Atoms or groups which have a greater electron withdrawing capacity than hydrogen are said to have $-I$ effect whereas atoms or groups which have a greater electron releasing power are said to have $+I$ effect.

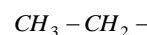
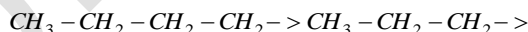


$-I$ power of groups in decreasing order with respect to the reference H

$ter. alkyl > sec. alkyl > pri. alkyl > CH_3 > H$

$+I$ power in decreasing order with respect to the reference H

$+I$ power \propto number of carbon in the same type of alkyl groups



$+I$ power in decreasing order in same type of alkyl groups

(3) Applications of Inductive effect

(i) **Magnitude of positive and negative charges**: Magnitude of $+ve$ charge on cations and magnitude of $-ve$ charge on anions can be compared by $+I$ or $-I$ groups present in it.

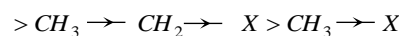
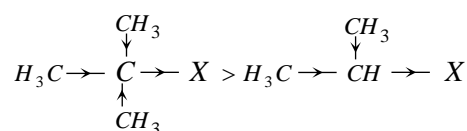
$$\bullet \text{ Magnitude of } +ve \text{ charge} \propto \frac{1}{+I \text{ power of the group}} \propto -I$$

power of the group.

$$\bullet \text{ Magnitude of } -ve \text{ charge} \propto \frac{1}{-I \text{ power of the group}} \propto +I$$

power of the group.

(ii) **Reactivity of alkyl halide**: $+I$ effect of methyl group enhances $-I$ effect of the halogen atom by repelling the electron towards tertiary carbon atom.

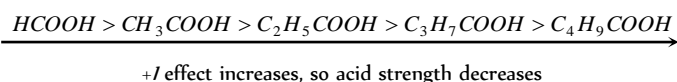


Tertiary > Secondary > Primary > Methyl

(iii) Relative strength of the acids:

(a) Any group or atom showing $+I$ effect decreases the acid strength as it increases the negative charge on the carboxylate ion which holds the hydrogen firmly. Alkyl groups have $+I$ effect.

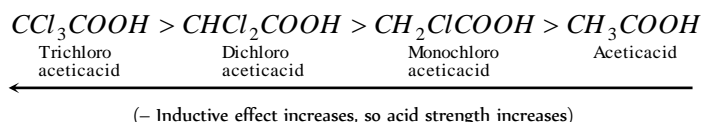
Thus, acidic nature is,



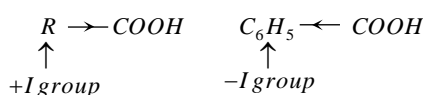
Formic acid, having no alkyl group, is the most acidic among these acids.

(b) The group or atom having $-I$ effect increases the acid strength as it decreases the negative charge on the carboxylate ion. Greater is the number of such atoms or groups (having $-I$ effect), greater is the acid strength.

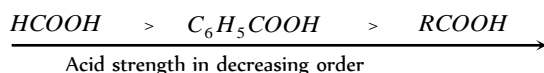
Thus, acidic nature is,



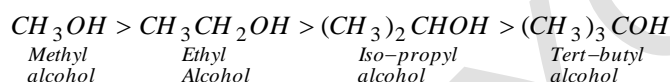
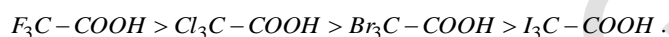
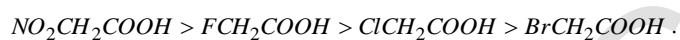
(c) Strength of aliphatic carboxylic acids and benzoic acid



Hence benzoic acid is stronger acid than aliphatic carboxylic acids but exception is formic acid. Thus,



□ Decreasing order of acids :



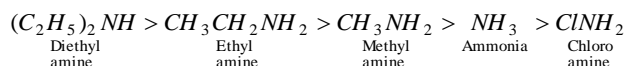
As compared to water, phenol is more acidic ($-I$ effect) but methyl alcohol is less acidic ($+I$ effect).



(vi) **Relative strength of the bases** (Basic nature of $-\text{NH}_2$)

The difference in base strength in various amines can be explained on the basis of inductive effect. The $+I$ effect increases the electron density while $-I$ effect decreases it. The amines are stronger bases than NH_3 as the alkyl groups increase electron density on nitrogen due to $+I$ effect while ClNH_2 is less basic due to $-I$ effect. "So more is the tendency to donate electron pair for coordination with proton, the more is basic nature, i.e., more is the negative charge on nitrogen atom (due to $+I$ effect of alkyl group), the more is basic nature".

Thus, the basic nature decreases in the order;



The order of basicity is as given below;

| Alkyl groups ($R-$) | Relative base strength |
|-----------------------|---|
| CH_3 | $\text{R}_2\text{NH} > \text{RNH}_2 > \text{R}_3\text{N} > \text{NH}_3$ |

| | |
|----------------------------|---|
| C_2H_5 | $\text{R}_2\text{NH} > \text{RNH}_2 > \text{NH}_3 > \text{R}_3\text{N}$ |
| $(\text{CH}_3)_2\text{CH}$ | $\text{RNH}_2 > \text{NH}_3 > \text{R}_2\text{NH} > \text{R}_3\text{N}$ |
| $(\text{CH}_3)_3\text{C}$ | $\text{NH}_3 > \text{RNH}_2 > \text{R}_2\text{NH} > \text{R}_3\text{N}$ |

□ The relative basic character of amines is not in total accordance with inductive effect ($t > s > p$) but it is in the following order: Secondary $>$ Primary $>$ Tertiary. The reason is the steric hindrance existing in the t -amines.

□ In gas phase or in aqueous solvents such as chlorobenzene etc, the solvation effect, i.e., the stabilization of the conjugate acid due to H -bonding are absent and hence in these media the basicity of amines depends only on the $+I$ effect of the alkyl group thus the basicity of amines follows the order : $3^\circ > 2^\circ > 1^\circ > \text{NH}_3$.

(vii) **Basicity of alcohols** : The decreasing order of base strength in alcohols is due to $+I$ effect of alkyl groups.



(viii) **Stability of carbonium ion** : $+I$ effect tends to decrease the (+ve) charge and $-I$ effect tends to increase the +ve charge on carbocation.



(ix) **Stability of carbanion** : Stability of carbanion increases with increasing $-I$ effect.



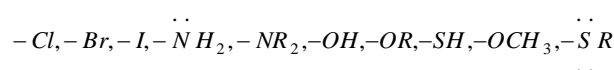
Resonance effect or mesomeric effect

(i) The effect in which π electrons are transferred from a multiple bond to an atom, or from a multiple bond to a single covalent bond or lone pair (s) of electrons from an atom to the adjacent single covalent bond is called **mesomeric effect** or simply as **M-effect**. In case of the compound with conjugated system of double bonds, the mesomeric effect is transmitted through whole of the conjugated system and thus the effect may better be known as **conjugative effect**.

(2) Groups which have the capacity to increase the electron density of the rest of the molecule are said to have $+M$ effect. Such groups possess lone pairs of electrons. Groups which decrease the electron density of the rest of the molecule by withdrawing electron pairs are said to have $-M$ effect, e.g.,

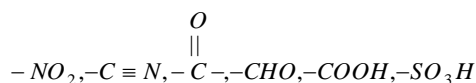
(a) The groups which donate electrons to the double bond or to a conjugated system are said to have $+M$ effect or $+R$ effect.

$+M$ effect groups :

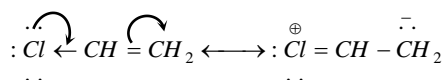


(b) The groups which withdraw electrons from the double bond or from a conjugated system towards itself due to resonance are said to have $-M$ effect or $-R$ effect.

$-M$ effect groups :



(3) The inductive and mesomeric effects, when present together, may act in the same direction or oppose each other. The mesomeric effect is more powerful than the former. For example, in vinyl chloride due to $-I$ effect the chlorine atom should develop a negative charge but on account of mesomeric effect it has positive charge.

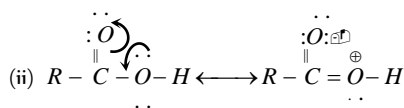
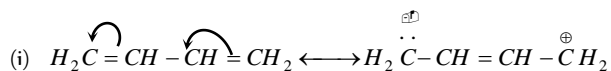


Application of mesomeric effect : It explains,

- (1) Low reactivity of aryl and vinyl halides,
- (2) The acidic nature of carboxylic acids,
- (3) Basic character comparison of ethylamine and aniline,
- (4) The stability of some free radicals, carbocations and carbanions.

Difference between Resonance and Mesomerism : Although both resonance and mesomerism represent the same phenomenon, they differ in the following respect : Resonance involves all types of electron displacements while mesomerism is noticeable only in those cases where a multiple bond is in conjugation with a multiple bond or lone pair of electron.

Example :



Both (i) and (ii) are the examples of mesomerism and resonance

effect. Let us consider the following example $\text{H}-\overset{\cdot\cdot}{\underset{\cdot\cdot}{\text{Cl}}} \longleftrightarrow \text{H}-\overset{\oplus}{\text{Cl}} \cdot$

Such an electron displacement is the example of resonance only (not the mesomerism).

Hyperconjugative effect

(1) When a $\text{H}-\text{C}$ bond is attached to an unsaturated system such as double bond or a benzene ring, the sigma (σ) electrons of the $\text{H}-\text{C}$ bond interact or enter into conjugation with the unsaturated system. *The interactions between the electrons of π systems (multiple bonds) and the adjacent σ bonds (single $\text{H}-\text{C}$ bonds) of the substituent groups in organic compounds is called hyperconjugation.* The concept of hyperconjugation was developed by Baker and Nathan and is also known as *Baker and Nathan effect*.

In fact hyperconjugation effect is similar to resonance effect. Since there is no bond between the α -carbon atom and one of the hydrogen atoms, the hyperconjugation is also called *no-bond resonance*.

(2) Structural requirements for hyperconjugation

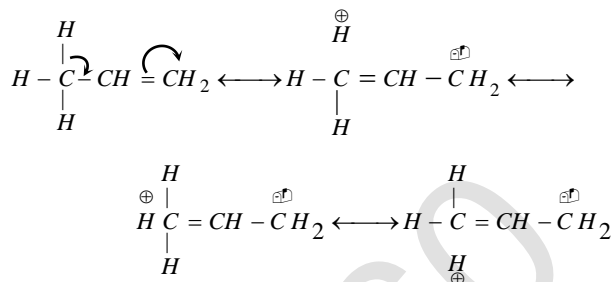
(i) Compound should have at least one sp^2 -hybrid carbon of either alkene alkyl carbocation or alkyl free radical.

(ii) α -carbon with respect to sp^2 hybrid carbon should have at least one hydrogen.

If both these conditions are fulfilled then hyperconjugation will take place in the molecule.

(iii) Hyperconjugation is of three types

(iv) Resonating structures due to hyperconjugation may be written involving "no bond" between the alpha carbon and hydrogen atoms.

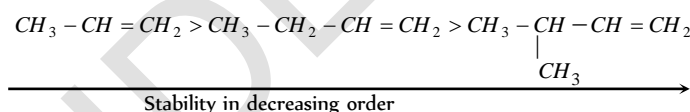


(v) Number of resonating structures due to the hyperconjugation = Number of α -hydrogens + 1.

Applications of hyperconjugation

(1) **Stability of alkenes :** Hyperconjugation explains the stability of certain alkenes over other alkenes.

Stability of alkenes \propto Number of alpha hydrogens \propto Number of resonating structures



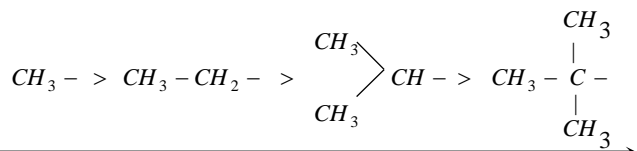
(2) **Carbon-carbon double bond length in alkenes :** As we know that the more is the number of resonating structures, the more will be single bond character in carbon-carbon double bond.

(3) **Stability of alkyl carbocations :** Stability of alkyl carbocations \propto number of resonating structures \propto number of alpha hydrogens.

(4) **Stability of alkyl free radicals :** Stability of alkyl free radicals can be explained by hyperconjugation. Stability depends on the number of resonating structures.

(5) **Electron releasing (or donating) power of R in alkyl benzene :** CH_3 - (or alkyl group) is +R group, ortho-para directing group and activating group for electrophilic aromatic substitution reaction because of the hyperconjugation.

The electron donating power of alkyl group will depend on the number of resonating structures, this depends on the number of hydrogens present on α -carbon. The electron releasing power of some groups are as follows,

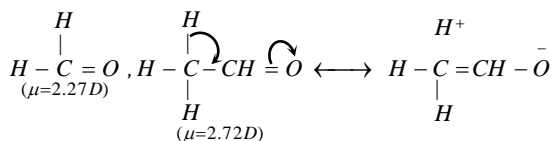



Electron donating power in decreasing order due to the hyperconjugation.

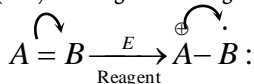
(6) **Heat of hydrogenation :** Hyperconjugation decreases the heat of hydrogenation.

(7) **Dipole moment :** Since hyperconjugation causes the development of charges, it also affects the dipole moment in the molecule.

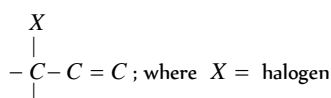
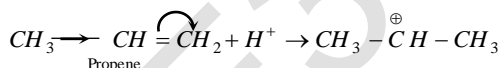
Electromeric effect



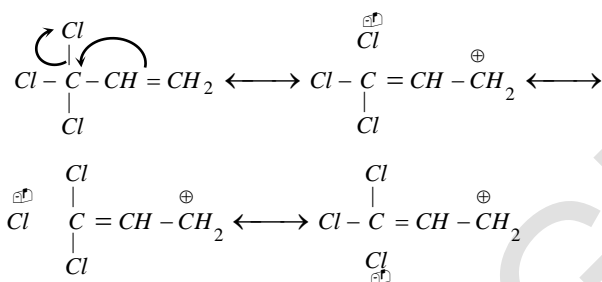
(i) The phenomenon of movement of electrons from one atom to another in multibonded atoms at the demand of attacking reagent is called electromeric effect. It is denoted as E-effect and represented by a curved arrow () showing the shifting of electron pair.



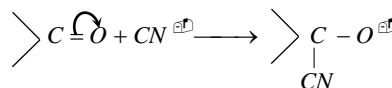
(2) (i) When the transfer of electrons take place towards the attacking reagent, the effect is called $+E$ effect. The addition of acids to alkenes.


$$\text{>C=C<} + \text{H}^{\oplus} \longrightarrow \text{>C}^+ - \underset{\text{H}}{\text{C}}\text{<}$$


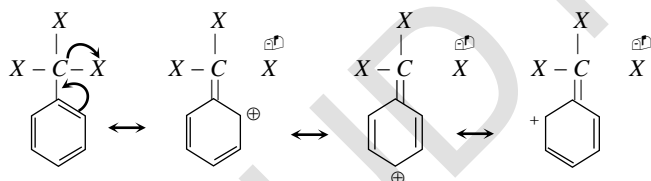
The attacking reagent is attached to that atom on which electrons have been transferred.



(ii) When the transfer of electrons takes place away from the attacking reagent, the effect is called $-E$ effect. Example, The addition of cyanide ion to carbonyl compounds.



(3) **Direction of the shift of electron pair :** The direction of the shift of electron pair can be decided on the basis of following points.

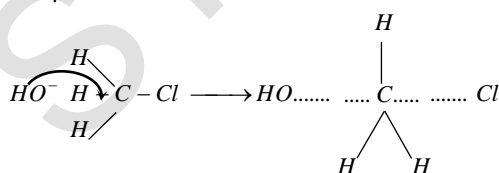


(ii) When the dissimilar groups are linked on the two ends of the double bond, the shift is decided by the direction of inductive effect.

Inductomeric effect

$$\text{>C=O} \xrightarrow{\text{H}^+} \text{>C}^+-\text{O}^- \text{H}^+$$

In cases where inductive effect and electromeric effect simultaneously operate, usually electrometric effect predominates.

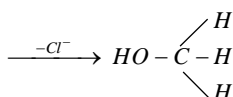


Cleavage (fission or breaking) of covalent bonds

(1) Homolytic bond fission or Homolysis

$$A \text{---} B \longrightarrow \dot{A} + \dot{B}$$

Free radical



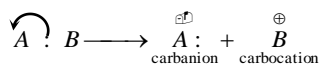
(ii) The factor which favours homolysis is that the difference in electronegativity between A and B is less or zero.

(iii) Homolysis takes place in gaseous phase or in the presence of non polar solvents (CCl_4, CS_2), peroxide, UV light, heat ($\geq 500^\circ C$), electricity and free radical.

(iv) Mechanism of the reaction in which homolysis takes place is known as homolytic mechanism or free radical mechanism.

(2) Heterolytic bond fission or heterolysis

(i) In heterolysis, the covalent bond is broken in such a way that one species (*i.e.*, less electronegative) is deprived of its own electron, while the other species gains both the electrons.



Thus formation of opposite charged species takes place. In case of organic compounds, if positive charge is present on the carbon then cation

is termed as **carbocation**. If negative charge is present on the carbon then anion is termed as **carbanion**.

(ii) The factor which favours heterolysis is greater difference of electronegativities between A and B .

(iii) Mechanism of the reaction in which heterolysis takes place is known as heterolytic mechanism or ionic mechanism.

(iv) The energy required for heterolysis is always greater than that for homolysis due to electrostatic forces of attraction between ions.

Reaction Intermediates

Short lived fragments called reaction intermediates result from homolytic and heterolytic bond fission. The important reaction intermediates are free radicals, carbocations, carbanions, carbenes, benzyne and nitrenes.

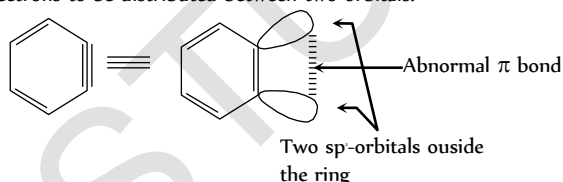
Table : 23.4

| Characteristic | Free radical | Carbocation | Carbanion | Carbene |
|-----------------|---|---|---|---|
| Nature | Neutral having odd electron | Positive charge on C | Negative charge on C | Neutral, divalent with 2 unshared electrons |
| Hybridisation | sp^2 | sp^2 | sp^3 (non-conjugated) sp^2 (Conjugated) | (i) sp^2 (singlet) (ii) sp (triplet) |
| Structure | Planar | Planar | Pyramidal/Planar | (i) Planar (singlet) (ii) Linear (triplet) |
| Magnetism | Paramagnetic | Diamagnetic | Diamagnetic | (i) Diamagnetic (ii) Paramagnetic |
| Stability order | $Ph_3\dot{C} > Ph_2\dot{C}H > Ph\dot{C}H_2 >$ $CH_2 = \dot{C}H - CH_2 > 3^\circ > 2^\circ >$ $1^\circ > \dot{C}H_2 > CH_2 = \dot{C}H$ | $Ph_3C^+ > Ph_2CH^+ > PhCH_2^+ >$ $CH_2 = CH - \dot{C}H_2^+ >$ $3^\circ > 2^\circ > 1^\circ > \dot{C}H_3$ | $Ph_3C^- > Ph_2CH^- >$ $PhCH_2^- > \text{Allyl}^- >$ $CH_2^- > 1^\circ > 2^\circ > 3^\circ$ | Triplet > singlet |

Benzyne

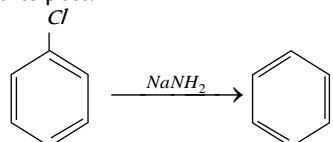
(1) 1, 2-Didehydrobenzene, C_6H_4 and its derivatives are called benzyne or arynes and the simplest member is benzyne.

(2) It is neutral reaction intermediate derived from benzene ring by removing two substituents, of *ortho* positions, one in the form of electrophile and other in the form of nucleophile leaving behind two electrons to be distributed between two orbitals.



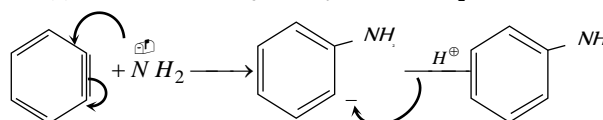
(3) Benzyne intermediate is aromatic in character.

(4) When halobenzene is heated with sodamide formation of benzyne takes place.



(5) (i) It behaves as dienophile and gives Diels-Alder reaction with diene.

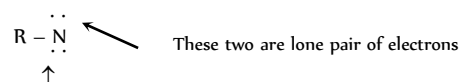
(ii) It reacts with strong nucleophile like NH_2



Nitrenes ($R - \ddot{N} :$)

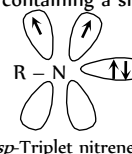
(1) The nitrogen analogues of carbenes are called nitrenes.

(2) There is possibility of two spin states for nitrenes depending on whether the two non-bonding electrons (the normal nitrogen lone pair remains paired) have their spins paired or parallel.



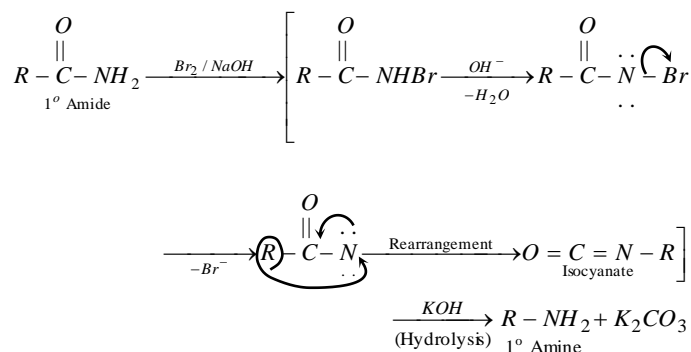
These two may be paired or unpaired

(3) In general nitrenes obey Hunds rule and the ground state triplet with two degenerate sp -orbitals containing a single electron each.

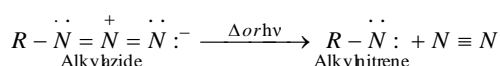


(4) Nitrenes can be generated, in situ, by the following methods,

(i) **By action of Br_2 in presence of a base on a 1° amide** (Hofmann-bromamide reaction),



(ii) **By decomposition of azides in presence of heat or light.**



(iii) Unsubstituted nitrene ($H - \ddot{N} :$) can be obtained by photolysis of (or by passing electric discharge through) NH_3 , N_2H_4 or N_3H .

Attacking reagents

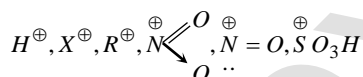
The fission of the substrate molecule to create centres of high or low electron density is influenced by attacking reagents. Most of the attacking reagents can be classified into two main groups.

Electrophiles or electrophilic reagents and Nucleophiles or nucleophilic reagents.

(i) **Electrophiles** : Electron deficient species or electron acceptor is an electrophile.

It can be classified into two categories :

(i) **Charged electrophiles** : Positively charged species in which central atom has incomplete octet is called charged electrophile.



All cations are charged electrophiles except cations of IA, IIA group elements, Al^{+++} and NH_4^+

(ii) **Neutral electrophiles** : It can be classified into three categories,

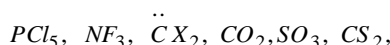
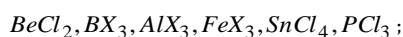
(a) Neutral covalent compound in which central atom has incomplete octet is neutral electrophile,



(b) Neutral covalent compound in which central atom has complete or expanded octet and central atom has unfilled d -sub-shell is neutral electrophile,



(c) Neutral covalent compound in which central atom is bonded only with two or more than two electronegative atoms is called neutral electrophile.

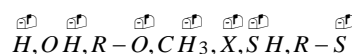


Cl_2 , Br_2 and I_2 also behave as neutral electrophiles.

Electrophiles are Lewis acids.

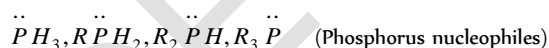
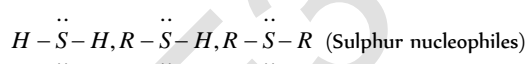
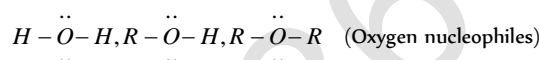
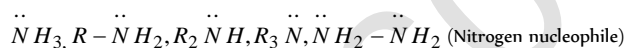
(2) **Nucleophiles** : Electron rich species or electron donors are called nucleophiles. Nucleophiles can be classified into three categories :

(i) **Charged nucleophiles** : Negatively charged species are called charged nucleophiles.



(ii) **Neutral nucleophiles** : It can be classified into two categories :

(a) Neutral covalent compound, in which central atom has complete octet, has at least one lone pair of electrons and all atoms present on central atom should not be electronegative, is neutral nucleophile.

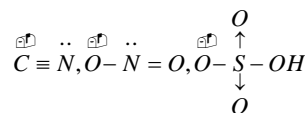


(b) Organic compound containing carbon, carbon multiple bond/bonds behaves as nucleophile.

Alkenes, Alkynes, Benzene,



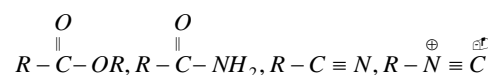
(iii) **Ambident nucleophiles** : Species having two nucleophilic centres out of which, one is neutral (complete octet and has at least one lone pair of electrons) and the other is charged (negative charge) behaves as ambident nucleophile



☐ Organometallic compounds are nucleophiles.

☐ Nucleophiles are Lewis bases.

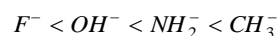
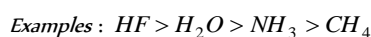
Organic compounds which behave as an electrophile as well as a nucleophile : Organic compound in which carbon is bonded with electronegative atom (O , N , S) by multiple bond/bonds behaves as electrophile as well as nucleophile :



☐ During the course of chemical reaction electrophile reacts with nucleophile.

☐ Strong Lewis acid is stronger electrophile

$CO_2 < N^+O_2 < S^+O_3H$. Stronger is an acid, weaker is its conjugated base or weaker is the nucleophile.



Increasing order of nucleophilicity.

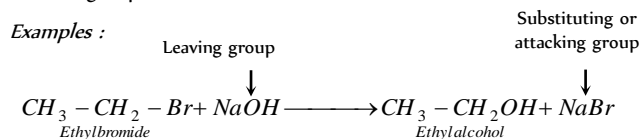
Types of organic reactions

It is convenient to classify the numerous reactions of the various classes of organic compound into four types,

- Substitution reactions,
- Addition reaction,
- Elimination reactions,
- Rearrangement reactions,

Substitution reactions

Replacement of an atom or group of the substrate by any other atom or group is known as substitution reactions.



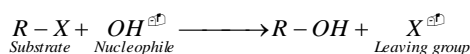
(Bromine atom is replaced by hydroxyl group)

Types of substitution reactions : On the basis of the nature of attacking species substitution reactions are classified into following three categories,

- (1) Nucleophilic substitution reactions
- (2) Electrophilic substitution reactions
- (3) Free radical substitution reactions

(1) Nucleophilic substitution reactions

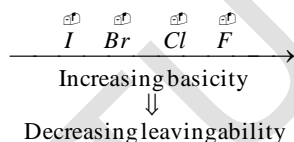
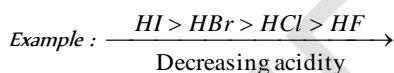
(i) Many substitution reactions, especially at the saturated carbon atom in aliphatic compounds such as alkyl halides, are brought about by nucleophilic reagents or nucleophiles.



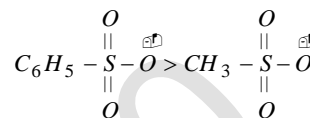
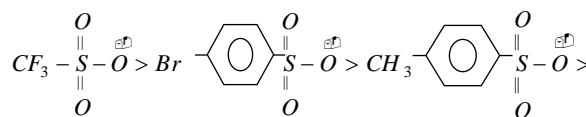
Such substitution reactions are called nucleophilic substitution reactions, i.e., S_N reactions (S stands for substitution and N for nucleophile).

(ii) The weaker the basicity of a group of the substrate, the better is its leaving ability.

$$\text{Leaving power of the group} \propto \frac{1}{\text{Basicity of the group}}$$



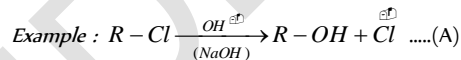
(iii) The leaving power of some nucleophilic groups are given below in decreasing order,



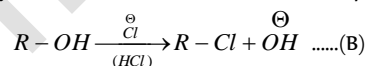
(iv) In these reactions leaving group of the substrate is replaced by another nucleophile. If reagent is neutral then leaving group is replaced by negative part of the reagent. Negative part of the reagent is always nucleophilic in character.



(v) In S_N reactions basicity of leaving group should be less than the basicity of incoming nucleophilic group. Thus strongly basic nucleophilic group replaces weakly basic nucleophilic group of the substrate.



Basicity of OH^- is more than Cl^- hence OH^- replaces Cl^- as Cl^- .



Basicity of Cl^- is less than OH^- , hence Cl^- will not replace OH^- as OH^- hence reaction (B) will not occur.

(vi) Unlike aliphatic compounds having nucleophilic group as leaving group, aromatic compounds having same group bonded directly with aromatic ring do not undergo nucleophilic substitution reaction under ordinary conditions.

The reason for this unusual reactivity is the presence of lone pair of electron or π bond on the key atom of the functional group. Another factor for the low reactivity is nucleophilic character of aromatic ring.

(vii) The S_N reactions are divided into two classes, S_N2 and S_N1 reactions.

Table : 23.5 Distinction between S_2 and S_1 reactions

| Factors | S_2 Reactions | S_1 Reactions |
|-------------------------|---|---|
| Number of steps | One: $\text{R} : \text{L} + \text{Nu}^- \rightarrow \text{R} : \text{Nu} + \text{L}^-$ | Two: (i) $\text{R} : \text{L} \xrightarrow{\text{Slow}} \text{R}^+ + \text{L}^-$ (ii) $\text{R}^+ + \text{Nu}^- \xrightarrow{\text{Fast}} \text{R} : \text{Nu}$ |
| Reaction rate and order | Second order: Rate $\propto [\text{Substrate}] [\text{Nucleophile}]$ or Rate $= K_2 [\text{RL}] [\text{Nu}^-]$ | First order: Rate $\propto [\text{Substrate}]$ or Rate $= K_1 [\text{RL}]$ |
| Molecularity | Bimolecular | Unimolecular |
| TS of slow step | $\delta^- : \text{Nu} \cdots \text{C} \cdots \text{L} : \delta^-$ | $\delta^+ : \text{Nu} \cdots \text{C} \cdots \text{L} \cdots \text{Nu} : \delta^-$ |
| Reacting nucleophile | The nucleophile attacks the carbon of the substrate exclusively from the back side. | The nucleophile can attack the carbon of the substrate both from the back and front sides although the back side attack |

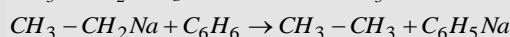
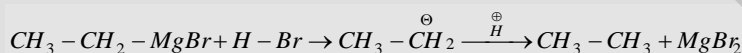
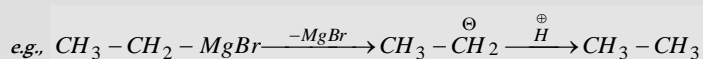
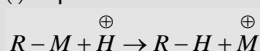
| | | |
|-----------------------------------|--|---|
| | | predominates. |
| Stereochemistry | Complete inversion of configuration takes place. | Inversion and retention takes place. |
| Reactivity order of alkyl halides | Methyl > 1° > 2° > 3° halides. ($I > Br > Cl > F$) | 3° > 2° > 1° > methyl halides. ($I > Br > Cl > F$) |
| Rearrangement | No rearranged product is formed (except for allylic). | Rearranged products can be formed. |
| Nature of nucleophiles | Favoured by strong and high concentration of nucleophiles. | Favoured by mild and low concentration of nucleophiles. |
| Polarity | Favoured by solvents of low polarity. | Favoured by solvents of high polarity. |
| Reaction rate determining factor | By steric hindrance. | By electronic factor (stability of R^{\oplus}). |
| Catalysis | Not catalysed by any catalyst (phase transfer). | Catalysed by Lewis and Bronsted acids, e.g., Ag^{\oplus} , $AlCl_3$, $ZnCl_2$ and strong HA. |

(2) **Electrophilic substitutions reactions** : Electrophilic substitution involves the attack by an electrophile. It is represented as S_E (S stands for substitution and E stands for electrophile). If the order of reaction is 1, it is

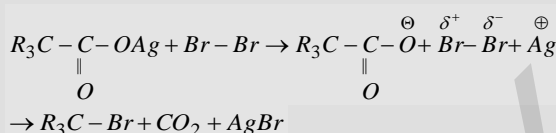
written as S_{E1} (unimolecular) and if the order is 2, it is S_{E2} (Bimolecular).

S_E Reaction mechanism : Electrophilic substitution in aliphatic compounds are very rare; some of the important examples are:

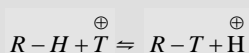
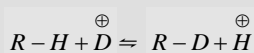
(i) Replacement of the metal atom in an organometallic compound by hydrogen :



(ii) Decarboxylation of silver salt of carboxylic acid by means of bromine:



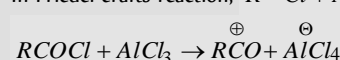
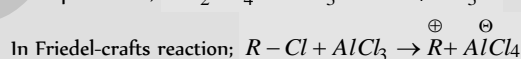
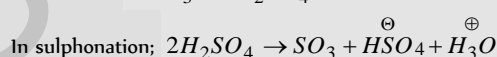
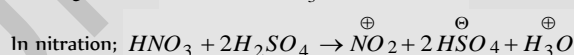
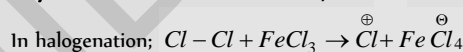
(iii) Isotopic exchange of hydrogen for deuterium or tritium:



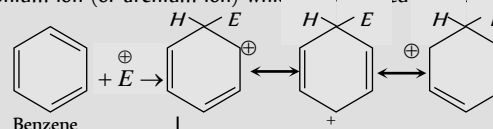
S_E Reaction mechanism : Electrophilic substitution is very common in benzene nucleus (aromatic compounds) in which π -electrons are highly delocalized and an electrophile can attack this region of high electron density.

In all electrophilic aromatic substitution reactions, it involves:

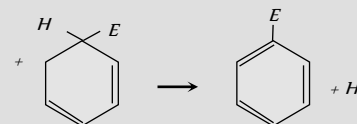
Step 1. The formation of an electrophile, E^{\oplus} , i.e.,



Step 2. The electrophile attacks the aromatic ring to form carbonium ion (or arenium ion) which is in resonance.



Step 3. Carbonium ion loses the proton to form substitution product.

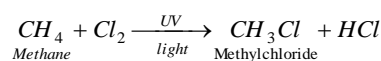


The bromination of benzene in the presence of $FeBr_3$ is an example of electrophilic substitution reaction.

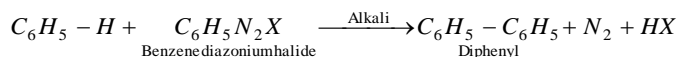
Similarly, Nitration, sulphonation and Friedel-Crafts reaction, etc., in benzene nucleus are the other examples of electrophilic substitution reactions.

(3) **Free radical substitution reactions** : Free radical substitution reactions involve the attack by a free radical. These reactions occur by a free radical mechanism which involves Initiation, Propagation and Termination steps. *Examples,*

(i) **Chlorination of methane** : The chlorination of methane in the presence of ultraviolet light is an example of free radical substitution.

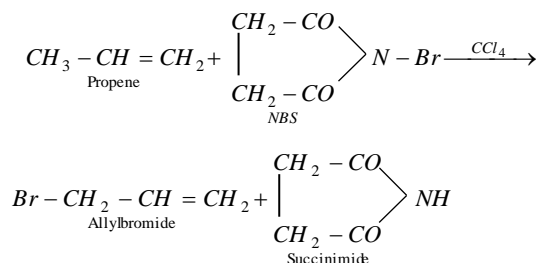


(ii) **Arylation of aromatic compounds** (Gomberg reaction) : The reaction of benzene diazonium halide with benzene gives diphenyl by a free radical substitution reaction.



(iii) **Wurtz reaction** : Ethyl bromide on treatment with metallic sodium forms butane, ethane and ethylene by involving free radical mechanism.

(iv) **Allylic bromination by NBS** (*N*-Bromosuccinimide) : NBS is a selective brominating agent and it normally brominates the ethylenic compounds in the allylic ($CH_2 = CH - CH_2 -$) position. This type of reaction involving substitution at the alpha carbon atom with respect to the double bond is termed Allylic substitution. It is also used for benzylic bromination. Some examples are:



Addition reactions

These reactions are given by those compounds which have at least one π bond,

i.e., ($>C=C<$, $-C \equiv C-$, $-C \equiv N$). In such reaction there is loss of one π bond and gain of two σ bonds. Thus product of the reaction is generally more stable than the reactant. The reaction is a spontaneous reaction.

Types of addition reactions : Addition reactions can be classified into three categories on the basis of the nature of initiating species.

- (1) Electrophilic additions
- (2) Nucleophilic additions
- (3) Free radical additions

(i) Electrophilic addition reactions

- (i) Such reactions are mainly given by alkenes and alkynes.
- (ii) Electrophilic addition reactions of alkenes and alkynes are generally two step reactions.
- (iii) Alkenes and alkynes give electrophilic addition with those reagents which on dissociation gives electrophile as well as nucleophile.
- (iv) If the reagent is a weak acid then electrophilic addition is catalysed by strong acids (Generally H_2SO_4).

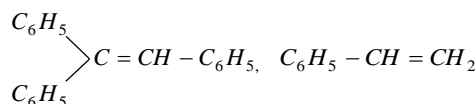
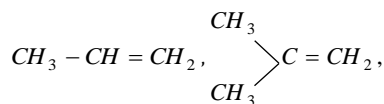
(v) Unsymmetrical alkenes and alkynes give addition reactions with unsymmetrical reagents according to Markownikoff's rule.

The negative part of the addendum adds on that doubly bonded carbon of the alkene which has least number of hydrogen atom.

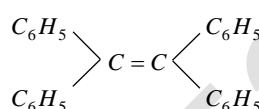
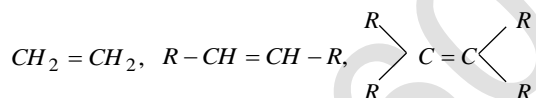
This rule can be used only in those alkenes which fulfil the following conditions:

- (a) Alkene should be unsymmetrical.
- (b) Substituent/substituents present on doubly bonded carbon/(s) should only be $+I$ group.
- (c) If phenyl group is present on doubly bonded carbon, then both doubly bonded carbons should be substituted by phenyl groups.

For example, the following alkenes will give addition according to the Markownikoff's rule.

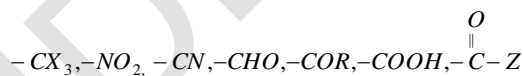


Following alkenes will not give addition reaction according to Markownikoff's rule.



(vi) Unsymmetrical alkenes having the following general structure give addition according to anti Markownikoff's rule.

$CH_2=CH-G$, where G is a strong $-I$ group such as

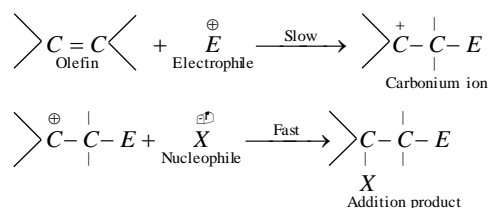


($Z = Cl, OH, OR, NH_2$)

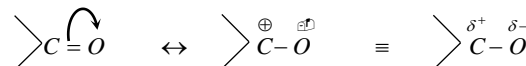
Example:



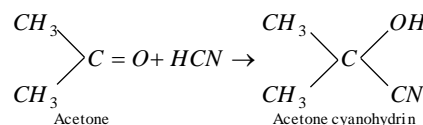
(vii) Mechanism of electrophilic addition reactions is as follows,



(2) **Nucleophilic addition reactions** : When the addition reaction occurs on account of the initial attack of nucleophile, the reaction is said to be a nucleophilic addition reaction. Due to presence of strongly electronegative oxygen atom, the π -electrons of the carbon-oxygen double bond in carbonyl group ($C=O$) get shifted towards the oxygen atom and thereby such bond is highly polarised. This makes carbon atom of the carbonyl group electron deficient.

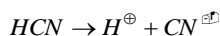


Example : The addition of HCN to acetone is an example of nucleophilic addition.

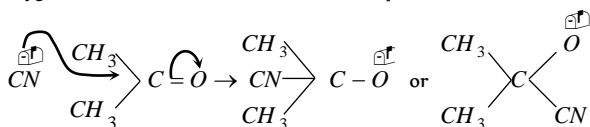


The mechanism of the reaction involves the following steps:

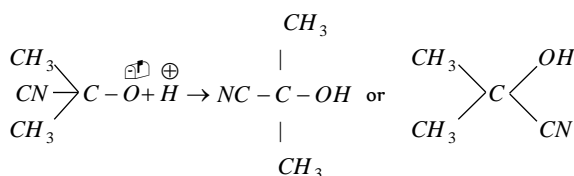
Step 1. HCN gives a proton (H) and a nucleophile, cyanide ion (CN^-).



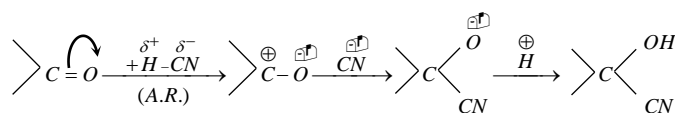
Step 2. The nucleophile (CN^{\ominus}) attacks the positively charged carbon so as to form an anion [H^{\oplus} does not initiate the negatively charged oxygen as anion is more stable than cation].



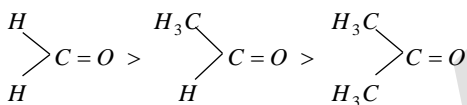
Step 3. The proton (H^+) combines with anion to form the addition product.



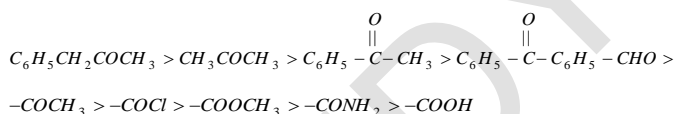
In $>C=O$ compounds, the addition of liquid HCN gives cyanohydrin and the addendum is CN^- ion and not HCN directly (addition is catalysed by bases or salts of weak acids and retarded by acids or unaffected by neutral compounds).



Nucleophilic addition (A) reactions on carbonyl compounds will be in order:



Decreasing order of nucleophilic addition in some species.

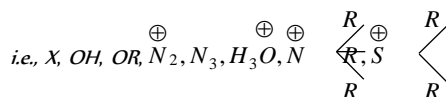


(3) **Free radical addition reactions** : Those reactions which involve the initial attack by a free radical are known as free radical reactions. Addition of hydrogen bromide to alkenes (say, propylene) in the presence of peroxide (radical initiator) follows free radical mechanism. Free radical reactions generally take place in non-polar solvents such as CCl_4 , high temperature, in presence of light or a free radical producing substance like O_2 and peroxides.

Elimination reactions

Elimination reactions are formally the reverse of addition reactions and involve the removal of the two groups (Generally, one being a proton) from one or two carbon atoms of a molecule to form an unsaturated linkage or centre.

Elimination reaction is given by those compounds which have a nucleophilic group as leaving group,

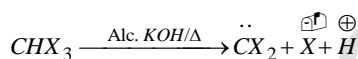


Elimination reactions are generally endothermic and take place on heating.

Elimination reactions are classified into two general types,

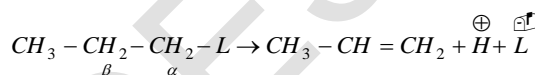
- (I) α -elimination reactions or 1, 1-elimination reactions.
- (II) β -elimination reaction or 1, 2-elimination reactions.

(I) **α -elimination reactions or 1,1-elimination reactions**: A reaction in which both the groups or atoms are removed from the same carbon of the molecule is called α -elimination reaction. This reaction is mainly given by gem dihalides and gem trihalides having at least one α -hydrogen.



Product of the reaction is halocarbenes or dihalocarbenes, which are key intermediates in a wide variety of chemical and photochemical reactions.

(II) **β -elimination reactions or 1, 2-elimination reactions**: Consider the following reactions,

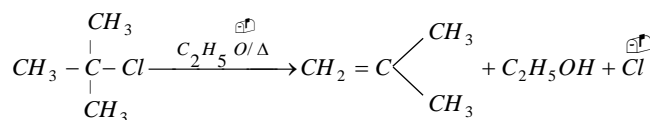


A reaction in which functional group (*i.e.*, leaving group) is removed from α -carbon and other group (Generally hydrogen atom) from the β -carbon is called β -elimination reaction. In this reaction there is loss of two σ bonds and gain of one π bond. Product of the reaction is generally less stable than the reactant.

(I) **Types of β -elimination reactions** : In analogy with substitution reactions, β -elimination reactions are divided into three types:

(i) E_i (Elimination unimolecular) reaction, (ii) E_c (Elimination bimolecular) reaction and (iii) E_{cb} (Elimination unimolecular conjugate base) reaction

(i) **E_i (Elimination unimolecular) reaction** : Consider the following reaction,



(a) Reaction velocity depends only on the concentration of the substrate; thus reaction is unimolecular reaction.

$$\text{Rate} \propto [\text{Substrate}]$$

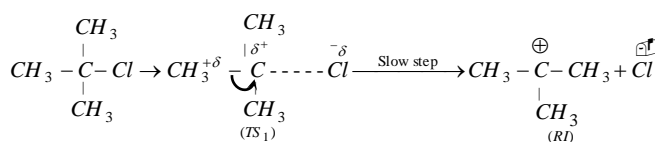
(b) Product formation takes place by the formation of carbocation as reaction intermediate (R^+).

(c) Since reaction intermediate is carbocation, rearrangement is possible in E reaction.

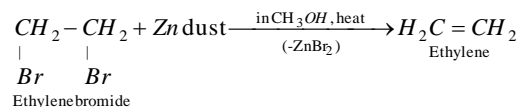
(d) Reaction is carried out in the presence of polar protic solvent.

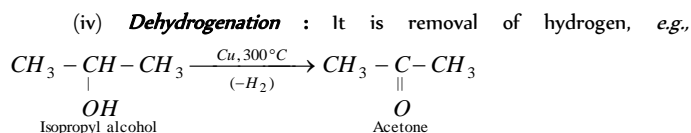
(e) The E reaction occurs in two steps,

Step 1.



Step 2.



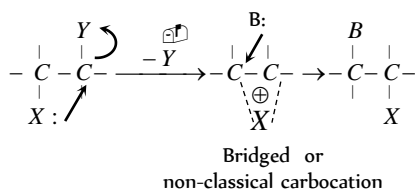


Rearrangement reactions

The reactions, which involve the migration of an atom or group from one site to another within the molecule (nothing is added from outside and nothing is eliminated) resulting in a new molecular structure, are known as rearrangement reactions. The new compound is actually the structural isomer of the original one.

It is convenient to divide rearrangement reactions into following types:

(1) **Rearrangement or migration to electron deficient atoms** (Nucleophilic rearrangement) : Those rearrangement reactions in which migrating group is nucleophilic and thus migrates to electron deficient centre which may be carbon, nitrogen and oxygen.

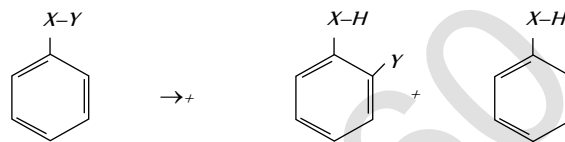


X = Nucleophilic species, Y = Electronegative group, B = Another nucleophile.

(2) **Rearrangement or migration to electron rich atoms** (Electrophilic rearrangement) : Those rearrangement reactions in which migrating group is electrophile and thus migrates to electron rich centre.

(3) **Rearrangement or migration to free radical species** (Free radical rearrangement) : Those rearrangement reactions in which the migrating group moves to a free radical centre. Free radical rearrangements are comparatively rare.

(4) **Aromatic rearrangement** : Those rearrangement reactions in which the migrating group moves to aromatic nucleus. Aromatic compounds of the type (I) undergo rearrangements in the manner mentioned below,



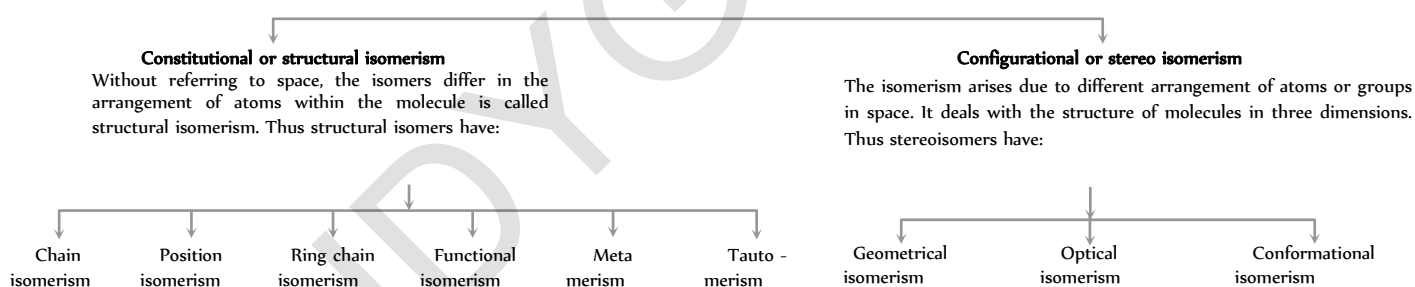
The element X from which group Y migrates may be nitrogen or oxygen.

Isomerism

Organic compounds having same molecular formula but differing from each other at least in some physical or chemical properties or both are known as isomers (Berzelius) and the phenomenon is known as isomerism.

The difference in properties of isomers is due to the difference in the relative arrangements of various atoms or groups present in their molecules. Isomerism can be classified as follows:

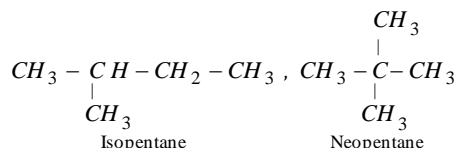
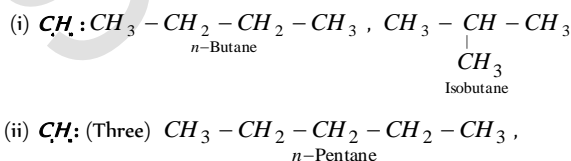
Isomerism



Constitutional or structural isomerism

(i) **Chain, nuclear or skeleton isomerism** : This type of isomerism arises due to the difference in the nature of the carbon chain (i.e., straight or branched) which forms the nucleus of the molecule.

Examples :



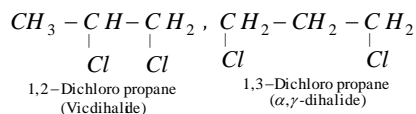
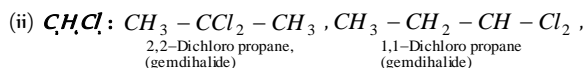
❑ Except alkynes chain isomerism is observed when the number of carbon atoms is four or more than four.

❑ Chain isomers differ in the nature of carbon chain, i.e., in the length of carbon chain.

❑ The isomers showing chain isomerism belong to the same homologous series, i.e., functional group, class of the compound (Cyclic or open) remains unchanged.

❑ Chain and position isomerism cannot be possible together between two isomeric compounds. If two compounds are chain isomers then these two will not be positional isomers.

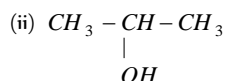
(2) **Position isomerism** : It is due to the difference in the position of the substituent atom or group or an unsaturated linkage in the same carbon chain.



☐ Aldehydes, carboxylic acids (and their derivatives) and cyanides do not show position isomerism.

☐ Monosubstituted alicyclic compounds and aromatic compounds do not show position isomerism.

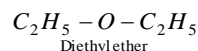
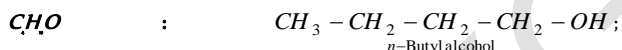
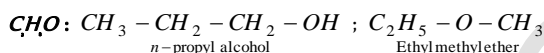
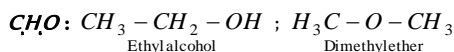
☐ Structural isomers which differ in the position of the functional group are called regiomers. For example, (i) $\text{CH}_3 - \text{CH}_2 - \text{CH}_2 - \text{OH}$



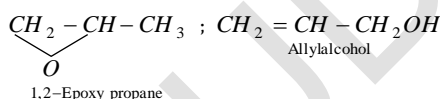
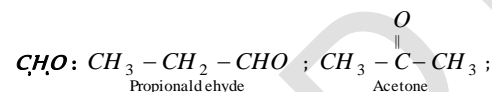
(3) **Functional isomerism** : This type of isomerism is due to difference in the nature of functional group present in the isomers. The following pairs of compounds always form functional isomers with each other.

Examples :

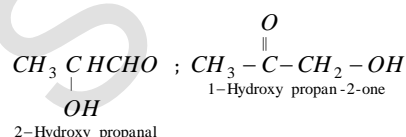
(i) **Alcohols and ethers ($\text{C}_2\text{H}_6\text{O}$)**



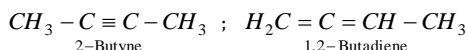
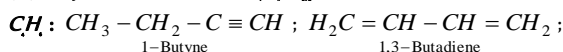
(ii) **Aldehydes, ketones and unsaturated alcohols ...etc. ($\text{C}_3\text{H}_6\text{O}$)**



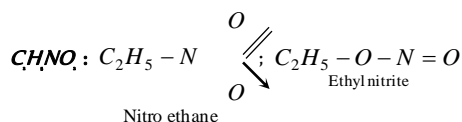
(iii) **Acids, esters and hydroxy carbonyl compounds ...etc. ($\text{C}_3\text{H}_6\text{O}_2$)**



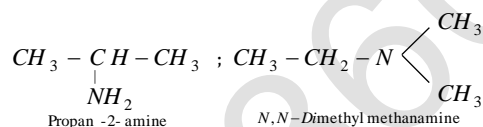
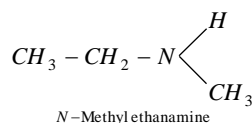
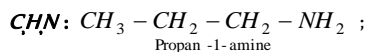
(iv) **Alkynes and alkadienes (C_4H_6)**



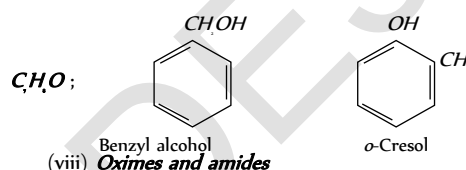
(v) **Nitro alkanes and alkyl nitrites ($-\text{NO}_2$ and $-\text{O} - \text{N} = \text{O}$)**



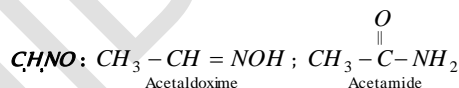
(vi) **Amines** (Primary, secondary and tertiary)



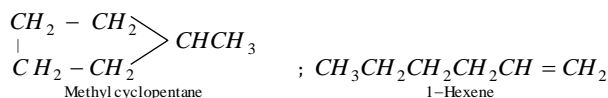
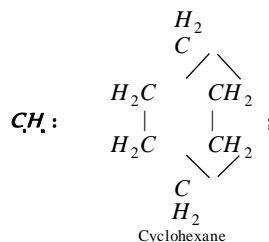
(vii) **Alcohols and phenols**



(viii) **Oximes and amides**

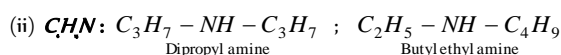
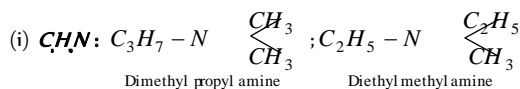


(4) **Ring-chain isomerism** : This type of isomerism is due to different modes of linking of carbon atoms, i.e., the isomers possess either open chain or closed chain structures.

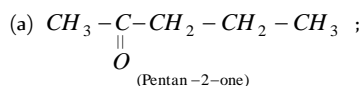


☐ Ring - chain isomers are always functional isomers.

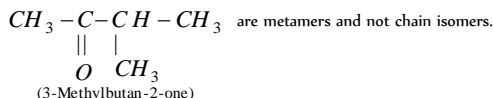
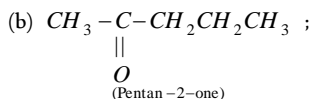
(5) **Metamerism** : This type of isomerism is due to the difference in the nature of alkyl groups attached to the polyvalent atoms or functional group. Metamers always belong to the same homologous series. Compounds like ethers, thio-ethers ketones, secondary amines, etc. show metamerism.



☐ If same polyvalent functional group is there in two or more organic compounds, then chain or position isomerism is not possible, there will be metamerism e.g.,



$CH_3CH_2-C(=O)-CH_2CH_3$ are metamers and not position isomers.
(Pentan-3-one)



☐ Alkenes does not show metamerism.

(6) Tautomerism

(i) The type of isomerism in which a substance exist in two readily interconvertible different structures leading to dynamic equilibrium is known as tautomerism and the different forms are called **tautomers** (or tautomerides).

The term **tautomerism** (Greek: *tauto* = same; *meros* = parts) was used by **Laar** in 1885 to describe the phenomenon of a substance reacting chemically according to two possible structures.

(ii) It is caused by the wandering of hydrogen atom between two polyvalent atoms. It is also known as **Desmotropism** (Desmos = bond and tropos = turn). If the hydrogen atom oscillates between two polyvalent atoms linked together, the system is a **dyad** and if the hydrogen atom travels from first to third atom in a chain, the system is a **triad**.

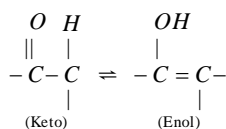
(a) **Dyad system** : Hydrocyanic acid is an example of dyad system in which hydrogen atom oscillates between carbon and nitrogen



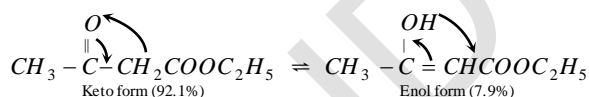
(b) **Triad system**

Keto-enol system : Polyvalent atoms are oxygen and two carbon atoms.

Examples :

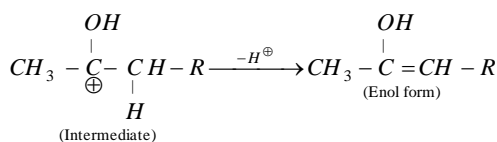
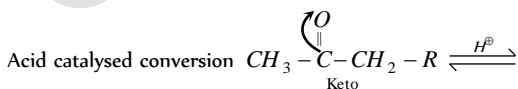
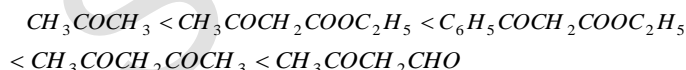


Acetoacetic ester (Ethyl acetoacetate) :

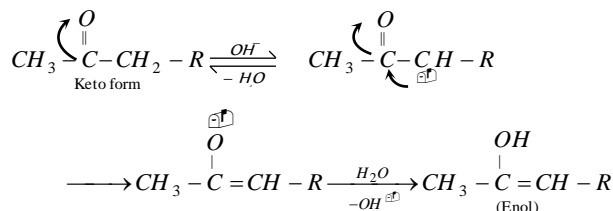


Acetoacetic ester gives certain reactions showing the presence of keto group (Reactions with HCN , H_2NOH , $H_2NNHC_6H_5$, etc.) and certain reactions showing the presence of enolic group (Reactions with Na , CH_3COCl , NH_3 , PCl_5 , Br_2 water and colour with neutral $FeCl_3$, etc.).

Enolisation is in order

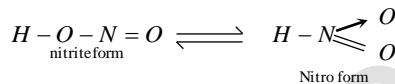


Base catalysed conversion



(c) Triad system containing nitrogen : Examples

Nitrous acid exists in 2 forms



Nitro acinitro system



(iii) **Characteristics of tautomerism**

(a) Tautomerism (cantonotropy) is caused by the oscillation of hydrogen atom between two polyvalent atoms present in the molecule. The change is accompanied by the necessary rearrangement of single and double bonds.

(b) It is a reversible intramolecular change.

(c) The tautomeric forms remain in dynamic equilibrium. Hence, their separation is a bit difficult. Although their separation can be done by special methods, yet they form a separate series of stable derivatives.

(d) The two tautomeric forms differ in their stability. The less stable form is called the labile form. The relative proportion of two forms varies from compound to compound and also with temperature, solvent etc. The change of one form into another is also catalysed by acids and bases.

(e) Tautomers are in dynamic equilibrium with each other and interconvertible (\rightleftharpoons).

(f) Two tautomers have different functional groups.

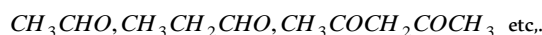
(g) Tautomerism has no effect on bond length.

(h) Tautomerism has no contribution in stabilising the molecule and does not lower its energy.

(i) Tautomerism may occur in planar or nonplanar molecules.

☐ Keto-enol tautomerism is exhibited only by such aldehydes and ketones which contain at least one α -hydrogen.

For example



☐ Tautomerism is not possible in benzaldehyde (C_6H_5CHO), benzophenone ($C_6H_5COC_6H_5$), tri methyl acetaldehyde, $(CH_3)_3C-CHO$ and chloral CCl_3-CHO as they do not have $\alpha-H$.

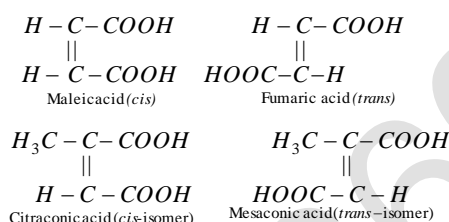
Number of structural isomers

| Molecular formula | Number of isomers |
|-------------------|-------------------|
| Alkanes | |
| C_4H_{10} | Two |
| C_5H_{12} | Three |
| C_6H_{14} | Five |
| C_7H_{16} | Nine |
| C_8H_{18} | Eighteen |
| C_9H_{20} | Thirty five |

| | |
|--|---|
| $C_{10}H_{22}$ | Seventy five |
| Alkenes and cycloalkanes | |
| C_3H_6 | Two (One alkene + one cycloalkane) |
| C_4H_8 | Six (Four alkene + 2 - cycloalkane) |
| C_5H_{10} | Nine (Five alkenes + 4 - cycloalkanes) |
| Alkynes | |
| C_3H_4 | Two |
| C_4H_6 | Six |
| Monohalides | |
| C_3H_7X | Two |
| C_4H_9X | Four |
| $C_5H_{11}X$ | Eight |
| Dihalides | |
| $C_2H_4X_2$ | Two |
| $C_3H_6X_2$ | Four |
| $C_4H_8X_2$ | Nine |
| $C_5H_{10}X_2$ | Twenty one |
| Alcohols and ethers | |
| C_2H_6O | Two (One alcohol and one ether) |
| C_3H_8O | Three (Two alcohols and one ether) |
| $C_4H_{10}O$ | Seven (Four alcohols and three ethers) |
| $C_5H_{12}O$ | Fourteen (Eight alcohols and six ethers) |
| Aldehydes and ketones | |
| C_3H_6O | Two (One aldehyde and one ketone) |
| C_4H_8O | Three (Two aldehydes and one ketone) |
| $C_5H_{10}O$ | Seven (Four aldehydes and three ketone) |
| Monocarboxylic acids and esters | |
| $C_2H_4O_2$ | Two (One acid and one ester) |
| $C_3H_6O_2$ | Three (One acid and two esters) |
| $C_4H_8O_2$ | Six (Two acids and four esters) |
| $C_5H_{10}O_2$ | Thirteen (Four acids and nine esters) |
| Aliphatic amines | |
| C_2H_7N | Two (One 1°-amine and one 2°-amine) |
| C_3H_9N | Four (Two 1°-amines, one 2°-amine and one 3°-amine) |
| $C_4H_{11}N$ | Eight (Four 1°-amines, three 2°-amines and one 3°-amines) |
| Aromatic compounds | |
| C_8H_{10} | Four |
| C_9H_{12} | Nine |
| C_7H_8O | Five |

The compounds which have same molecular formula but differ in the relative spatial arrangement of atoms or groups in space are known as geometrical isomers and the phenomenon is known as geometrical isomerism. The isomer in which same groups or atoms are on the same side of the double bond is known as *cis* form and the isomer in which same groups or atoms are on the opposite side is called *trans*-isomer.


Examples :

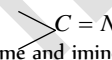


(i) **Conditions for geometrical isomerism** : Compound will show geometrical isomerism if it fulfils the following two conditions

(i) There should be frozen rotation about two adjacent atoms in the molecule.

(a)  frozen rotation about carbon, carbon double bond in alkenes.

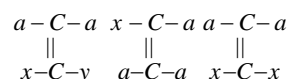
(b)  frozen rotation about carbon, carbon single bond in cycloalkanes.

(c)  frozen rotation about carbon, nitrogen double bond in oxime and imine.

(ii) Both substituents on each carbon should be different about which rotation is frozen.

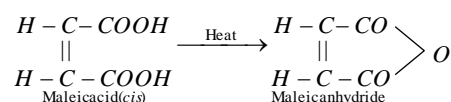
If these two conditions are fulfilled, then compound will show geometrical isomerism.

☐ The compounds of the following type will not show geometrical isomerism.

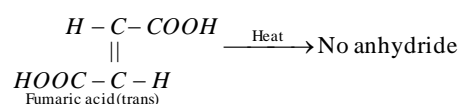


(2) **Distinction between *cis*- and *trans*- isomers**

(i) **By cyclization method** : Generally, the *cis*-isomer (e.g. maleic acid) cyclises on heating to form the corresponding anhydride while the *trans*-isomer does not form its anhydride.



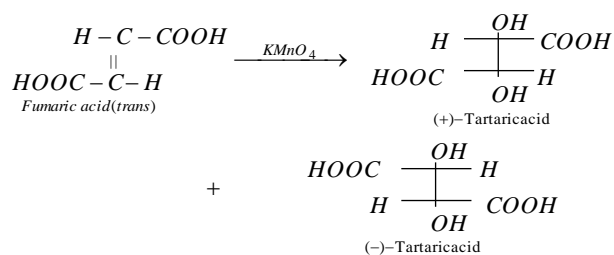
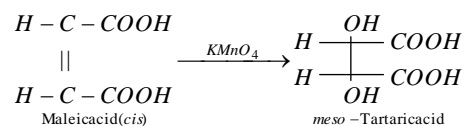
☐ Note that the two reacting groups ($-COOH$) are near to each other.



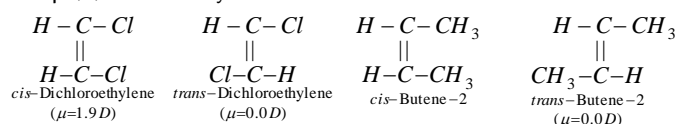
☐ Note that the two reacting groups ($-COOH$) are quite apart from each other, hence cyclisation is not possible.

(ii) **By hydroxylation** (Oxidation by means of $KMnO_4$, OsO_4 or H_2O_2 in presence of OsO_4) : Oxidation (Hydroxylation) of alkenes by means of these reagents proceeds in the *cis*-manner. Thus the two geometrical isomers of an alkene leads to different products by these reagents. For example,

Geometrical or cis-trans isomerism



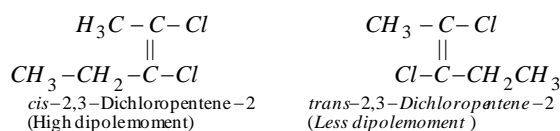
(iii) **By studying their dipole moments** : The *cis*-isomer of a symmetrical alkene (Alkenes in which both the carbon atoms have similar groups) has a definite dipole moment, while the *trans*-isomer has either zero dipole moment or less dipole moment than the *cis*-isomer. For example, 1,2-dichloroethylene and butene-2.



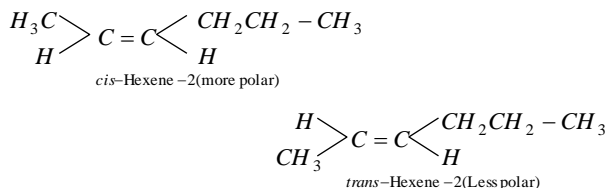
In *trans*-isomer of the symmetrical alkenes, the effect produced in one half of the molecule is cancelled by that in the other half of the molecule.

In case of unsymmetrical alkenes, the *cis*-isomer has higher dipole moment than the corresponding *trans*-isomer.

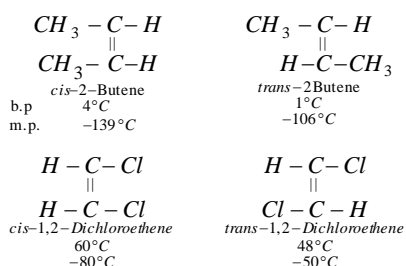
For Example,



Similar is the case with hexene-2.



(iv) **By studying other physical properties.** (a) The *cis*-isomer of a compound has higher boiling point due to higher polarity, higher density and higher refractive index than the corresponding *trans*-isomer (*Auwers-skita rule*).



(b) The *trans*-isomer has higher melting point than the *cis*-isomer due to symmetrical nature and more close packing of the *trans*-isomer.

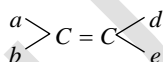
(v) **Stability:** *Trans*-isomer is more stable than *cis*-isomer due to symmetrical structure.

□ *Terminal alkenes such as propene, 1-butene and 2-methylpropene do not show geometrical isomerism.*

□ *Cis-trans isomers are configurational isomers but not mirror images, hence cis and trans isomers are always diastereomers.*

□ *Non-terminal alkenes with the same atoms or groups either on one or both the carbon atoms of the double bond such as 2-methyl-2-butene, 2,3-dimethyl-2-butene etc. do not show geometrical isomerism.*

(3) **E and Z system of nomenclature:** 'Cis' and 'Trans' designations cannot be used if four different atoms or groups are attached to the carbon atoms of a double bond.

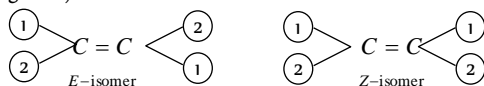


In such cases, *E* and *Z* system of nomenclature is used. This system is based on a priority system developed by *Cahn, Ingold and Prelog*.

In this system, the two atoms or groups attached to each of the doubly bonded carbon are put in order of preference on the basis of sequence rules.

The symbol '*E*' is assigned to an isomer in which the atoms or groups of higher preference are on the opposite side (*E* from German word *Entgegen* = across or opposite).

The symbol '*Z*' is assigned to an isomer in which the atoms or groups of higher preference are on the same side (*Z* from German word, *Zusammen* = together).



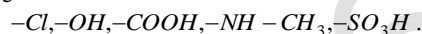
□ 1 signifies higher preference and 2 signifies lower preference. Preference in most of the cases '*Z*' corresponds to *cis*-form and '*E*' to *trans*-form. However, there are many exceptions.

The following rules are followed for deciding the precedence order of the atoms or groups;

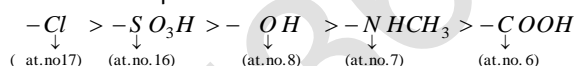
(i) Higher priority is assigned to the atoms of higher atomic number. For example, the order of preference in the following atoms, *H, Cl, I, Br* is: *I* (at. no. 53) > *Br* (at. no. 35) > *Cl* (at. no. 17) > *H* (at. no. 1).

(ii) If isotopes of the same element are attached, the isotope with higher mass number is given higher order of preference. For example, deuterium (${}^2_1\text{D}$) is assigned higher priority in comparison to hydrogen (${}^1_1\text{H}$).

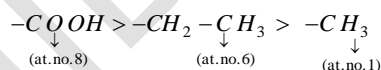
(iii) In the groups, the order of preference is also decided on the basis of atomic number of first atom of the group. For example, in the following set,



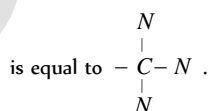
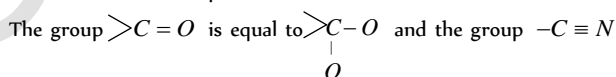
The order of the precedence is:



When the order of preference of the groups cannot be settled on the first atom, the second atom or the subsequent atoms in the groups are considered. For example, in the set $-\text{CH}_2-\text{CH}_3, -\text{CH}_3, -\text{COOH}$, the order cannot be decided on the basis of first atom as it is same in all the groups. However, in $-\text{CH}_2-\text{CH}_3$, the second atom is carbon, in $-\text{CH}_3$, the second atom is hydrogen while in $-\text{COOH}$, the second atom is oxygen. Hence, the order of preference is:



(iv) A doubly or triply bonded atom is considered equivalent to two or three such atoms. For example,



is equal to $-\text{C}-\text{N}$.

(4) Number of geometrical isomers in polyenes

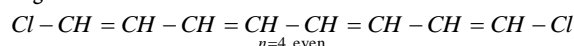
(i) When a compound has *n* double bonds and ends of a polyene are different, the number of geometrical isomers = 2^n



The given compound has four double bonds and the two ends are different (One is C_6H_5 and other is Cl). Therefore, number of geometrical isomers = $2^n = 2^4 = 16$.

(ii) When the ends of polyene are same.

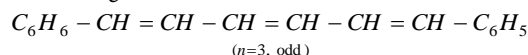
Case I: When number of double bonds (=n) is even then the number of geometrical isomers = $2^{n-1} + 2^{[(n/2)-1]}$



Number of geometrical isomers = $2^{n-1} + 2^{(n/2)-1} = 2^3 + 2^1 = 8 + 2 = 10$.

Case II: When number of double bonds (=n) is odd.

Number of geometrical isomers = $2^{n-1} + 2^{\left[\frac{n+1}{2}\right]-1}$



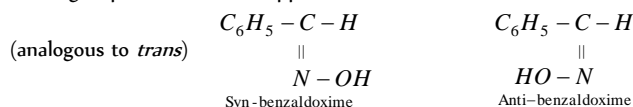
Number of geometrical isomers = $2^2 + 2^{2-1} = 2^2 + 2^1 = 4 + 2 = 6$.

(5) Geometrical Isomerism in nitrogen compounds

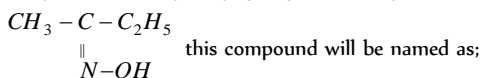
(i) Geometrical isomerism due to $C=N$ bond.

The important class of compounds exhibiting geometrical isomerism due to $C=N$ bond are oximes, nitrones, hydrazones and semicarbazones. But the most common compound is oxime.

Oximes : In aldoxime, when hydrogen and hydroxyl groups are on the same side, the isomer is known as syn. (analogous to *cis*) and when these groups are on the opposite side, the isomer is known as anti (analogous to *trans*)



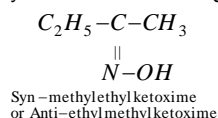
In ketoximes the prefixes **syn** and **anti** indicate which group of ketoxime is syn or anti to hydroxyl group. For example:



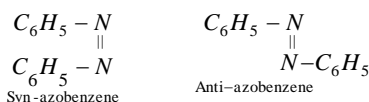
(a) Syn-ethyl methyl ketoxime \Rightarrow *HO* and C_2H_5 are syn or

(b) Anti-methyl ethyl ketoxime \Rightarrow *HO* and C_2H_5 are anti.

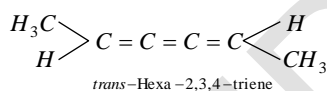
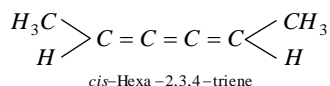
Similarly consider the following structure



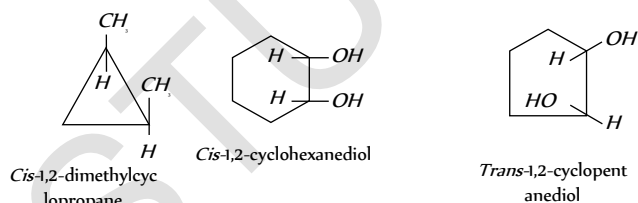
(ii) Geometrical isomerism due to $N=N$ bond.



(6) **Geometrical isomerism show by cumulatienes** : Cumulatienes (Trienes with three adjacent double bonds) show only geometric isomerism. This is because their molecule is planar, as such the terminal $-CH_3$ groups and H - atoms lie in the same plane. Therefore, in this case their planar structure can exist in two diastereoisomeric forms, *cis*- and *trans*- but no enantiomeric forms are possible.



(7) **Geometrical isomerism in cycloalkanes** : Disubstituted cycloalkanes show geometrical isomerism.



Certain compounds show geometrical as well optical isomerism. Such type of isomerism is known as **geometrical enantiomerism**.

Optical isomerism

(i) Compounds having similar physical and chemical properties but they have the ability to rotate the plane of polarised light either to the right (Clockwise) or to the left (Anticlockwise) are termed as optically active or optical isomers and the property is called optical activity or optical isomerism.

The optical activity was first observed in organic substances like quartz, rock-crystals and crystals of potassium chlorate ($KClO_3$), potassium bromate ($KBrO_3$) and sodium periodate ($NaIO_4$).

(2) **Measurement of optical activity** : The measurement of optical activity is done in terms of *specific rotation which is defined as the rotation produced by a solution of length of 10 centimetres (One decimetre) and unit concentration (1 g/mL) for the given wavelength of the light at the given temperature.*

$$\text{Specific rotation, } [\alpha]_{\text{wavelength}}^{t^\circ C} = \frac{\alpha_{\text{obs}}}{l \times C}$$

Where α_{obs} is the rotation observed, l is the length of the solution in decimeters and C is the number of grams in 1 mL of solution. The specific rotation of the sucrose at $20^\circ C$ using sodium light (D -line, $\lambda=5893\text{\AA}$) is $+66.5^\circ C$ and is denoted as: $[\alpha]_D^{20^\circ C} = +66.5^\circ C (C = 0.02 \text{ g/mL water})$

+ sign indicates the rotation in clockwise direction.

(3) On the basis of the study of optical activity, the various organic compounds were divided into four types :

(i) The optical isomer which rotates the plane of the polarised light to the right (Clockwise) is known as dextrorotatory isomer (Latin: *dextro* = *right*) or *d*-form or indicated by +ve sign.

(ii) The optical isomer which rotates the plane of the polarised light to the left (Anticlockwise) is known as laevorotatory isomer (Latin; *laevo* = *left*) or *l*-form or indicated by -ve sign.

(iii) The optical powers of the above two isomers are equal in magnitude but opposite in sign. An equimolar mixture of the two forms, therefore, will be optically inactive due to external compensation. This mixture is termed as racemic mixture or *dl*-form or (\pm) mixture.

(iv) Optical isomer with a plane of symmetry is called *meso* form. It is optically inactive due to internal compensation, i.e., the rotation caused by upper half part of molecule is neutralised by lower half part of molecule.

(4) **Chirality, (i) Definition** : A molecule (or an object) is said to be chiral or dissymmetric, if it does not possess any element of symmetry and not superimposable on its mirror image and this property of the molecule to show non-superimposability is called chirality.

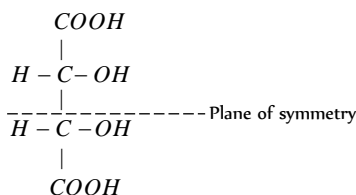
On the other hand, a molecule (or an object) which is superimposable on its mirror image is called achiral (non-dissymmetric or symmetric).

To understand the term chiral and achiral let us consider the alphabet letters 'P' and 'A' whereas 'P' is chiral, 'A' is achiral as shown in fig.

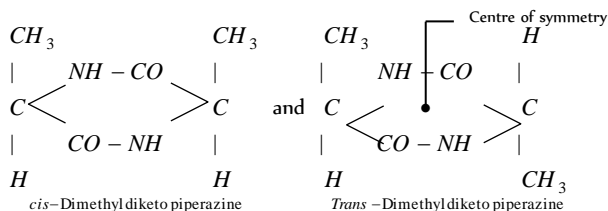


(ii) **Elements of symmetry** : There are three elements of symmetry,

(a) **Plane of symmetry** : It may be defined as a plane which divides a molecule in two equal parts that are related to each other as an object and mirror image. e.g.,

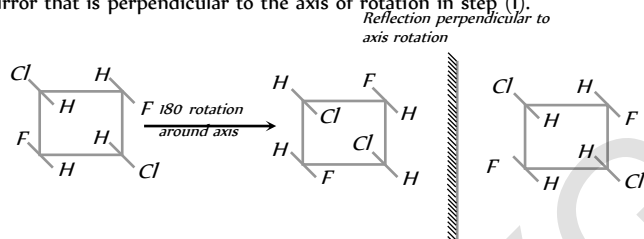


(b) **Centre of symmetry** : It may be defined as a point in the molecule through which if a line is drawn in one direction and extended to equal distance in opposite direction, it meets another similar group or atom, eg.



Since *trans* form contains a centre of symmetry, it is optically inactive.

(c) **Alternating axis of symmetry** : A molecule is said to possess an alternating axis of symmetry if an orientation indistinguishable from the original is obtained when molecule is rotated Q degree around an axis passing through the molecule and the rotated molecule is reflected in a mirror that is perpendicular to the axis of rotation in step (1).

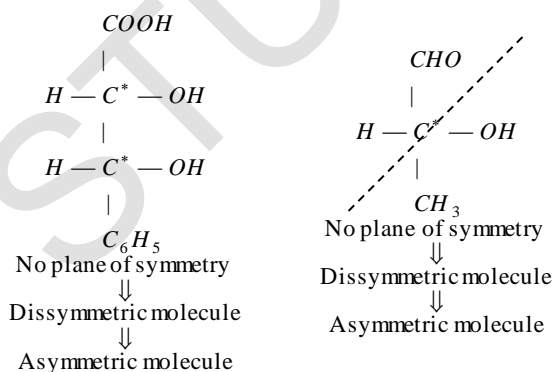


(iii) Symmetric, Asymmetric and Dissymmetric molecules

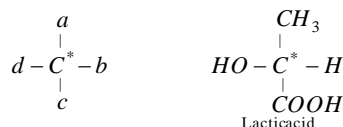
(a) **Symmetric molecules** : If any symmetry is present in the molecule then molecule will be symmetric molecule.

(b) **Dissymmetric molecules** : Molecule will be a dissymmetric molecule if it has no plane of symmetry, no centre of symmetry and no alternating axis of symmetry.

(c) **Asymmetric molecules** : Dissymmetric molecule having at least one asymmetric carbon is known as asymmetric molecule. All asymmetric molecules are also dissymmetric molecules but the reverse is not necessarily true.

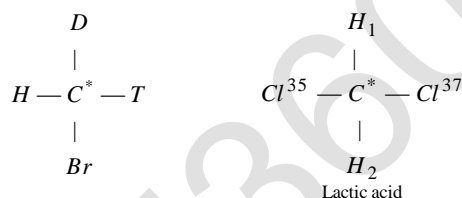


(iv) **Chiral or asymmetric carbon atom** : A carbon bonded to four different groups is called a chiral carbon or a chirality centre. The chirality centre is indicated by asterisk. eg.,



☐ Carbons that can be chirality centres are sp^3 -hybridised carbons; sp^2 and sp -hybridised carbons cannot be chiral carbons because they cannot have four group attached to them.

☐ Isotopes of an atom behave as different group in stereoisomerism.



☐ Carbon of the following groups will not be a chiral carbon



☐ Maleic acid ($\text{HOOC} - \text{CH} = \text{CH} - \text{COOH}$) show geometrical isomerism while malic acid

($\text{HOOC} - \text{CH}_2 - \text{CHOH} - \text{COOH}$) show optical isomerism.

(5) Calculation of number of optical isomers

(i) If molecule is not divisible into two identical halves and molecule has n asymmetric carbon atoms then

$$\text{Number of optically active forms} = 2^n = a$$

$$\text{Number of enantiomeric pair} = a / 2$$

$$\text{Number of racemic mixture} = a / 2$$

$$\text{Number of meso form} = 0$$

(ii) If molecule is divisible into two identical halves, then the number of configurational isomers depends on the number of asymmetric carbon atoms.

Case I : When compound has even number of carbon atoms, i.e., $n = 2, 4, 8, 10, 12, \dots$:

$$(i) \text{ Number of optically active forms} = a = 2^{n-1}$$

$$(ii) \text{ Number of enantiomeric pairs} = a / 2$$

$$(iii) \text{ Number of racemic mixture} = a / 2$$

$$(iv) \text{ Number of meso forms} = m = 2^{(n/2)-1}$$

$$(v) \text{ Total number of configurational isomers} = a + m$$

Case II : When compound has odd number of carbon atoms, i.e., $n = 3, 5, 7, 9, 11, \dots$:

$$(i) \text{ Number of optically active forms} = a = 2^{n-1} - 2^{(n-1)/2}$$

$$(ii) \text{ Number of enantiomeric pairs} = a / 2$$

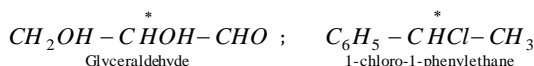
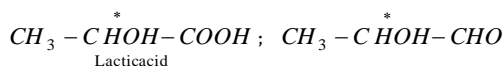
$$(iii) \text{ Number of racemic mixture} = a / 2$$

$$(iv) \text{ Number of meso forms} = m = 2^{(n-1)/2}$$

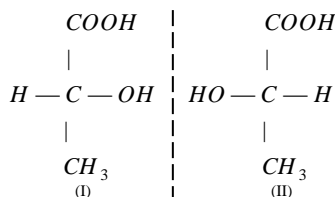
$$(v) \text{ Total number of configurational isomers} = a + m$$

(6) **Optical activity of compounds containing one asymmetric carbon**

Examples :



Any molecule having one asymmetric carbon atom exists in two configurational isomers which are nonsuperimposable mirror images.



(I) and (II) have the same molecular formula, the same structure but different configurations, hence (I) and (II) are known as configurational isomers. (I) and (II) are nonsuperimposable mirror images, hence (I) and (II) are optical isomers. Configurational isomers which are nonsuperimposable mirror images are known as **enantiomers**. Thus (I) and (II) are enantiomers. Pair of (I) and (II) is known as enantiomeric pair.

(i) **Properties of Enantiomers** : All chemical and physical properties of enantiomers are same except two physical properties.

Mode of rotation : One enantiomer rotates light to the right and the other by an **equal magnitude** to the left direction.

(ii) **Racemic Mixture** : An equimolar mixture of two enantiomers is called a racemic mixture (or racemate, \pm form, (*dl*) form or racemic modification). Such a mixture is optically inactive because the two enantiomers rotate the plane polarised light equally in opposite directions and cancel each other's rotation. This phenomenon is called **external compensation**.

\Rightarrow Racemic mixture can be separated into (+) and (–) forms. The separation is known as **resolution**.

\Rightarrow The conversion of (+) or (–) form of the compound into a racemic mixture is called **racemisation**. It can be caused by heat, light or by chemical reagents.

\Rightarrow Racemic mixture is designated as being (\pm) or (*dl*).

(7) Optical activity of compounds containing two asymmetric carbon

Case I : When molecule is not divisible into two identical halves.

The number of optical isomers possible in this case is four ($a = 2^2 = 4$). Further there will be two pairs of enantiomers and two racemic modifications. In practice also it is found to be so.

Configurational isomers which are not mirror images are known as **diastereomers**.

Properties of Diastereomers : Diastereomers have different physical properties, *e.g.*, melting and boiling points, refractive indices, solubilities in different solvents, crystalline structures and specific rotations. Because of differences in solubility they often can be separated from each other by fractional crystallisation; because of slight differences in molecular shape and polarity, they often can be separated by chromatography.

Diastereomers have different chemical properties towards both **chiral** and **achiral** reagents. Neither any two diastereomers nor their transition states are mirror images of each other and so will not necessarily have the same energies. However, since the diastereomers have the same functional groups, their chemical properties are not very dissimilar.

Case II : When molecule is divisible into two identical halves.

$$\text{Number of optical isomers} = a = 2^{2-1} = 2$$

$$\text{Number of meso forms} = m = 2^0 = 1$$

$$\text{Total number of configurational isomers} = 3$$

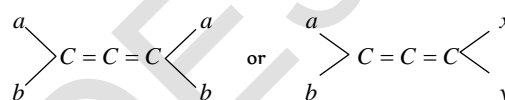
(8) Optical activity in compounds containing no asymmetric carbon

: Although the largest number of known optically active compounds are optically active due to the presence of chiral carbon atom, some compounds are also known which do not possess any chiral carbon atom, but on the whole their molecules are chiral (such molecules were earlier called **dissymmetric**); hence they are optically active. Various types of compounds belonging to this group are allenes, alkylidene cycloalkanes, spiro compounds (spirans) and properly substituted biphenyls.

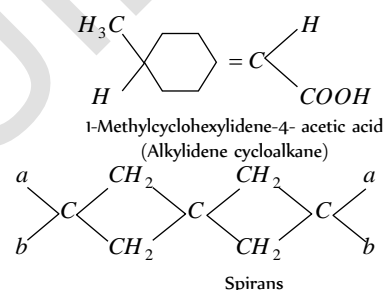
(i) **Allenes** : Allenes are the organic compounds of the following general formulae.



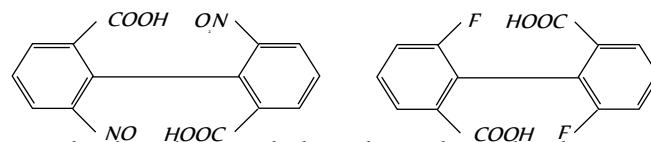
Allenes exhibit optical isomerism provided the two groups attached to each terminal carbon atom are different, *i.e.*,



(ii) **Alkylidene cycloalkanes and spiro compounds** : When one or both of the double bonds in allenes are replaced by one and two rings, the resulting systems are respectively known as alkylidene cycloalkanes and spirans.



(iii) **Biphenyls** : Suitably substituted diphenyl compounds are also devoid of individual chiral carbon atom, but the molecules are chiral due to restricted rotation around the single bond between the two benzene nuclei and hence they must exist in two non-superimposable mirror images of each other. Such types of stereoisomerism which is due to restricted rotation about single bond, is known as **atropisomerism** and the stereoisomers are known and **atropisomers**. Examples



The above discussion leads to the conclusion that the **essential condition for optical isomerism is the molecular dissymmetry or molecular chirality** and not the mere presence of a chiral centre. However, it may be noted that the **molecules having only one chiral centre are always chiral and exhibit optical isomerism**.

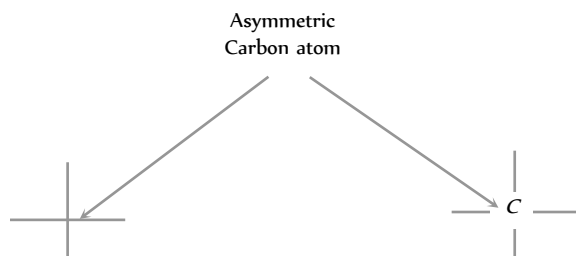
(9) **Fischer projection formulae** : The arrangement of the atoms or groups in space that characterises a stereoisomer is called its configuration.

Emil Fischer (1891) provided an easy method to represent the three dimensional formulae of various organic molecules on paper. **Fischer projection is, thus, a planar representation of the three dimensional structure**.

By convention, the following points are followed in writing the Fischer formula.

(i) The carbon chain of the compound is arranged vertically, with the most oxidised carbon at the top.

(ii) The asymmetric carbon atom is in the paper plane and is represented at the intersection of crossed lines.



(iii) Vertical lines are used to represent bonds going away from the observer, *i.e.*, groups attached to the vertical lines are understood to be present behind the plane of the paper.

(iv) Horizontal lines represent bonds coming towards the observer, *i.e.*, groups attached to the horizontal lines are understood to be present above the plane of the paper.

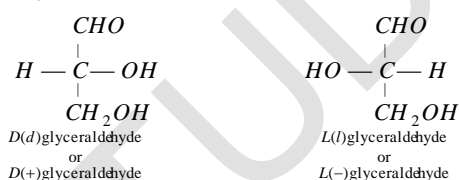
(10) **Name of optical isomers** : Following three nomenclatures are used for optically active compounds,

(i) ***D,L* System of nomenclature** : This nomenclature is mainly used in sugar chemistry or optically active polyhydroxy carbonyl compounds. This nomenclature was given by Emil Fischer to designate the configurations of various sugars relative to the enantiomeric (+) and (–) glucose as reference.

All sugars whose Fischer projection formula shows the *OH* group on the chiral carbon atom adjacent to the terminal *CH₂OH* group on the right hand side belong to the *D*-series. Similarly if *OH* is on the left hand side, then the sugars belong to the *L*-series.



Examples :



⇒ It must be noted that there is no relation between the sign of rotation (+, – or *d, l*) and the configuration (*D* and *L*) of an enantiomer.

⇒ Any compound that can be prepared from, or converted into *D*(+) glyceraldehyde will belong to *D*-series and similarly any compound that can be prepared from, or converted into *L*(–) glyceraldehyde will belong to the *L*-series.

⇒ This nomenclature is also used in α -amino acids.

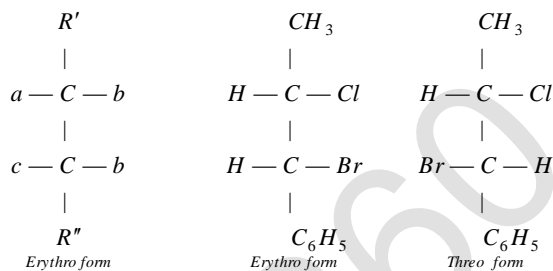
(ii) ***Erythro* and *Threo* system of nomenclature** : This nomenclature is used only in those compounds which have

(a) Only two chiral carbons and

(b) The following structure, $R' - Cab - Cbc - R''$

i.e., out of six substituents on two asymmetric carbons, at least two should be same.

When two like groups in Fischer projection formula are drawn on the same side of the vertical line, the isomer is called *erythro* form; if these are placed on the opposite sides, the isomer is said to be *threo* form.



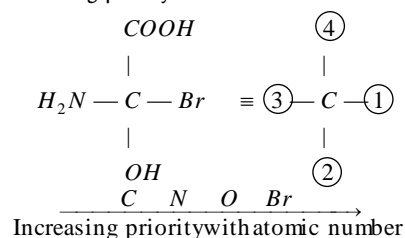
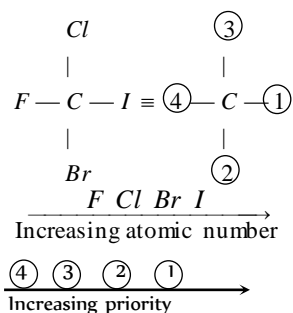
(c) ***R,S* Nomenclature** (Absolute configuration)

The order of arrangement of four groups around a chiral carbon (stereocentre) atom is called the absolute configuration around that atom. System which indicates the absolute configuration was given by three chemists **R.S. Cahn, C.K. Ingold** and **V. Prelog**. This system is known as (R) and (S) system or the **Cahn-Ingold Prelog** system. The letter (R) comes from the latin **rectus** (means right) while (S) comes from the latin **sinister** (means left). Any chiral carbon atom has either a (R) configuration or a (S) configuration. Therefore, one enantiomer is (R) and other is (S). A racemic mixture may be designated (R) (S), meaning a mixture of the two. (R) (S) nomenclature is assigned as follows :

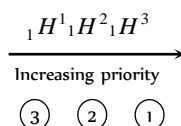
Step 1 : By a set of sequence rules given below the atoms or groups connected to the chiral carbon are assigned a priority sequence.

Sequence Rules for Order of Priority

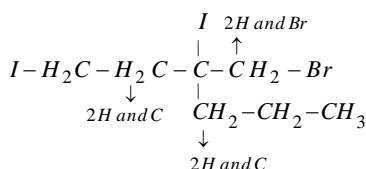
Rule 1 : If all four atoms directly attached to the chiral carbon are different, priority depends on their atomic number. The atom having highest atomic number gets the highest priority, *i.e.*, (1). The atom with the lowest atomic number is given the lowest priority, *i.e.*, (2), the group with next higher atomic number is given the next higher priority (3) and so on. Thus,



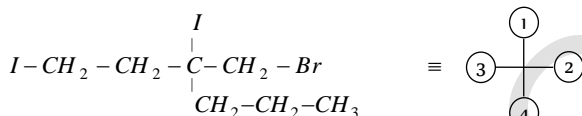
Rule 2 : If two or more than two isotopes of the same element is present, the isotope of higher atomic mass receives the higher priority.



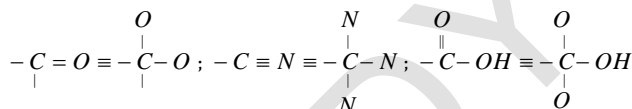
Rule 3 : If two or more of the atoms directly bonded to the chiral carbon are identical, the atomic number of the next atoms are used for priority assignment. If these atoms also have identical atoms attached to them, priority is determined at the first point of difference along the chain. The atom that has attached to it an atom of higher priority has the higher priority.



In this example the atoms connected directly to the chiral carbon are iodine and three carbons. Iodine has the highest priority. Connected, to the three carbons are 2H and Br; 2H and C and 2H and C. Bromine has the highest atomic number among C, H and Br and thus CH_2Br has highest priority among these three groups (i.e., priority no. 2). The remaining two carbons are still identical (C and 2H) connected to the second carbons of these groups are 2H and I and 2H and C. Iodine has highest priority among these atoms, so that $-\text{CH}_2-\text{CH}_2-\text{I}$ is next in the priority list and $\text{CH}_2-\text{CH}_2-\text{CH}_3$ has the last priority.



Rule 4 : If a double or a triple bond is linked to chiral centre the involved atoms are duplicated or triplicated respectively.



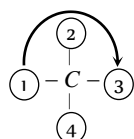
By this rule, we obtained the following priority sequence :



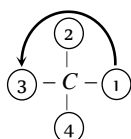
Increasing priority

Step 2 : The molecule is then visualised so that the group of lowest priority (4) is directed away from the observer. Observe (At this position the lowest priority is at the bottom of the plane). The remaining three groups are in a plane facing the observer. If the eye travels clockwise as we look from the group of highest priority to the groups of second and third priority (i.e., $1 \rightarrow 2 \rightarrow 3$ with respect to 4) the configuration is designated as *R*. If arrangement of groups is in anticlockwise direction, the configuration is designated as *S*.

For example:

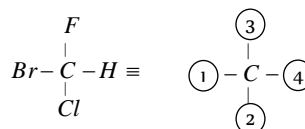


Clockwise arrangement of
1, 2 and 3 $\Rightarrow R$



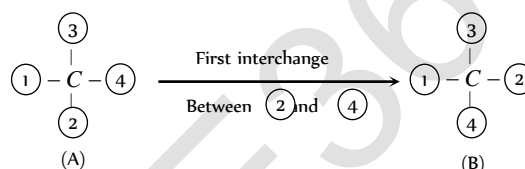
Anticlockwise arrangement of
1, 2 and 3 $\Rightarrow S$

Let us apply the whole sequence to bromochlorofluoro methane.

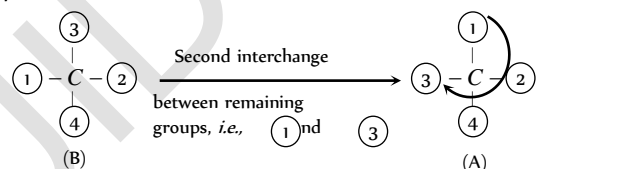


In this Fischer projection the least priority number is not at the bottom of the plane.

In such cases the Fischer projection formula of the compound is converted into another equivalent projection formula in such a manner that atom or group having the lowest priority is placed vertically downward. This may be done by two **interchanges** between four priority numbers. The first interchange involves the two priority numbers, one is the least priority number and other is the priority number which is present at the bottom of the plane. In the above case first interchange will take place between 2 and 4.

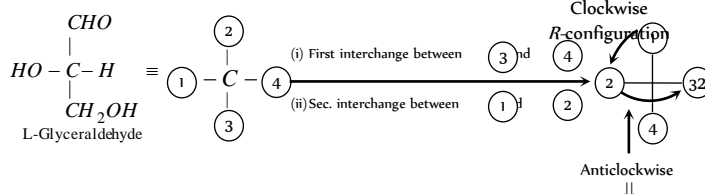
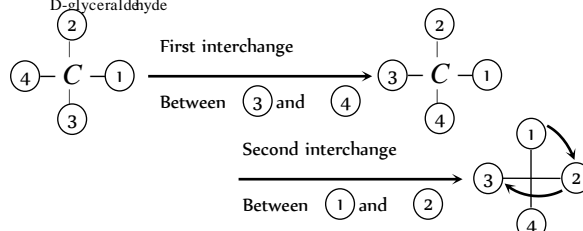


First interchange of two groups at the chiral centre inverts the configuration and this gives enantiomer of the original compound. Thus (A) and (B) are enantiomer. The second interchange involves the remaining two groups.



Example :

Arrangement of
clockwise, hence configuration is *R*

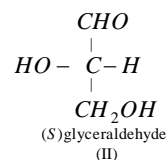
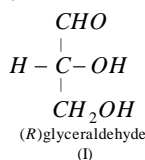


Anticlockwise

↓

S-configuration

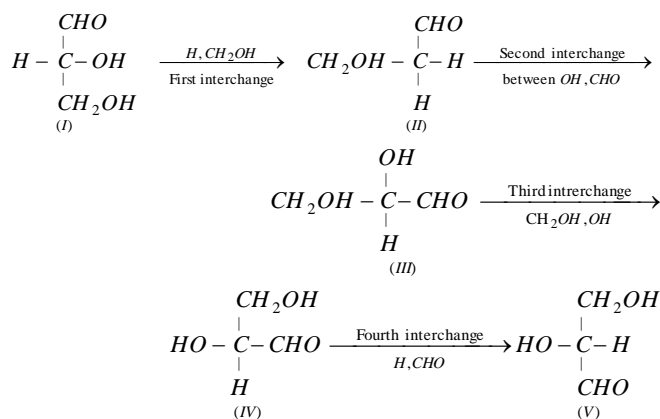
Glyceraldehyde (For example) has one asymmetric carbon, hence it has two configurational isomers (I) and (II).



One can draw a number other configurations for glyceraldehyde but each of them will be a repetition of either (I) or (II). In this connection it is

important to note that if two projection formulae differ by an odd number of interchanges (1, 3, 5, 7,) of positions of groups on the chiral carbon, they are different. But if the two differ by an even number of interchanges (2, 4, 6,) they are identical.

For example :



Thus (I), (III) and (V) are identical. Similarly (II) and (IV) are identical.

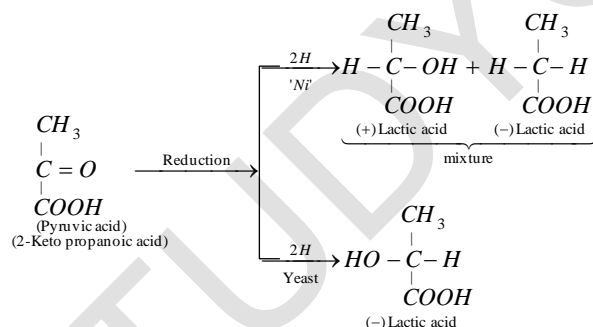
(11) **Resolution of racemic modifications** : The separation of racemic mixture into its enantiomers is known as resolution.

□ Group X reacts with group O to give new group W.

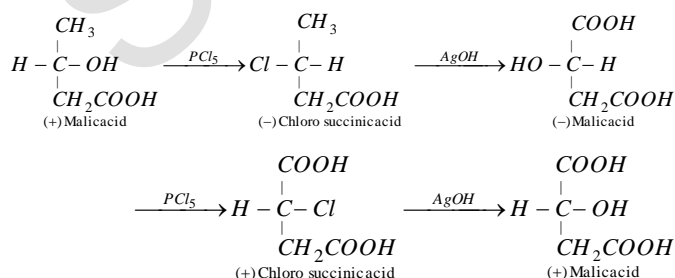
(12) **Asymmetric synthesis and Walden inversion**

(i) **Asymmetric synthesis** : The synthesis of an optically active compound (asymmetric) from a symmetrical molecule (having no asymmetric carbon) without resolution to form (+) or (–) isomer directly is termed **asymmetric synthesis**. For example the reduction of pyruvic acid

$\text{CH}_3 - \overset{\text{O}}{\underset{\text{||}}{\text{C}}} - \text{COOH}$ in presence of nickel catalyst gives (±) lactic acid (racemic mixture). On the other hand, pyruvic acid is reduced to (–) lactic acid only by yeast.



(ii) **Walden inversion**: The conversion of (+) form into (–) form and vice-versa is called **Walden inversion**. When an atom or group directly linked to an asymmetric carbon atom is replaced; the configuration of the new compound may be opposite to (inverse) that of the original, i.e.,



Conformational isomerism

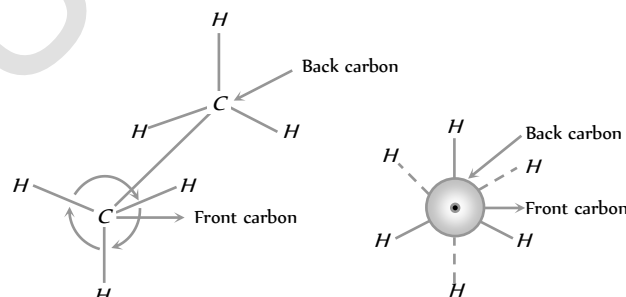
(1) **Definition** : The different arrangement of atoms in a molecule which can be obtained due to rotation about carbon-carbon single bond are called conformational isomers (conformers) or rotational isomers (rotamers). This type of isomerism is found in alkanes and cycloalkanes and their substituted derivatives.

It may be noted that rotation around a C–C sigma bond is not completely free. It is in fact hindered by an energy barrier of 1 to 20 kJ mol^{–1} in different bonds. There is a possibility of weak repulsive interactions between the bonds or electron pairs of the bonds on adjacent carbon atoms. Such type of repulsive interaction is known as **torsional strain**.

(2) **Difference between conformation and configuration** : The term conformation should not be confused with the *configuration* which relates to those spatial arrangements of the atoms of a molecule that can be changed only by the breaking and making of bonds whereas the spatial arrangements in conformation are changed simply by rotation about a single bond.

(3) **Representation of conformations** : Conformers can be represented in two simple ways. These are : (i) Saw horse representation and (ii) Newman projection

(i) **Saw horse representation** : In this projection, the molecule is viewed along the axis of the model from an oblique angle. The central carbon-carbon bond (C–C) is drawn as a straight line slightly tilted to right for the sake of clarity. The front carbon is shown as the lower left hand carbon and the rear carbon is shown as the upper right hand carbon. The three bonds around each carbon atom (C–H in ethane or C–C in higher alkanes) are shown by three lines.



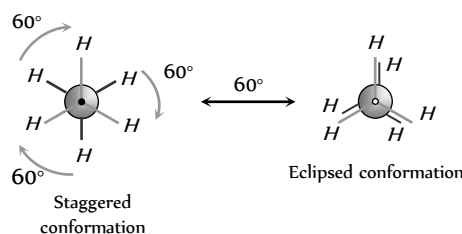
(ii) **Newman projection** : This is a simple method to represent the conformations. In this method, the molecule is viewed from the front along the carbon-carbon bond axis. The two carbon atoms forming the σ-bond are represented by two circles; one behind the other so that only the front carbon is seen. The front carbon atom is shown by a point whereas the carbon further from the eye is represented by the circle. Therefore, the C–H bonds of the front carbon are depicted from the centre of the circle while C–H bonds of the back carbon are drawn from the circumference of the circle at an angle of 120° to each other.

(4) **Conformation in alkanes**

(i) **Conformations of ethane** : When one of the carbon atom is kept fixed and other is rotated about C–C bond an infinite numbers of isomers are possible. Out of all the conformations for ethane, only two extreme conformations are important and these are:

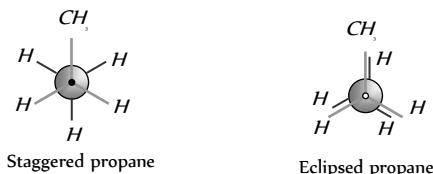
(a) Staggered conformation

(b) Eclipsed conformation



Staggered conformation of ethane is more stable than eclipsed.

(ii) **Conformations of propane** : The next higher member in alkane series, propane ($\text{CH}_3 - \text{CH}_2 - \text{CH}_3$) also has two extreme conformations, the energy barrier in propane is 14 kJ/mol , which is slightly higher than that in ethane.

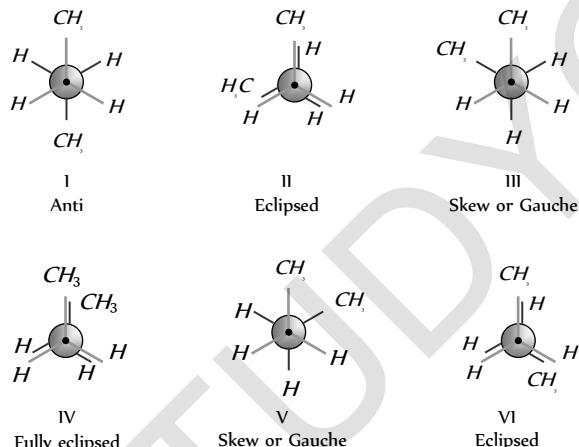


Newman projection of propane

(iii) **Conformations of butane** : As the alkane molecule becomes larger, the conformation situation becomes more complex. In butane ($\text{CH}_3 - \text{CH}_2 - \text{CH}_2 - \text{CH}_3$), for example, the rotation about the single bond between two inner atoms (C_2 and C_3) is considered. In this case, all the staggered as well as eclipsed conformations will not have same stability and energy because of different types of interaction between $\text{C}-\text{C}$ (of methyl) and $\text{C}-\text{H}$ bonds.

The lowest energy conformation will be the one, in which the two methyl groups are as far apart as possible i.e., 180° away from each other.

This conformation will be maximum staggered, most stable and is called **anti or trans conformation** (marked I). Other conformations can be obtained by rotating one of the C_2 or C_3 carbon atoms through an angle of 60° as shown ahead.



As is clear from the above Newman projection, the Gauche or Skew conformations (III and V) are also staggered. However, in these conformations, the methyl groups are so close that they repel each other. This repulsion causes gauche conformations, to have about 3.8 kJ/mol more energy than anti conformation. These conformations II and VI are **eclipsed conformations**. These are unstable because of repulsions. These are 16 kJ/mol less stable than anti conformation. Conformation IV is also eclipsed and it is least stable having energy 19 kJ/mol more than anti conformation. This is because of repulsion between methyl-methyl groups which are very closed together. It is called **fully eclipsed conformation**.

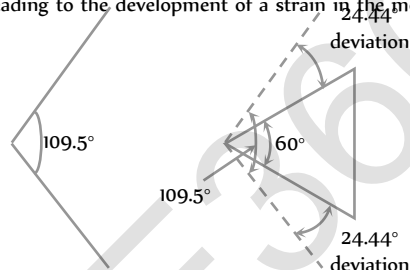
The **order of stability** of these conformations is, Anti > Skew or Gauche > Eclipsed > Fully eclipsed.

(5) Conformations in cycloalkanes

(i) **Stability of cycloalkanes** : Compounds with three and four membered rings are not as stable as compounds with five or six membered rings.

The German chemist Baeyer was the first to suggest that the instability of these small rings compounds was due to angle strain. This theory is known as **Baeyer-strain theory**.

Baeyer strain theory was based upon the assumption that when an open chain organic compound having the normal bond angle 109.5° is convert into a cyclic compound, a definite distortion of this normal angle takes place leading to the development of a strain in the molecule.



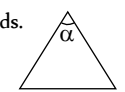
Baeyer assumed that cyclic rings are planar. Assuming that the rings are planar, the amount of strain in various cycloalkanes can be expressed in terms of angle of deviation (d).

$$d = \frac{1}{2} \left[109.5 - \frac{2(n-2)}{n} \times 90 \right] \quad \text{or} \quad d = \frac{1}{2} [109.5 - \alpha]$$

Where n = number of carbon-carbon bonds in cycloalkane ring; α = inner bond angle in the cycloalkane ring.

$$\text{Angle strain} \propto d \propto \frac{1}{\text{inner angle}}; \text{Stability} \propto \frac{1}{d} \propto \text{inner angle}(\alpha)$$

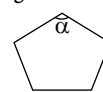
Now let us take the case of three to eight membered cyclic compounds.



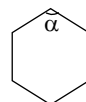
Cyclopropane
 $\alpha = 60^\circ$
 $d = 22.44^\circ$



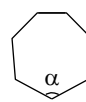
Cyclobutane
 $\alpha = 90^\circ$
 $d = 9.4^\circ$



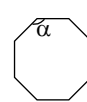
Cyclopentane
 $\alpha = 108^\circ$
 $d = 0.44^\circ$



Cyclohexane
 $\alpha = 120^\circ$
 $d = -5.16^\circ$



Cycloheptane
 $\alpha = 128.6^\circ$
 $d = -9.33^\circ$



Cyclooctane
 $\alpha = 135^\circ$
 $d = -12.46^\circ$

The positive and negative values of (d) indicate whether the inner angle is less than or more than the normal tetrahedral value.

Baeyer thus predicted that a five membered ring compound would be the most stable. He also predicted that six membered ring compounds would be less stable and as the cyclic compounds become larger than five membered ring, then they would become less and less stable.

Contrary to what Baeyer predicted, however cyclohexane is more stable than cyclopentane. Furthermore, cyclic compounds do not become less and less stable as the number of sides increase. Thus Baeyer strain theory is applicable only to **cyclopropane, cyclobutane and cyclopentane**.

The mistake that Baeyer made was to assume that all cyclic compounds are planar. But only cyclopropane is planar and other cycloalkanes are not planar. Cyclic compounds **twist** and **bend** in order to

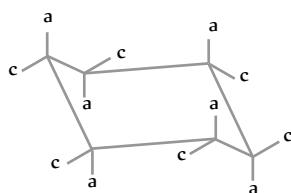
achieve structure that minimises the three different kinds of strain and that can destabilise a cyclic compound.

(a) **Angle strain** is the strain that results when the bond angle is different from desired tetrahedral bond angle of 109.5° .

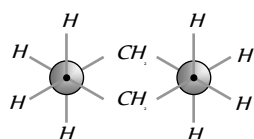
(b) **Torsional strain** is caused by repulsion of the bonding electrons of one substituent with bonding electrons of a nearby substituent.

(c) **Steric strain** is caused by atoms or groups of atoms approaching each other too closely.

(ii) **Conformation of cyclohexane** : Despite Baeyer's prediction that five-membered cyclic compounds would be the most stable, the six membered cyclic compound is the most stable. Six membered cyclic compound are most stable because they can exist in a conformation that is almost completely free of strain. This conformation is called the **chair conformation**. In a chair conformation of cyclohexane all bond angles are 109.38° which is very close to the 109.5° and all the adjacent carbon-hydrogen bonds are staggered.



Chair conformation of cyclohexane



Newmann projection of the chair conformation

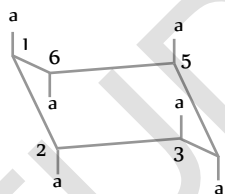
⇒ Each carbon in chair conformation has an axial bond and an equatorial bond.

⇒ Axial bonds are perpendicular to the plane of the ring and equatorial bonds are in the plane of the ring.

⇒ If axial bond on carbon-1 is above the plane of the ring then axial bond on carbon-2 will be below the plane of the ring. Thus

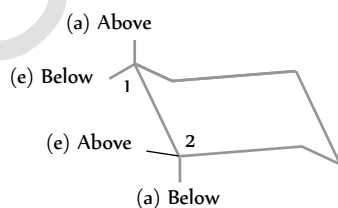
$C-1, C-3$ and $C-5$ axial bonds are above the plane

$C-2, C-4$ and $C-6$ axial bonds are below the plane



⇒ Thus $C-1$ axial and $C-2$ axial are *trans* to each other. Similarly $C-1$ and $C-5$ axials are *cis* to each other.

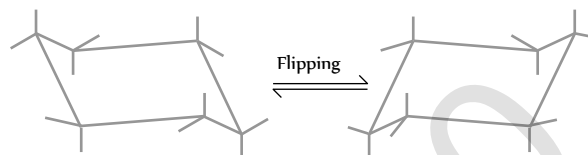
⇒ If axial bond on carbon-1 will be above the plane then equatorial bond on this carbon will be below the plane.



(a) Thus $C-1$ equatorial and $C-2$ equatorial bonds are *trans*.

(b) $C-1$ axial and $C-2$ equatorial will be *cis*.

⇒ As a result of rotation about carbon-carbon single bonds cyclohexane rapidly interconverts between two stable chair conformations. This interconversion is known as ring -flip. When the two chair forms interconvert, axial bonds become equatorial and equatorial bonds become axial.



⇒ Cyclohexane can also exist in a boat conformation. Like the chair conformation, the boat conformation is free of angle strain. However, the boat conformation is less stable than the chair conformation by 11 kcal/mole . Boat conformation is less stable because some of the carbon-hydrogen bonds in boat conformation are eclipsed.

The boat conformation is further destabilised by the close proximity of the flagpole hydrogens. These hydrogens are 1.8 \AA apart but the vander Waal's radii is 2.4 \AA . The flagpole hydrogens are also known as *trans* nuclear hydrogens.

□ The relative stabilities of the four conformations of cyclohexane decrease in the order:

Chair > twist boat > boat > half chair.

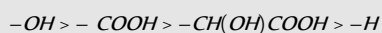
Tips & Tricks

✍ Wohler synthesised the first organic compound urea in the laboratory.

✍ The number of optical isomers of a compound depends on its structure and number of asymmetric carbon atoms present in its molecule.

✍ Stereoisomers that are not mirror images of each other are called diastereomers.

✍ Order of priority for both asymmetric carbon atoms using sequence rules is



✍ The nitration and sulphonation of alkanes involve free radicals.

✍ Carbenes undergo insertion reactions.

✍ Alkanes usually undergo free radical substitution when hydrogen is replaced by a halogen. It is catalysed by benzoyl peroxide (CH_3COO).

✍ The polymerisation of alkenes is free radical addition reaction.

✍ Allyl free radical ($CH_2=CH-CH_2$) is more stable than *n*-propyl free radical ($CH_3CH_2CH_2$).

✍ The stability of free radicals is explained on the basis of hyperconjugation or conjugation.

✍ Propene is more reactive than ethene towards electrophilic addition reaction due to the formation of more stable 2° carbocation.

✍ The reactivity of alkyl halides in *SN* is 3° > 2° > 1° > methyl while *SN* is methyl > 1° > 2° > 3°.

✍ Polar solvents favour *SN* while non polar solvents favour *SN* reactions.

✍ Dipole moment of $CHCl_3$ is less than that of CH_2Cl_2 . This is because in CH_2Cl_2 all bond moments reinforce each other while in $CHCl_3$ the bond moment of one of the *Cl* opposes the net moment of the other two.

✍ Low concentration of nucleophiles favour *SN* while high concentration favour *SN*.

✍ In *SN* the attack of the nucleophile may be from either side and so racemization takes place. However, in *SN* the attack of the nucleophile takes place from back side. So it leads to inversion of configuration.

✍ Hunsdieker reaction proceeds via free radical mechanism.

✍ Propene reacts with chlorine at 673 K to form allyl chloride and the intermediate is allyl free radical.