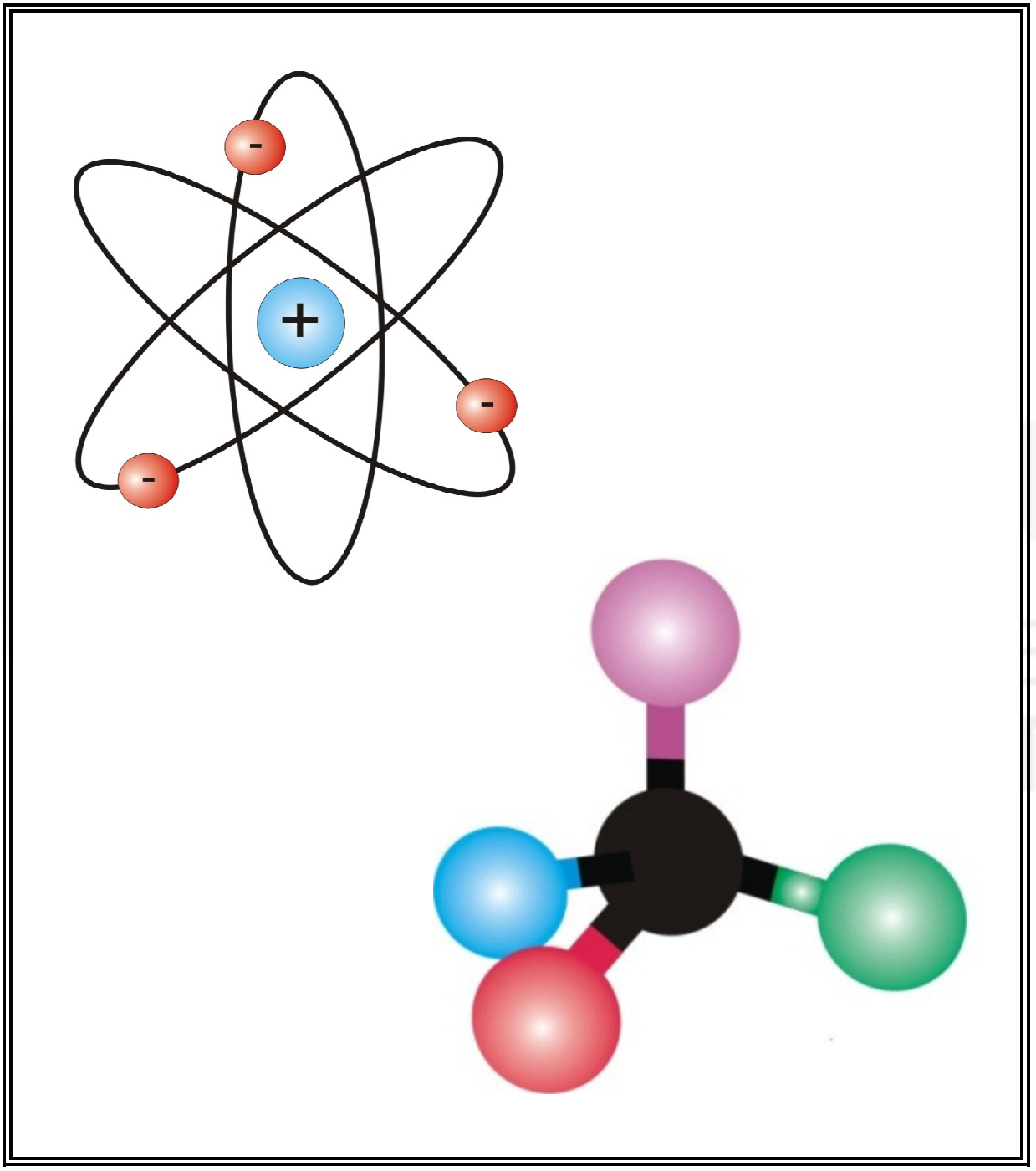
Indira Gandhi National
Open University
School of Sciences

BCHCT-131
ATOMIC STRUCTURE,BONDING, GENERAL ORGANIC CHEMISTRY AND ALIPHATIC HYDROCARBONS



FUNDAMENTALS OF ORGANIC CHEMISTRY

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ATOMIC STRUCTURE, BONDING, GENERAL ORGANIC CHEMISTRY AND ALIPHATIC HYDROCARBONS

Block

3

FUNDAMENTALS OF ORGANIC CHEMISTRY

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BLOCK 3: FUNDAMENTALS OF ORGANIC CHEMISTRY

This is the third Block of the course on 'Atomic Structure, Bonding, General Organic Chemistry and Aliphatic Hydrocarbons' (BCHCT-131).It discusses in detail the stereochemistry and structure – reactivity relationships of organic compounds.

There are four units in this Block. The first three units, i.e. Units 10, 11 and 12 deal with stereochemistry in detail while the fourth unit, i.e. Unit 13 describes the structure – reactivity relationships.

Unit 10 on 'Stereochemistry- I: Geometrical and Optical Isomerisms' begins with a brief outline of types of isomerism exhibited by organic compounds. This is followed by a discussion on geometrical isomerism. The *cis*-/*trans*- and *E*/*Z* nomenclatures of geometrical isomers have been explained. Then, the characterization of geometrical isomers has been discussed. After this, optical isomerism has been described wherein the origin of optical activity has been explained. The concept of chirality has been illustrated and the classification of optical isomers into enantiomers, diastereomers and *meso* compounds have been discussed.

Unit 11 on 'Stereochemistry- II: Configurational Isomers' begins with a description of the concept of configuration and writing of Fischer projection formulae for organic compounds. The configurational notations such as *R*/*S* and *Erythro*/*Threo* have been described in detail. Finally, the racemic mixtures and their resolution has been discussed in this unit.

Unit 12 on 'Stereochemistry – III: Conformational Isomerism' discusses the representation of various conformational isomers using Newman and Sawhorse representations. Then, the conformations of ethane, butane and cyclohexane have been illustrated along with their relative stabilities.

Unit 13 on 'Structure – Reactivity Relationships' deals with various ways of classification of acids and bases. The concept of pK_a to express the strengths of acids and bases has been discussed in detail. The unit elaborates extensively on various factors affecting the strengths of acids and bases. These include inductive effect, resonance effect, hyperconjugation, hydrogen bonding, steric effect and solvent. Finally, the concept of tautomerism has been briefly explained.

Unit 14 on 'Reactions and Reactive Intermediates' begins with a discussion on the various ways of cleavage of bonds in organic molecules. Then, the types of reagents and types of reactions have been described. Finally, different reactive intermediates have been explained in detail.

Some video programmes related to various units of this block are available. It is suggested that you should with these programmes. This will help you in understanding the concepts given in these units.

Expected Learning Outcomes

After studying this Block, you should be able to:

- identify the type of isomerism exhibited by a set of organic compounds;
- write the *cis*-/*trans*- or *E*/*Z* forms of a given organic molecule;
- explain the methods of distinguishing geometrical isomers;
- discuss the origin of chirality in organic compounds;
- write the optical isomers of a given compound;

- classify the optical isomers as enantiomers or diastereomers;
- write possible configurational isomers of an organic compound and assign their configuration as *R*/*S* or *Erythro*/*Threo*;
- explain racemic mixtures and discuss various methods of their resolution;
- draw various conformations of ethane and butane in Newman and sawhorse representations and explain their relative stabilities;
- draw various conformations of cyclohexane and discuss their relative stabilities;
- define acids and bases according to Arrhenius, Brönsted-Lowry and Lewis classifications;
- explain pK_a and discuss the effect of various electronic and steric factors on the strengths of the acids and bases;
- discuss tautomerism and give examples of various types of tautomerism;
- explain various ways of cleavage of bonds in organic molecules; and
- describe different types of reactions of organic molecules and the reactive intermediates involved in them.

UNIT 10

STEREOCHEMISTRY–I: GEOMETRICAL AND OPTICAL ISOMERISMS

Structure

10.1 INTRODUCTION

Although we are habitual of writing the structures of organic molecules in two dimensions but actually they have three-dimensional structures. The term **stereochemistry** is coined from the Greek word *stereos* meaning "solid" and it deals with the chemistry of molecules in three dimensions. In addition to the study of the geometry of molecules which is referred to as **stereoisomerism,** stereochemistry is concerned also with the effect of molecular geometry (i.e., the three-dimensional structure of molecules) on chemical reactions and chemical equilibria. While these aspects will be dealt with at appropriate places in this course and later courses of Organic Chemistry; here, we will confine our discussion mainly to stereoisomerism.

We will begin with the concept of isomerism in general and then study geometrical and optical isomerisms in detail. After defining isomerism, its various types will be explained. Then, under *geometrical* isomerism, *cis*–and *trans*–nomenclature will be discussed. This will be followed by illustration of Cahn-Ingold-Prelog rules for determining the priorities of the substituent

groups. These rules will, then, be applied to designate the geomentrical isomers according to the *E* and *Z* nomenclature. After that the characterisation of geometrical isomers will be described.

The discussion an *optical isomerism* will begin with a description of the nature of plane polarised light and optical activity. Then, the origin of optical activity in molecules will be described. The concept of chirality will be illustrated. We will also explain what is a chiral centre and how to locate the chiral centre(s) in the molecule. Here, you will also learn that the presence of a chiral centre in compound leads to the existence of its two enantiomers. Further, if there are two chiral centres present in a molecule, then its enantiomers as well as diastereomers are capable of existence.

Here, you will study an interesting case of *meso* compounds which have two chiral centres but are still optically inactive.

While studying this unit, Unit11 and Unit 12 which also deal with stereochemistry, you are advised to take help of the models. You can make models using the students set of models provided to you. Before using the models, go through the guidelines for using the models given in study guide. For better understanding of the material, you should yourself do the various activities given in the margin in these units.

Expected Learning Outcomes

After studying this unit, you should be able to:

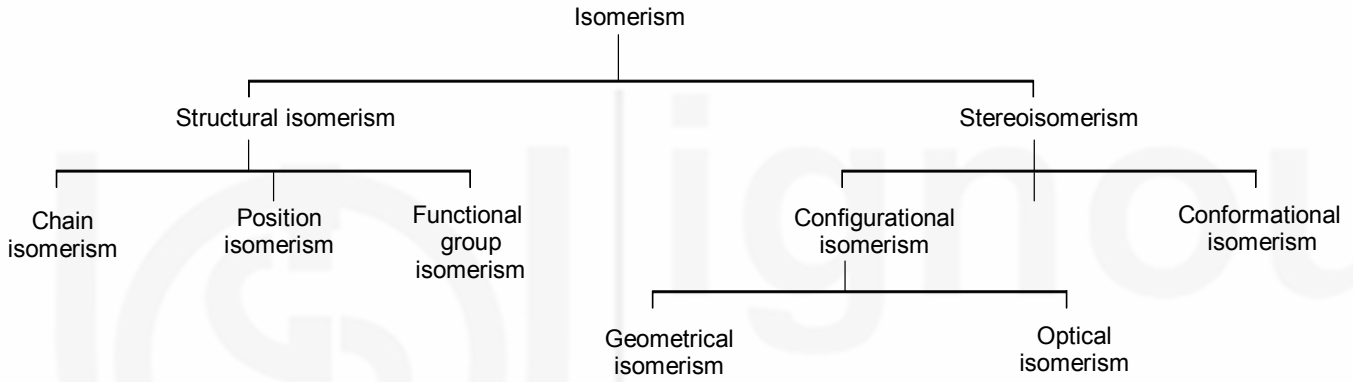
- list and explain various types of isomerism;
- write geometrical isomers and designate them as *cis*– or *trans*– and *E* and *Z* isomers;
- explain the physical properties of geometrical isomers;
- discuss how *cis*–, *trans*– isomers can be differentiated on the basis of their physical properties and chemical reactions;
- explain optical isomerism;
- discuss the phenomenon of optical activity;
- define chirality;
- locate chiral centres in a molecule;
- predict whether a compound will show optical activity or not just by examining its structure;
- write the enantiomers and diastereomers for a given compound;
- differentiate between enantiomers and diastereomers;
- identify the chiral centres present in a compound; and
- give reason why *meso*compounds are optically inactive.

10.2 ISOMERISM

Isomerism, which is one of the important characteristics of organic compounds, arises because of the number and variety of ways in which carbon atoms, which form the back-bone of organic molecules, can link with each other. In addition to this, the position and linking of various heteroatoms like O,N,S, halogens etc., give rise to a varying number of isomers. The number increases with the number and variety of atoms present in a molecule. So, a study of the structure of the molecule is implicit and molecular formula alone is not enough.

The phenomenon of existence of two or more compounds having the same molecular formula is known as **isomerism** and these compounds are individually referred to as **isomers.** Isomers have same molecular formula but they differ from each other in their physical and chemical properties.

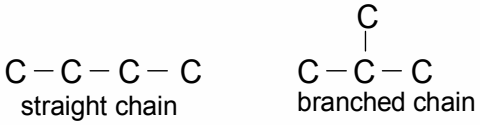
Isomerism can be of various types. The different types of isomerism are represented below in a flow chart.



Let us now study each type of isomerism in detail.

1. **Structural Isomerism** arises due to differences in the structures of the molecules. Therese structural differences can be further classified into three types; accordingly, the three types of structural isomerism are as given below:

   a) **Chain isomerism** is exhibited by the compounds which differ from each other in the way the carbon atoms form the basic skeleton. If four carbon atoms are to be arranged in a chain, they can be linked to each other in two different ways to form either a straight chain of carbon atoms or a branched chain, as shown below:



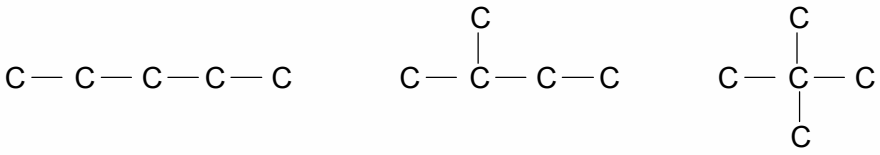
   These straight chain and branched chain carbon skeletons correspond to two different hydrocarbons having the molecular formula C_4H_{10}. These are commonly called *n*–butane and *iso*butane and are shown below.

The two isomeric butanes are distinct entitles having different boiling points.

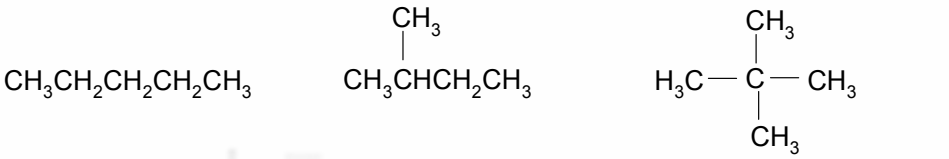
butane
(common name: *n*-butane)
bp 272.5 K

2-methylpropane
(common name: *iso*butane)
bp 263 K

Thus, butane and 2–methylpropane exhibit chain isomerism. Similarly, five carbon atoms can have any of the following arrangements:



Corresponding to these arrangements, the isomeric hydrocarbons are shown below.

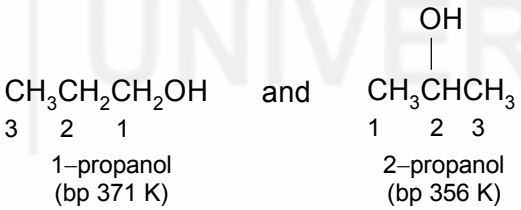


pentane
(common name: *n*-pentane)

2–methylbutane
(common name: *iso*pentane)

2,2–dimethylpropane
(common name: *neo*pentane)

b) **Position Isomerism** is different from chain isomerism in the sense that here the isomers have the same carbon skeleton but they differ from each other in the position of the substituent groups. For example, in a straight chain hydrocarbon having three carbon atoms, a substituent can be either at C-1 position or at C-2 position, i.e. if the substituent is a hydroxyl group, then the two position isomers are:



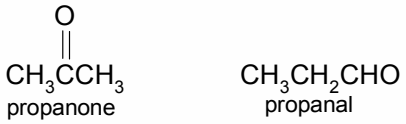
1–propanol
(bp 371 K)

and

2–propanol
(bp 356 K)

(common name: *n*-propanol) (common name: *iso*propanol)

c) **Functional Group Isomerism** is exhibited by compounds having the same molecular formula but different functional groups. For example, C_3H_6O corresponds to both propanone and propanal as shown below:



propanone

propanal

Here, the functional groups are the keto and the aldehyde groups, respectively. Such isomers, thus, belong to different classes of compounds.

2. **Stereoisomerism** is exhibited by compounds which have the **same** Lewis structure (or structural formula) but differ from each other in the spatial arrangement of the atoms or groups in their molecules. Such isomers are called **stereoisomers.** Stereoisomerism can be further classified into two types as given below:

   a) **Configurational Isomerism:** The absolute configuration of a compound can be defined as the actual orientation of the groups in space. This type of isomerism is exhibited by those stereoisomers which cannot be converted to each other without breaking of bonds. It can be further classified into geometrical isomerism and optical isomerism.

      i) **Geometrical isomerism** is caused by different arrangements of the groups around a rigid framework. This rigid framework can be a double bond or a cyclic structure around which the various groups are attached. Later, you will study that due to this rigid framework, interconversionisomers is not easily possible.

      ii) **Optical isomerism** arises due to molecular asymmetry and as the name indicates, this type of isomerism is manifested by the rotation of the plane of plane-polarised light. In this unit, you will study geometrical and optical isomerisms in detail.

   b) **Conformational Isomerism** arises due to different spatial arrangement of groups in a molecule which are obtained by rotation about single bonds. Each such arrangement is called a **conformation.** You will study more about conformations in Unit 12 of this block.

At this stage, you can check your understanding about various kinds of isomerism by answering the following SAQ.

SAQ 1

Write all possible structural isomers having molecular formula C_3H_8O.

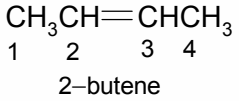
10.3 GEOMERTICAL ISOMERISM

It was pointed out in the last section that geometrical isomerism in possible when groups are attached to a rigid framework like a double bond. You also studied in earlier classes that a double bond is constituted by a *sigma* and a *pi* bond. Since, the π bond is formed by the lateral overlap of *p*orbitals, rotation about the double bond is not possible without breaking it.

Let us now study how geometrical isomerism arises when such a rigid framework is present and how are the geometrical isomers named.

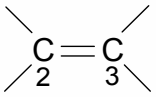
10.3.1 *Cis*- and *Trans*-Nomenclature

Let us consider the case of 2–butene. We can write its structure as shown below.

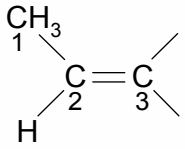


2–butene

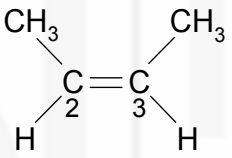
But actually, two different compounds corresponding to this structure exist. You can yourself see this by writing the structural formulae for these two compounds. To do this, start by writing the C-2 and C-3 carbon atoms of the carbon skeleton as:



As shown in the structure of 2–butene, a methyl group and a hydrogen atom are linked to C–2 carbon; hence, attach a CH_3 group and a hydrogen to C–2 carbon as shown below:

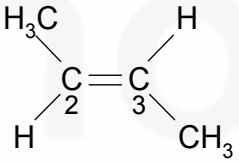


Similarly, a CH_3 group and a hydrogen atom are linked to the C–3 carbon atom. When you try to put this second methyl group at C–3 carbon, you have two possibilities:



cis-2-butene

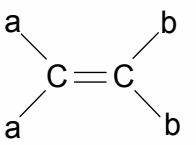
or



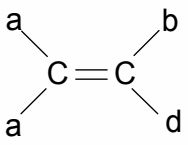
trans-2-butene

Clearly, in the first case, the two methyl groups are on the *same side* of the double bond and in the second structure one methyl group ison one side and the other methyl group is on the *opposite side* of the double bond. These two butenes are differentiated from each other by attaching the prefixes *cis*–(a Latin word meaning *on this side*) and *trans*–(a Latin word meaning *across*) in their names. Hence, these two butenes are names as *cis*–2–butene and *trans*–2–butene, respectively. Thus, *cis*– and *trans*–2–butenes exhibit geometrical isomerism and therefore, they are called **geometrical isomers**.

In other words, we can say that *cis*–, *trans*–or geometrical isomers are the isomers of the type baC=Cab. Hence, in the molecules of the type given below as

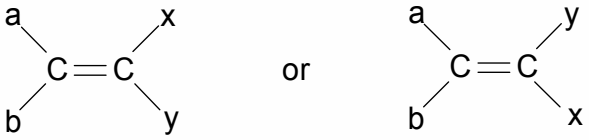


or



where the carbon atoms forming the double bond carry identical substituents, such an isomerism is not possible.

Let us now see what happens when all the four substituents around the double bond are different. For such a case, the following different arrangements of the groups are possible,



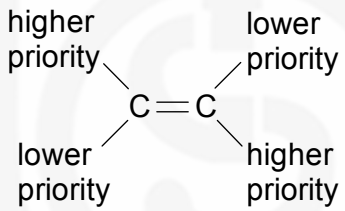
The question that immediately arises is how to differentiate these two compounds? Can you designate them as *cis*– or *trans*–? The answer is **No** because the *cis*–, *trans*–nomenclature does not provide clear guidelines about how to designate these isomers.

To designate such isomers, an unambiguous system of nomenclature called *E*/*Z* system is used. This system of nomenclature is based on the sequence rules developed by Cahn, Ingold and Prelog and is discussed below.

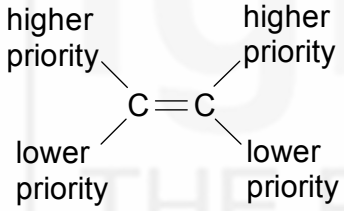
Although the Cahn-Ingold-Prelog sequence rules and the *E*/*Z* system have been sanctioned by IUPAC, use of *cis*–,*trans*–nomenclature, in the cases where it can be used unambiguously, is allowed by IUPAC.

10.3.2 *E/Z* Nomenclature

In this system, each of the two groups attached to same carbon atom of the double bond is assigned priority according to the sequence rules. This is done for both the carbon atoms forming the double bond. If the groups of higher priority are on *opposite sides* of the double bond, then the isomer is said to have *E* configuration. Otherwise, when the groups having higher priority are on the *same side* of the double bond, then the isomer is known as *Z* isomer. The letters *E* and *Z* are derived from the German words *entgegen* meaning **opposite** and *zusammen* meaning **together**. Thus, we can say that,



E isomer



Z isomer

Let us now study the sequence rules given by Cahn, Ingold and Prelog.

10.3.3 Cahn-Ingold-Prelog Rules

These rules are explained below:

1. Atoms of the higher atomic number have higher priority. For example, oxygen (At. No. 8) has higher priority than carbon (At. No. 6) which in turn has higher priority than hydrogen (At. No. 1).

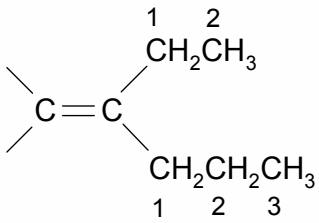
2. When the priority is to be decided between the atoms which are isotopes of the same element, then the isotope of higher atomic mass has higher priority.

   Therefore, deuterium ($^{2}_{1}H$), an isotope of hydrogen has higher priority than hydrogen ($^{1}_{1}H$).

3. When the two groups attached to the carbon atom involved in the formation of double bond have the same atoms as points of attachment, then the priorities are assigned according to the first point of difference,

applying the same considerations of atomic number and atomic mass as given above in Rules 1 and 2.

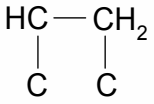
To understand this, consider that the two groups attached to the carbon atom involved in the formation of double bond are ethyl and propyl groups, as shown below:

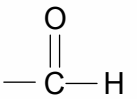
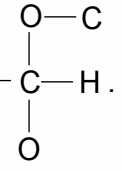


Here, both these groups are attached to the carbon atom forming the double bond by carbon atoms. To decide which of the two groups will have higher priority, look at the substituents on C–1 carbon atoms of the ethyl and propyl groups. You will find that in both the groups, two hydrogens are attached to the C–1 carbon atom. Let us move to the next carbon, C–2.

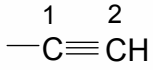
In case of the ethyl group, there are three hydrogens attached to C–2 carbon while the propyl group has two hydrogens and one carbon attached to the C–2 carbon. Clearly, then this is the first point of difference where the C–2 carbon of propyl group has the substituents C, H, H while that of the ethyl group has the substituents H, H, H. Hence, the propyl group has priority over the ethyl group.

4. When we come across double or triple bonds while assigning the priorities, then these groups are visualised in such a way that the bonded atoms are duplicated or triplicated as the case may be. For example, in the group –HC=CH_2, a carbon atom attached to another carbon atom by a double bond is considered to be bonded to two carbon atoms. Thus, this group can be regarded as follows:

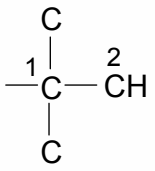


Similarly, the  group is treated as equivalent to  .

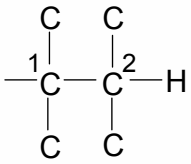
This is a kind of expansion of the groups attached to a multiple (double) bond in such a way that each atom is shown as linked to the other atom by a single bond. Thus, to write for the group shown below,



first expand at C–1 carbon which has all the three bonds linked to the carbon atom numbered as C–2. Thus, C–1 is to be shown as if it is linked to three carbon atoms like this,



Now repeat the same for the C–2 carbon, which is expanded in such a way that it is shown to be linked to three carbon atoms. This is shown below:



The above is the equivalent form of –C≡H group considered for assigning the priority.

Thus, –C≡Hgroup has higher priority than –HC=CH_2group because in the expanded form of –C≡Hgroup, carbon atom shown by number 1 has two carbon atoms linked to it whereas in –HC=CH_2group, carbon atom shown by number 1 has only one carbon atom linked to it in the expanded form.

In the guidelines provided by these sequence rules, some commonly occurring groups can be arranged in the decreasing order of their priority as follows:

$$I- > Br- > Cl- > HS- > F- > CH_3\overset{\overset{O}{\|}}{C}-O- > H\overset{\overset{O}{\|}}{C}-O- > CH_3CH_2O- >$$

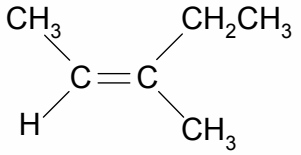
$$HO- > H_2N- > CH_3O\overset{\overset{O}{\|}}{C}- > HO\overset{\overset{O}{\|}}{C}- > CH_3\overset{\overset{O}{\|}}{C}- > H-\overset{\overset{O}{\|}}{C}- > HOCH_2- >$$

$$(CH_3)_3C- > CH_2{=}CH- > (CH_3)_2CH- > CH_3CH_2- > CH_3- > H$$

Let us now study some examples which illustrate how a given compound is designated as *E* or *Z*, using the above sequence rules.

Example 1:

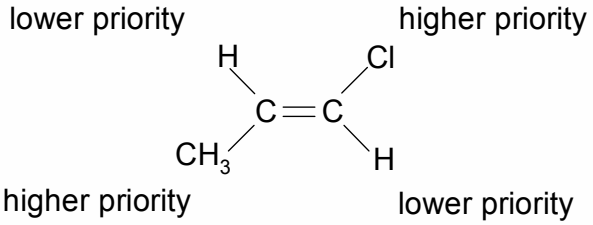
higher priority higher priority



lower priority lower priority

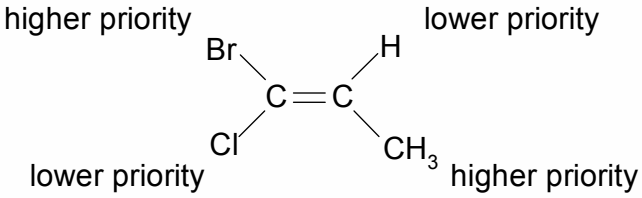
In this compound, groups of higher priority are on same sides of the double bond; hence, it is the (*Z*)–isomer.

Example 2:



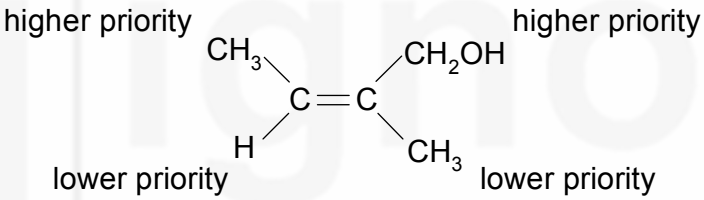
In this case, groups of higher priority are on opposite sides of the double bond; hence, it is the (*E*)–isomer

Similarly, the isomer shown below,



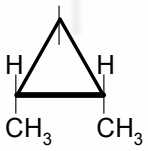
is (*E*)–isomer and can be named as (*E*)–1–bromo–1–chloropropene.

And, the isomer

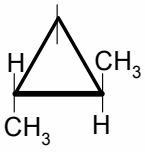


is (*Z*)–isomer and can be named as (*Z*)–2–methyl–but–2–enol.

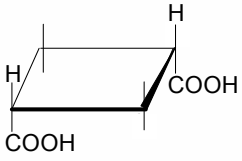
Similar to the geometrical isomerism exhibited about a double bond, the compounds having a cyclic rigid framework can also show geometrical isomerism. Some cyclic compounds which exhibit the geometrical isomerism are shown below.



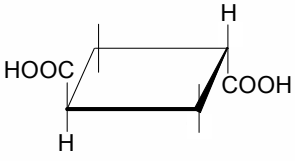
cis–1,2–dimethylcyclopropane



trans–1,2–dimethylcyclopropane



cis–1,3–cyclobutanedicarboxylic acid



trans–1,3–cyclobutanedicarboxylic acid

You will study more about the stereochemistry of simple cyclic compounds such as cyclohexane in Unit 12. However, the general aspects of the chemistry of cycloalkanes will be dealt in Unit 15 of Block 4 of this course.

The geometrical isomers vary widely in their physical properties. The physical properties of some geometrical isomers are listed in Table 10.1.

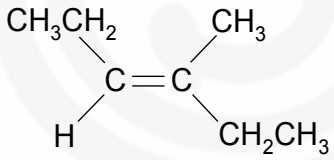
Table 10.1: Physical properties of some geometrical isomers

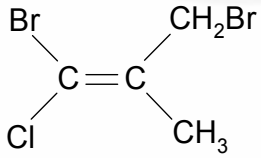
Compound	Melting point (K)	Boiling point (K)	$\frac{\text{Dipole moment}}{10^{-30}\text{(Cm)}}$
cis–2–butene	134	277	1.10
trans–2–butene	167	274	0
cis–1,2–dichloroethene	193	333	6.17
trans–1,2–dichloroethene	223	321	0
cis–1,2–dibromoethene	220	383	4.5
trans–1,2–dibromoethene	267	381	0
cis–1,2–diiodoethene	259	345	2.50
trans–1,2–diiodothene	461	465	0

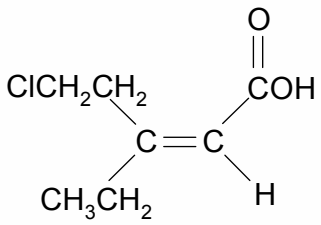
In the next section, we will these physical properties to characterise geometrical isomers. But before that answer the following SAQ.

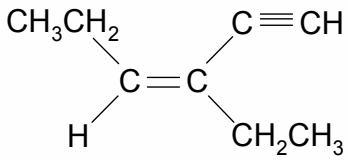
SAQ 2

Assign the configuration as *E* or *Z* to the following compounds:

i) 

ii) 

iii) 

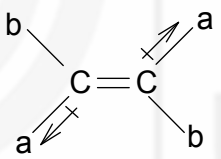
iv) 

10.4 CHARACTERISATION OF GEOMETRICAL ISOMERS

There are several physical and chemical methods for differentiating between the geometrical isomers. Let us first study the characterisation of geometrical isomers based on their physical properties and then we will study how chemical properties can be used for the characterisation of these isomers.

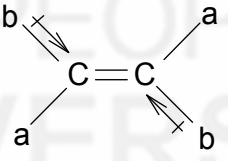
The *cis*–and *trans*–geometrical isomers differ from each other in their physical properties like melting point, boiling point, dipole moment and spectral characteristics. Table 10.1 clearly shows that the *trans*– isomer has a higher melting point than the corresponding *cis*– isomer. The reason for this is that the *trans*– isomer being more symmetrical, fits into the crystal lattice more easily and hence, has a higher melting point than the *cis*– isomer. However, the correlation of boiling points with configuration of the isomer is not as exact as is the case with melting points, because of its dependence on molecular volume. Hence, boiling points are not of much use for such determinations.

Another physical property useful for differentiation of such isomers is dipole moment. In geometrical isomers of the type abC=Cab, the *trans*–isomer has zero dipole moment. Some such examples are listed in Table 10.1. This is so because in the *trans*– isomer, the same substituents are located in the opposite directions and hence, whatever be the magnitude of dipole moment due to one bond in one direction, it is cancelled by an equal moment operating in the opposite direction; thus, the net or resultant dipole moment is zero. Depending upon whether the substituents are electron-withdrawing or electron-donating, the directions of the dipole moments due to individual bonds for the *trans*– isomer are as given below.



(When group a is an electron–withdrawing group)

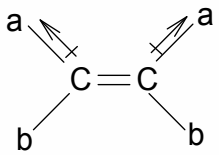
or



(When group b is an electron–donating group)

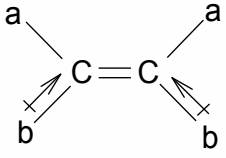
However, the resultant dipole moment, μ, for both the cases is zero.

But in the *cis*– isomer, depending upon whether the groups are electron-withdrawing or electron-donating, the direction of individual bond moments is as shown below:



(When group a is an electron–withdrawing group)

or

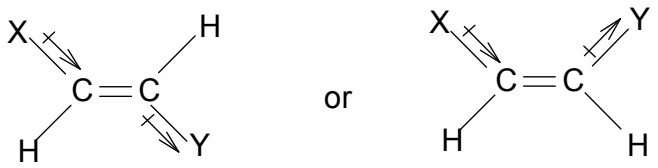


(When group b is an electron–donating group)

In both these situations, the individual dipole moments add vectorally leading to a definite resultant dipole moment. Hence, the molecule is said to have

some dipole moment. You can check from Table 10.1 that *cis*–compounds of this type always have some definite positive value for the dipole moment.

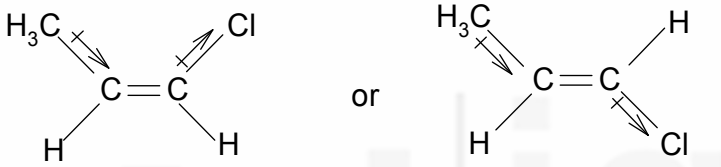
Let us next consider a molecule in which one substituent is electron-donating and the other is electron-withdrawing. Let X be an electron-donating substituent and Y be an electron-withdrawing substituent. The bond moments in the geometrical isomers of this type are shown below:



trans– isomer *cis*– isomer

An acid anhydride is formed by the elimination (or loss) of a water molecule from an acid. A dicarboxylic acid can lose a molecule of water and form an anhydride easily only if the carboxyl (–COOH) groups are on the same side of the double bond.

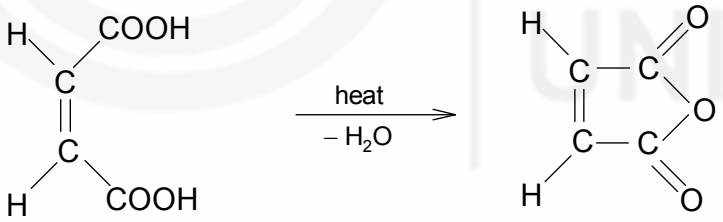
In case of the *trans*– isomer, the bond moments add vectorially and reinforce each other leading to higher dipole moment for this isomer. The vectorial addition for the *cis*– isomer leads to a lower value for the resultant dipole moment. This is illustrated in the example given below.



cis–1–chloro–1–propene
$\mu = 5.70 \times 10^{-30}$ C m

trans–1–chloro–1–propene
$\mu = 6.56 \times 10^{-30}$ C m

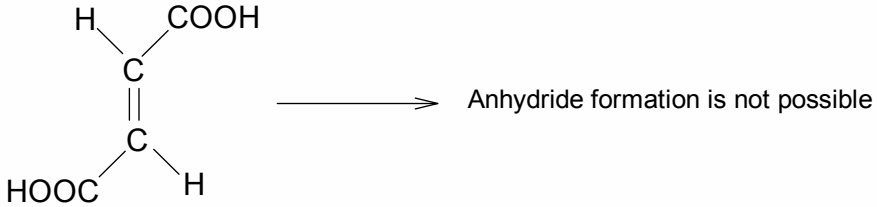
For a particular pair of geometrical isomers, the functional groups present are the same; hence, it is difficult to distinguish them on the basis of their chemical reactions. But, there are some reactions which are possible with one isomer only because of the spatial arrangement of its groups. One such reaction is the formation of an anhydride by the maleic acid which is the *cis*– isomer of



maleic acid
(*cis*– isomer)

maleic anhydride

but–2–ene–1,4–dioic acid. The two carboxyl (–COOH) groups are in close proximity in this isomer and hence, it can yield an anhydride by the elimination of a molecule of water. But, in the *trans*–isomer, i.e. in fumaric acid, since the two carboxyl groups are in opposite directions, such a reaction is not possible and hence, it does not form an anhydride.

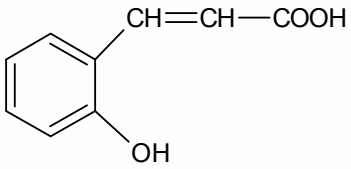


However, when strongly heated, it forms the anhydride of maleic acid. Thus, we can differentiate between the *cis*– and the *trans*–isomers in this case on the basis of chemical reactivity.

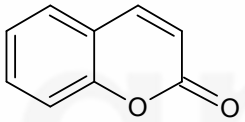
Before proceeding to the study of optical isomerism in the next section, you can check your understanding of geometrical isomerism by answering the following SAQ.

SAQ 3

a) Write the geometrical isomers of *o*–hydroxycinnamic acid having the following structure:



b) Which of the two isomers of *o*–hydroxycinnamic acid would undergo cyclisation easily to yield the following lactone:



coumarin

Give reason for your answer.

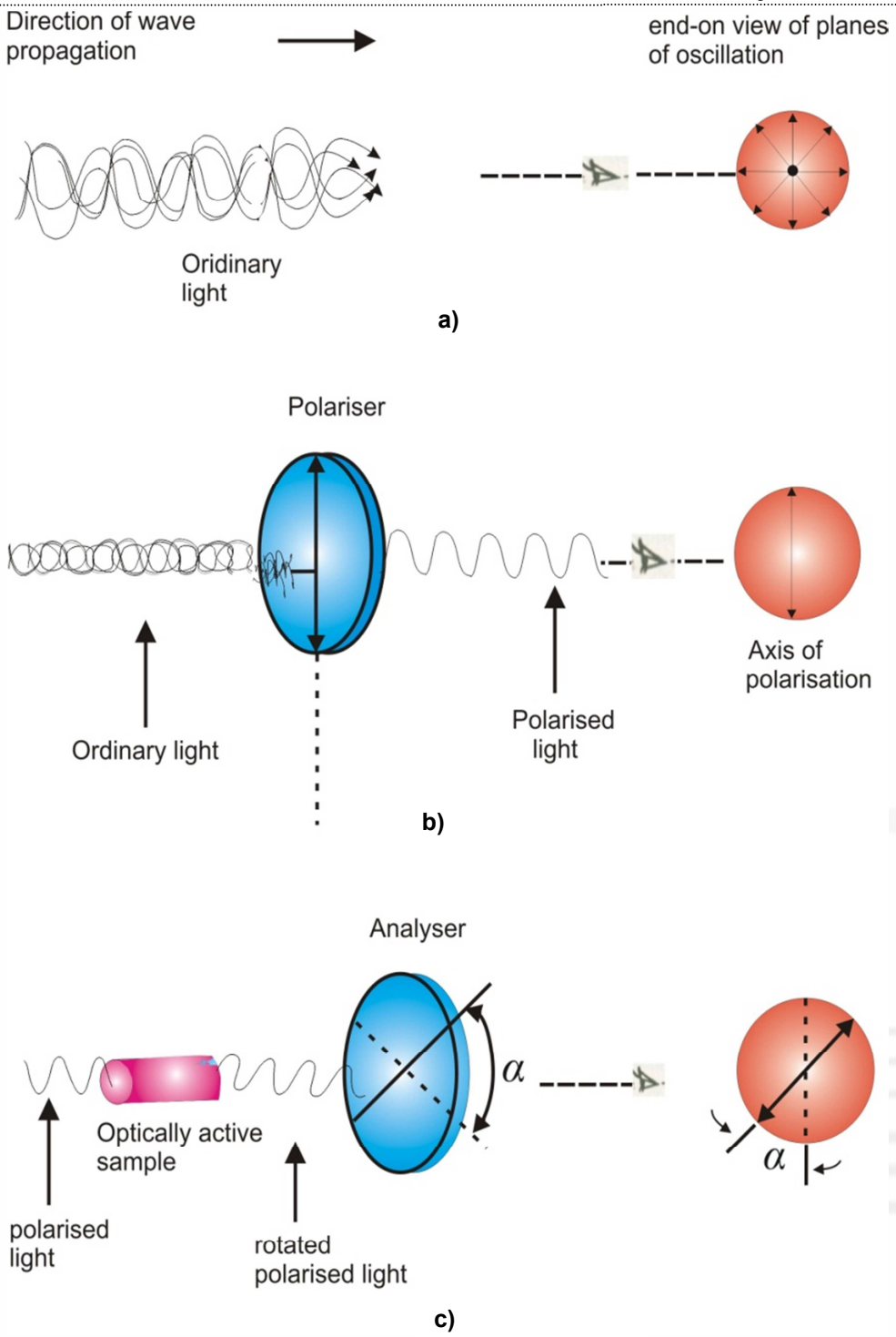
Hint: Note that the coumarin is formed by the loss of water; for removal of water, H and OH groups to be removed as water must remain spatially near to each other.

10.5 OPTICAL ISOMERISM

As pointed our earlier, optical isomerism in manifested by the rotation of the plane–polarised light. Let us first understand what is plane–polarised light and then see how it is used in the determination of optical activity.

10.5.1 Plane-polarised Light and Optical Activity

You are already familiar with the fact that light can be regarded as an electromagnetic radiation having oscillating electric and magnetic fields associated with it. The vectors describing these electric and magnetic fields are at right angles to each other (see Fig. 2.1, Unit 2, Block 1 of this course). Ordinary light consists of light waves of different wavelengths. A monochromatic light (light having a single wavelength having λ = 589 nm, called sodium D line) obtained from the sodium lamp is used in the experiments. This monochromatic light still vibrates in many different planes as shown in Fig. 10.1 a).



Nicol prism, is named after its discover Nicol who passed ordinary light through a prism made by cementing two pieces of crystalline calcium carbonate, also known as Iceland spar, at specific angles to obtain plane-polarised light.

Fig. 10.1: a) Ordinary light. b) Plane-polarised light. c) Rotation of plane of plane-polarised light.

Such a light is called unpolarised light. When a beam of monochromatic light is passed through a polariser such as a polaroid lens or a device known as Nicol prism, the light, (i.e. its electric field) vibrating in **only one plane** is obtained. Such a light is called **plane-polarised light,** see Fig. 10.1b). It was observed that many substances such as quartz crystals and organic compounds like camphor and tartaric acid rotated the plane of plane-polarised light, see Fig. 10.1c). Such substances are called **optically active.**

The instrument used for the determination of optical activity is known as polarimeter. A schematic diagram of a polarimeter is shown in Fig. 10.2.

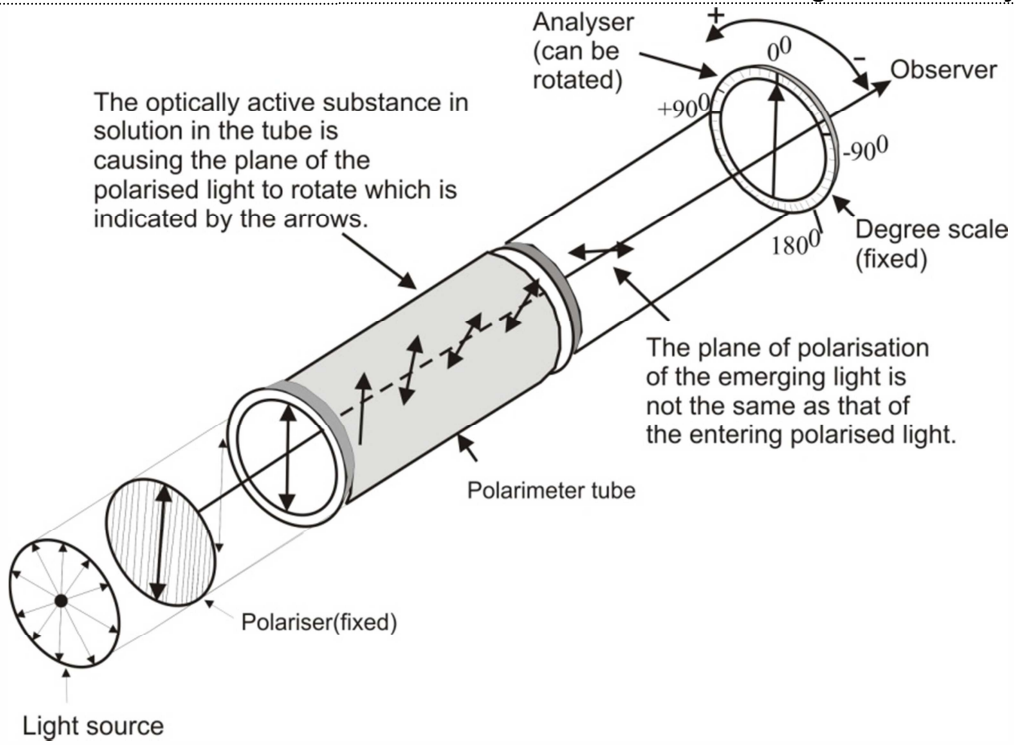


Fig. 10.2: A schematic diagram of a polarimeter.

For an optically active compound, the extent of rotation, α, depends upon thickness of the sample (which is given by the length of the cell, *l*, its concentration (*c*), solvent, temperature and wavelength of the light used. When *l* is taken in decimeters and *c* is taken in kg dm^{-3}, then the rotation in degrees is termed as **specific rotation** and is denoted by [α]. Thus, the specific rotation can be calculated using the following expression,

$$[\alpha] = \frac{\alpha}{l \times c} \quad \ldots (10.1)$$

The temperature, *t* and the wavelength, λ, of the light used are specified as superscript and subscript, respectively. The solvent and the concentration of the solution are given in brackets. Hence, the specific rotation of a sample is expressed as,

$$[\alpha]_{\lambda}^{t} \quad \text{(solvent, } c\text{)}$$

Thus, $[\alpha]_{D}^{293}$ denotes the specific rotation at the temperature 293 K when the measurement is done using the D line of sodium having λ = 589 nm.

The direction of rotation is specified as **dextrorotation** or **levorotation.** When a compound rotates the plane of plane–polarised light in the clockwise direction, it is called **dextrorotatory** and this positive rotation is denoted by the plus (+) sign prefixed to the name of the compound. On the other hand, the compound rotating the plane of plane–polarised light in the anticlockwise direction is called **levorotatory** and such a rotation is taken as rotation in the negative direction. Hence, it is indicated by prefixing a minus (–) sign to the name of the compound. Earlier, the letters *d* and *l* were used to denote the dextrorotation and levorotation, respectively.

Let us now study why some compounds are optically active and the others are not.

10.5.2 Origin of Optical Activity

The origin of optical activity can be traced back to the observations of the French physicist Biot who in 1813 discovered the existence of two types of quartz crystals as shown in Fig. 10.3.

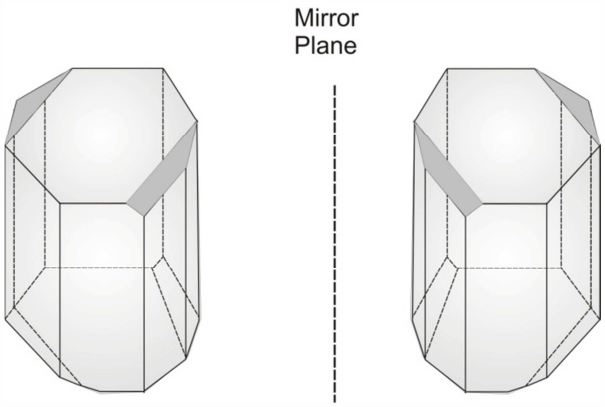


Fig. 10.3: Two types of quartz crystals.

One type of crystals rotated the plane of plane–polarised light to the left and the other type of crystals rotated it to the right. After two years, he observed that such optical activity is not restricted to the **crystalline structure** and some compounds such as camphor and tartaric acid exhibited the optical activity even **in solution.** He also realised that the optical activity in solution is due to some molecular property which is retained even in solution.

Later Pasteur studied tartaric acid and its nineteen different salts and observed that two types of crystals of tartaric acid existed; one being right-handed with respect to certain faces and other being left-handed. These two types of crystals were mirror images of each other. Pasteur proposed that since the optical activity is retained in the solution phase also, it must be a property of the molecules themselves. And, just as the crystals of quartz are mirror images of each other, the molecules of which these crystals are formed, are also mirror images of each other.

This led to the possibility of the existence of compounds whose molecules are mirror images of each other. These mirror image isomers being otherwise identical, exhibit identical physical properties; even the extent of rotation of the plane of plane–polarised light is the same for such pairs. The only difference in their physical properties is in the direction of rotation of plane-polarised light: one isomer being dextrorotatory and the other being levorotatory.

Table 10.2 gives the physical properties for the mirror image isomers of 2–octanol.

Table 10.2: Physical properties of isomeric 2–octanols

Physical property	(–)–2–Octanol	(+)–2–Octanol
Specific rotation $[\alpha]_D^{290}$	–9.9°	+9.9°
Boiling point (K)	448	448
Refractive index (n^{298})	1.4254	1.4258
Specific gravity (d^{293})	0.838	0.822

The next question that you may ask is: What kind of molecules are capable of existing as mirror image isomers? The answer is that the molecule and its mirror image isomer should be non–superimposable. This is explained in detail in the next section.

10.6 CHIRALITY

The most general example that helps us to understand the nonsuperimposabilityis that of our hands as shown in Fig. 10.4. You can see that our two hands are mirror images of each other but they are not superimposable on each other. This becomes more obvious if we try to put the right hand glove on the left hand and *vice-versa*.

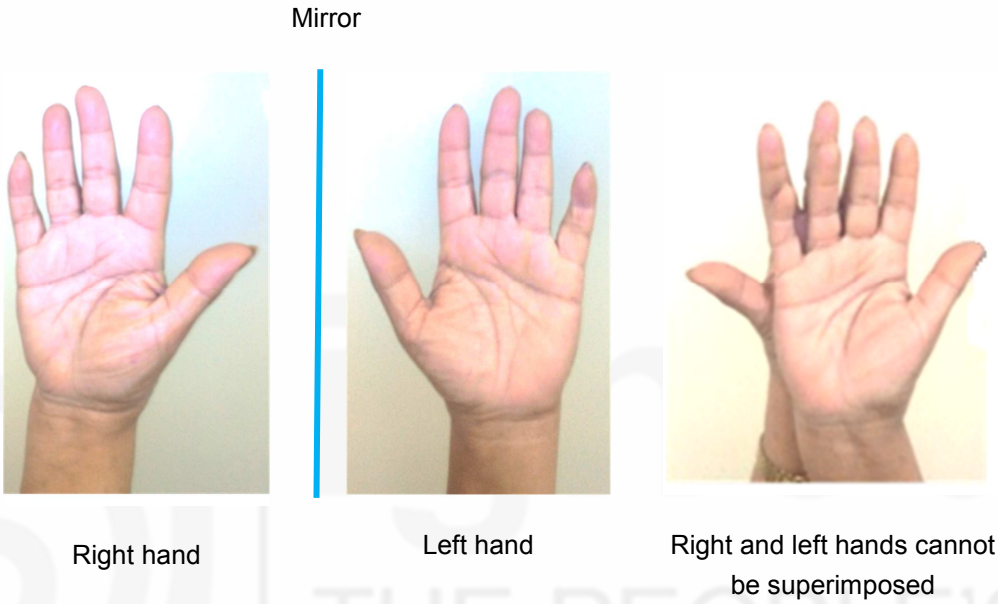
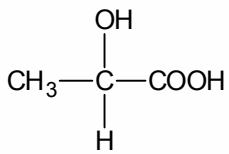


Fig. 10.4: The nonsuperimposability of right and left hands.

Chiral is pronounced as ki-rall.

In the Greek language, the world *cheir* means *hand* and hence, a molecule which is non-superimposable on its mirror image is said to be **chiral** and the term **chirality** means showing *handedness*. Handedness means existence of non-superimposbale mirror image structures. On the other hand, when a molecule is superimposable on its mirror image, it is said to be **achiral.** Hence, lactic acid is a chiral molecule and it said to exhibit chirality.



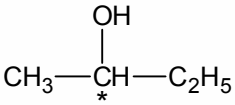
Lactic acid

Rutherford, on observing the recoil of some α-particles from thin gold foil, exclaimed “It was quite the most incredible event that has ever happened to me in my life. It was almost as if you fired a 15 inch shell into a piece of tissue paper and it came back and hit you”.

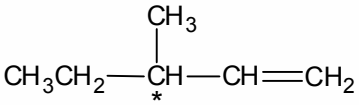
Such molecules which have four different substituents attached to a carbon atom are called **asymmetric**, i.e. they are without symmetry. The tetrahedral carbon atom bearing the four different substituents is referred to as an **asymmetric centre** or a **chiral centre.**

Since, it is the molecule itself which is chiral rather than one of its atoms, it has been suggested that it is more correct to call the carbon atoms of this type as **stereocentres.**

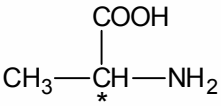
The IUPAC rules for stereochemical notation use the term chiral centre. Given below are some asymmetric compounds in which the chiral centre is shown by an asterisk (*) mark.



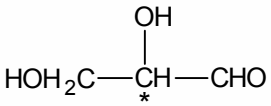
2–butanol



3–methyl–1–pentene



alanine



glyceraldehyde

Remember that a carbon atom forming a double bond cannot be a chiral centre because it cannot have four different substituents.

The satisfactory explanation of the origin of optical activity at the molecular level was given by van't Hoff and Le Bel simultaneously and independently in 1874. van't Hoff realised that it was necessary to think of molecular structures in three dimensions in order to solve the problem of isomers that were being discovered in the laboratory. He proposed that a carbon atom with four different substituents arranged tetrahedrally around it, would account for the existence of mirror image isomers. The tetrahedral arrangement of groups about the carbon atom makes it possible to have left-and right-handed structures (or isomers), see Fig. 10.5.

The first Nobel Prize in Chemistry in 1901 was awarded to van't Hoff.

The phenomenon of optical activity, thus, finds a satisfactory explanation in the tetrahedral geometry of saturated carbon compounds. Le Bel suggested that a carbon atom with four different substituents around it, is the basis of optical activity but he did not specify the tetrahedral arrangement.

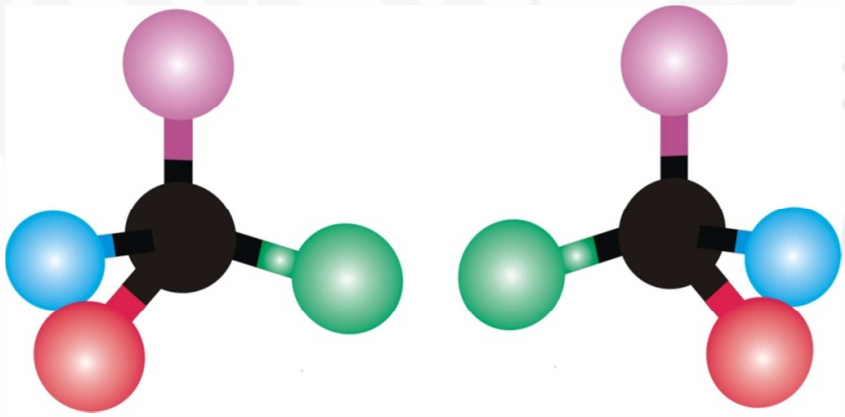


Fig. 10.5: Arrangement of four different substituents on carbon atom.

Let us study more about such isomers as given below.

10.6.1 Enantiomers

Consider the case of lactic acid in which all the four substituents, i.e. H, CH_3, OH and COOH attached to the carbon atom, are different and are arranged tetrahedrally around it. Its two possible isomers are shown below in Fig. 10.6. These isomers are the non–superimposable mirror image isomers (see Fig.10.6). Such non–superimosable mirror image isomers are called **enantiomers. Thus, for a compound to exist as two enantiomers, non-superimposability of mirror image structures is a condition.**

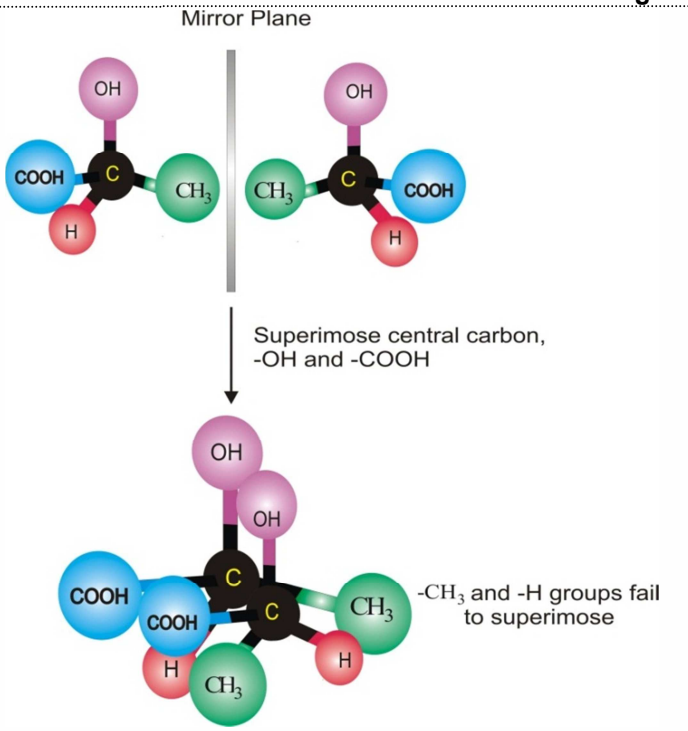


Fig. 10.6: Enantiomers of lactic acid.

To decide whether the two given mirror image structures are enantiomers or are molecules of same isomer, try to superimpose one over the other. If they are non-superimoposable, then they are enantiomers. And, if they are superimposable, they are the molecules of the same isomer, as shown below in Fig. 10.7.

The enantiomers have opposite chirality.

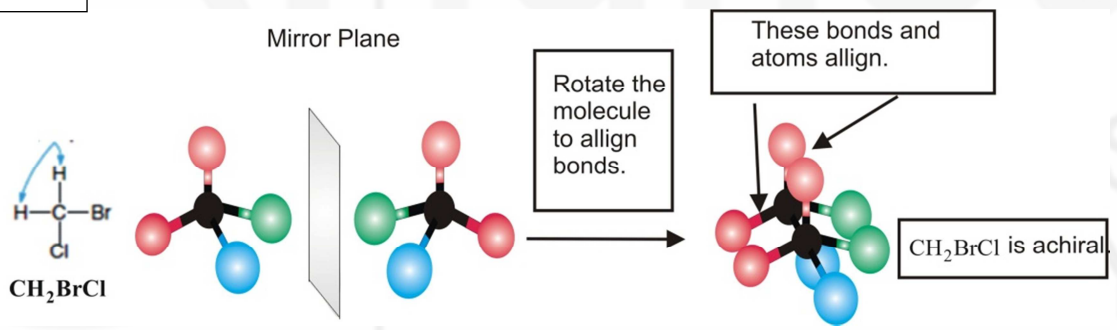


Fig. 10.7: Two molecules of the same compound are superimposable.

Thus, chirality is a necessary and sufficient condition for the existence of enantiomers. Only chiral molecules can exist as enantiomers.

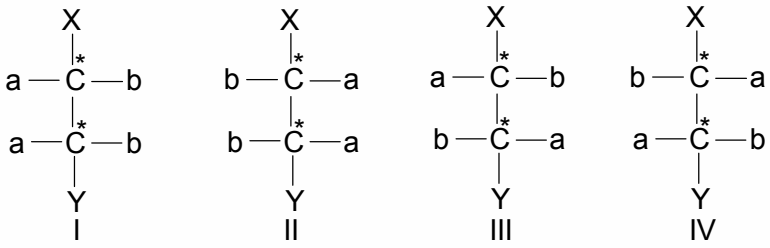
Till now we were dealing with the compounds having only one chiral centre. Let us now study what happens when there is more than one chiral centre in a molecule. But before studying that answer the following SAQ.

SAQ 4

Explain why enantiomers have different optical rotation.

10.6.2 Diastereomers

For a molecule, abXC* - C*abY which has two chiral centres; the following four isomers are possible:

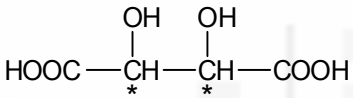


You can see that the isomers I and II are mirror image isomers. Similarly, III and IV are mirror image isomers. Since I and II are nonsuperimposable and so also are isomers III and IV. Hence, I and II, and III and IV are two enantiomeric pairs. But what is the relationship between the following pairs?

I and III; I and IV; II and III; and II and IV.

Certainly, they are not mirror image isomers though they are isomeric. Stereoisomers which are **not enantiomers** are called **diastereoisomers** or **diastereomers.** Hence, I and III, and I and IV are two pairs of diastereomers. Similarly, II and III, and II and IV are two other pairs of diastereomers.

Now let us take the specific example of tartaric acid. It has two chiral centres as shown below.



Tartaric acid

The possible isomers of tartaric acid are given below in Fig. 10.8 as V, VI, VII and VIII.

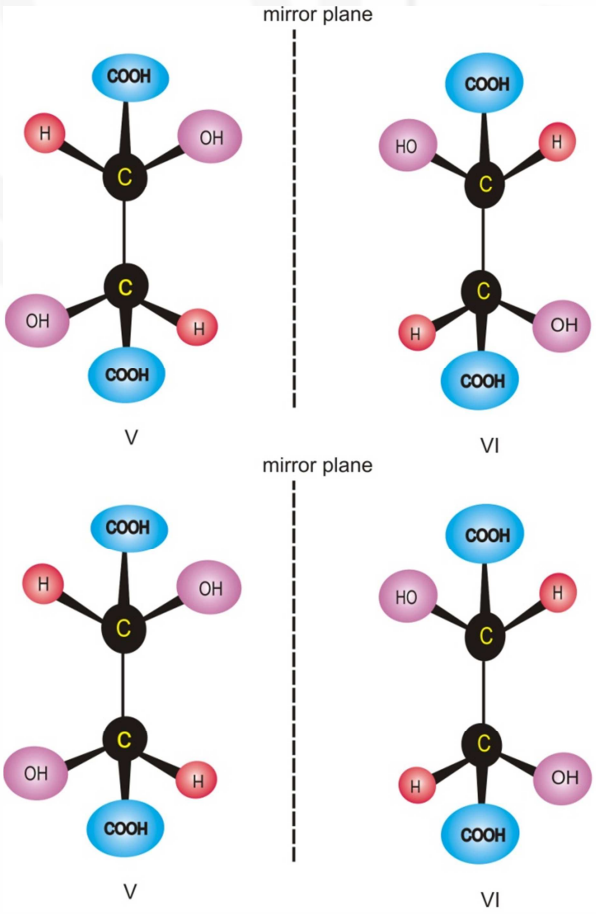


Fig. 10.8: Possible isomers of tartaric acid.

Here, you can categorise V and VI as enantiomers. What about VII and VIII? Although they are mirror isomers, but when we try to superimpose them, we find that they are **superimposable.** Thus, they are not different but are identical; hence, **they represent the two molecules of the same isomer.** Thus, for tartaric acid we have only three isomers.

In general, for a compound having *n* chiral centres, the number of possible stereoisomers is given by 2^n. Thus, for a molecule having two chiral centres, four stereoisomers are possible. But, in some cases (as in tartaric acid), when the chiral centres are *equivalently substituted*, (i.e. the substituents on the chiral centres are the same), fewer isomer than predicted by 2^n, exist.

Of the above isomers. (V and VII (or VIII)) and (VI and (VII or VIII)) are diastereoisomers. Because the diastereoisomers are not mirror image isomers, they often have different physical and chemical properties.

Table 10.3 shows identical physical properties (except for sign of rotation) for the enantiomers V and VI but their diastereomer (VII (or VIII) has physical properties different from those of V or VI.

Table 10.3: Some physical properties for the isomers of tartaric acid

Physical property	**V**	**VI**	**VII (or VIII)**
Melting point/(K)	441 – 443	441–443	419 – 421
Density/(kg dm^{-3})	1.7598	1.7598	1.666
$[\alpha]_D^{293}$	+12	−12	0

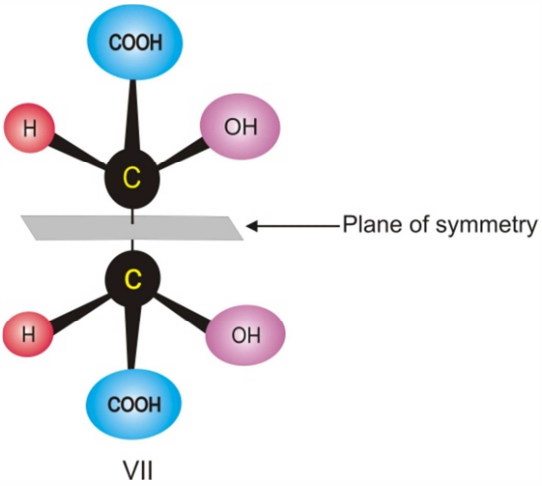
Table 10.3 shows that the compounds having structures V and VI are optically active but the compound represented as VII or VIII is optically inactive, although, it also has two chiral centres. Why is this so? You will find an answer to this question in the next section. But before studying that, answer the following SAQ.

SAQ 5

Write the stereoisomers for the compound $HOH_2CCHOHCHOHCHO$ and group them as enantiomers and diastereomers.

10.6.3 *Meso* Compounds

Let us now go back to the problem we let unanswered at the end of the last sub-section i.e., sub.-Sec. 10.6.2. Since, the third isomer of tartaric acid, represented by structure VII, has a *plane of symmetry,* it is optically inactive. This plane is shown in Fig. 10.9 and can be easily visualised by making a model of structure VII. Such compounds, in which one half of the molecule is the mirror image of the other half, are called *meso* compounds.



VII

Fig. 10.9: *Meso*–tartaric acid

The word *meso* means middle or *in between*.

A *meso* compound is optically inactive due to *internal compensation*; i.e. optical activity due to one half of the molecule is cancelled by that due to the other half.

Thus, *meso*–tartaric acid represented by structure VII (or VIII), has two chiral centres but as it has a plane of symmetry, the optical activity caused by one chiral centre is **cancelled** by that caused by the other chiral centre. This is so because the two halves, being the mirror images of each other, cause equal and opposite rotations. Hence, *meso* compounds are optically inactive.

In other words, it one half of the molecule causes a rotation of $+X^0$ and the opposite half causes a rotation of $-X^0$, then it leads to a zero rotation for the molecule or no optical activity. This type of cancellation is called *internal compensation*. There is another way in which compounds containing chiral centres can behave as optically inactive. You will study about this in the next unit.

10.7 SUMMARY

In this unit, you have learnt that

- Isomerism is the phenomenon of existence of two or more compounds having the same molecular formula.
- Various types of isomerism are possible, the important ones are structural isomerism and stereoisomerism.
- Structural isomerism can be further sub-divided into chain isomerism, position isomerism and functional group isomerism. Stereoisomerism can be further classified as conformational isomerism or configurational isomerism.
- The geometrical isomers can be named according to *cis–, trans– or E, Z* nomenclature.
- The geometrical isomers have different physical properties such as melting point, boiling point and dipole moment.
- The geometrical isomers can be characterised on the basis of their physical properties as well as chemical reactions.
- Optically active compounds rotate the plane of the plane polarised light. The stereoisomers which rotate the plane of the plane polarised light

towards right are called dextrorotatory while the stereoisomers which rotate the plane of the plane polarised light towards left are called levorotatory.

- There are two types of optical isomers: enantiomers and diastereoisomers. The non–superimposable mirror image isomers are called enantiomers whereas diastereoisomers are stereoisomers other than enantiomers.
- Enantiomers have *identical* physical properties (except the direction of optical rotation) but diastereomers have different physical properties.
- Molecules having one chiral centre can exist as enantiomers. However, molecules having more than one chiral centremay or may not be optically active, e.g. *meso* compounds are optically inactive.
- The tetrahedral nature of carbon was postulated on the basis of the observations of optical activity.

10.8 TERMINAL QUESTIONS

1. Write structural formulas for each of the following compounds. Be sure that you write the correct stereochemistry.

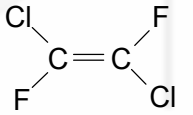
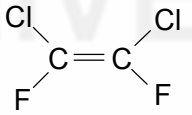
   a) (*Z*)–5–Chloro–2–pentene

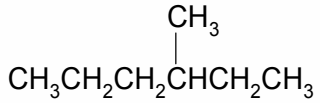
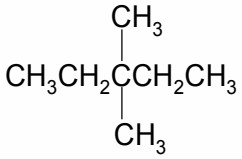
   b) *trans*–1,2–Dimethylcyclopropane

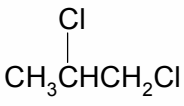
   c) *meso*–2,3–Dibromobutane

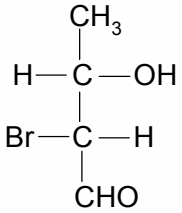
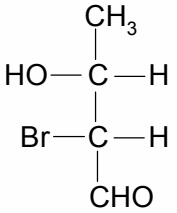
   d) *cis*–1,2–Dichlorocyclopentane

2. Look at the following pairs of compounds carefully and state which type of isomerism they exhibit.

   a)  and 

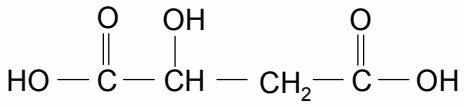
   b)  and 

   c) $Cl_2CHCH_2CH_3$ and 

   d)  and 

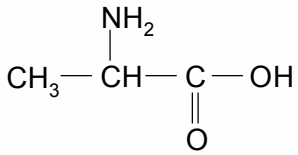
3. a) Locate the chiral carbon in the following compounds and mark them with an asterisk.

i)



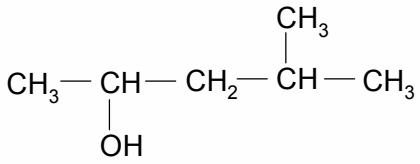
malic acid

ii)



alanine

iii)



4. How many *meso* stereoisomers are possible for 2,3,4–pentanetriol? Write their structures.

10.9 ANSWERS

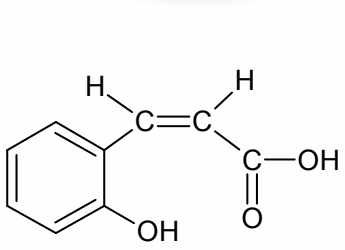
Self-Assessment Questions

1. Structural isomers having molecular formula C_3H_8O are as given below

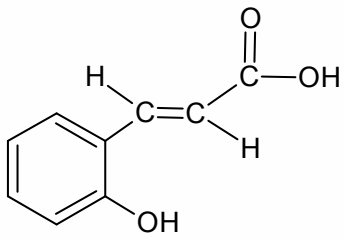
i) $CH_3CH_2CH_2OH$ ii) $CH_3CH(OH)CH_3$ iii) $CH_3OCH_2CH_3$

2. i) *E* ii) *Z* iii) *Z* iv) *Z*

3. a)



cis – isomer

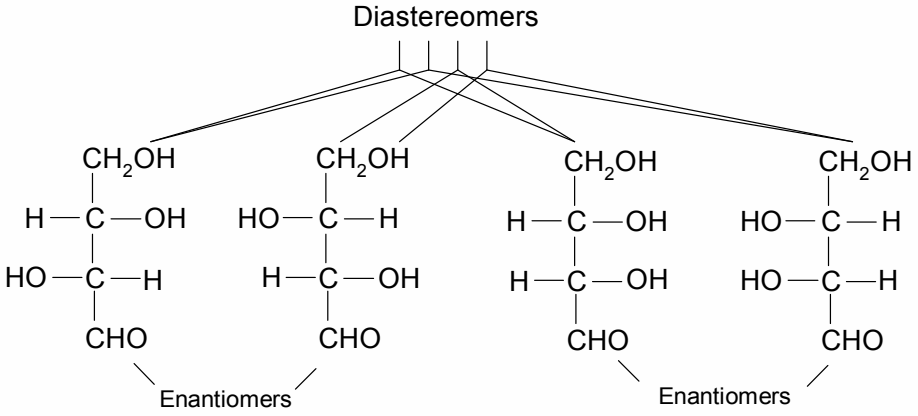


trans – isomer

b) Since –OH and –COOH groups are in close proximity in *cis*–isomer, it can yield the required coumarin by loss of a water molecule.

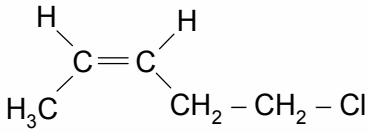
4. The difference in optical activity of enantiomers is due to their different molecular structures. The molecules of the two enantiomers are mirror image isomers; one of which rotates the plane of plane polarised light towards right whereas the other rotates the plane of plane polarised light towards left.

5.

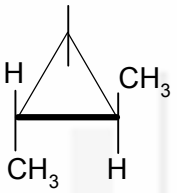


Terminal Questions

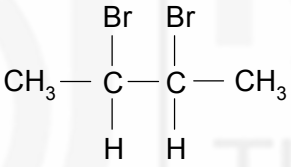
1. a)



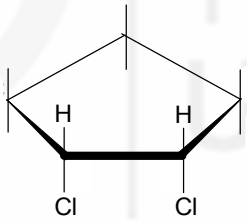
b)



c)

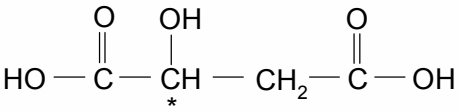


d)

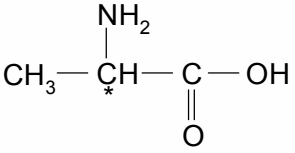


2. geometrical b) chain c) position d) optical (diastereomers)

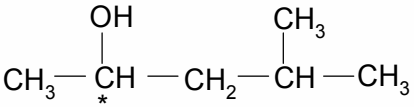
3. a) i)



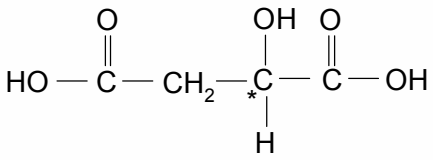
ii)



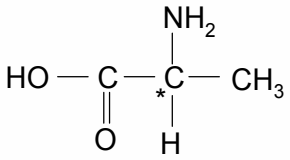
iii)



b) i)



ii)



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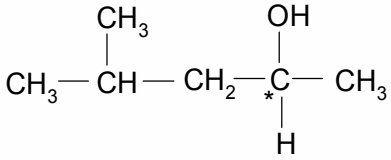
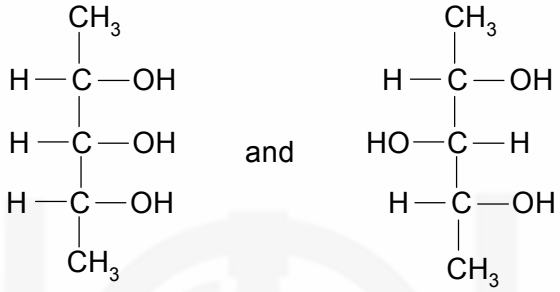


4. The two *meso* stereoisomers of 2,3,4-pentanetriol are as follows:



UNIT 11

STEREOCHEMISTRY–II: CONFIGURATIONAL ISOMERS

Structure

11.1 INTRODUCTION

In Unit 10, you studied the geometrical and optical isomerisms. The arrangement of atoms or groups in space about a rigid framework was referred to as **'configuration'** in Unit 10. In geometrical isomerism, you learnt that the geometrical isomers can be assigned the configuration as *cis*– or *trans*– and *E*– or *Z*–, depending upon the spatial arrangement of groups about the rigid framework. You also studied about the existence of optical isomers such as enantiomers and diastereomers. These optical isomers have different configurations.

In this unit, you will study how to designate the configuration of optical isomers. Before that, writing the three-dimensional structures of molecules in two-dimensions using Fischer projections will be explained. We will then describe *R* / *S* system and *Erythro*– and *threo*– nomenclature for designating the configurational isomers.

We will also discuss how configuration is affected in chemical reactions. Under the laboratory conditions, chemical reactions yield an equimolar mixture of the two enantiomers called racemic mixture. Here, you will also learn how to separate these mixtures in order to obtain optically pure compounds.

Expected Learning Outcomes

After studying this unit, you should be able to:

- explain configurational isomerism;
- define configuration;
- write Fischer projection formulae for simple organic compounds;
- assign the configuration as either *R* or *S* to the chiral centre in a compound , describe the *erythro*– and *threo*– system of designating the diastereoisomers; and
- describe a racemic mixture and explain various methods of resolution for such a mixture.

11.2 CONFIGURATION AND FISCHER PROJECTION FORMULAE

The term *configuration* was used earlier in case of geometrical isomers to indicate the spatial arrangement of groups around a rigid framework. Similarly, the term configuration as applied to optical isomers indicates the spatial arrangement of atoms or groups around the chiral centre.

You know that the actual molecules are three-dimensional in nature. So, the spatial arrangement of groups in a molecule, i.e. its configuration, can be specified either by making its three-dimensional model or by writing the corresponding projection formulas. Also, to specify the configuration of a molecule having several chiral centres, the configuration at each chiral centre needs to be specified.

Emil Fischer
(Recived Nobel Prize in 1902)

A Fischer projection formula is a standard way of depicting tetrahedral carbon atoms and their substituents in two dimensions.

This specification of configuration for a molecule becomes more and more difficult as the number of chiral centres goes on increasing. Thus, a need was felt for a convention to represent the *actual three-dimensional structure* of molecules *in two dimensions*, (i.e. in the plane of the paper) in a simple and convenient way. The German chemist Fischer introduced such a convention. He called his representations as projection formulas. These representations are now known after his name as **Fischer projection formulae.**

Before proceeding to the study of Fischer projection formulae, it is necessary to familiarise you with another representation known as *perspective drawing*. Such a representation is used to represent three-dimensional structures of molecules in two dimensions. Fig. 11.1a) illustrates such a perspective drawing. In a perspective drawing, a broken wedge represents the bond which is **behind** the plane of the paper and the solid wedge represents the bond which points **towards** the observer in front of the plane of the paper. The other two bonds which are represented by ordinary lines show the substituents which are **in** the plane of the paper.

Let us now learn how to write Fischer projection formula of the molecule whose perspective drawing is shown in Fig. 11.1a). It is better if you take the help of the models sent to you. Make a model of such a molecule by attaching

four different substituents to a tetrahedral carbon atom. Now look at the model in such a way that the two substituents which point **towards** you are in the **horizontal plane** and the other two substituents which point **away from you** are in the **vertical plane,** as shown in Fig. 11.1a). You can see in Fig. 11.1b) that the angle between the horizontal and vertical planes is a right angle. Hence, the substituents in the horizontal plane are **at right angles** to the substituents in the vertical plane. We can represent these two sets of substituents at right angles to each other in one plane (obviously plane of paper), by drawing two lines at right angles to each other.

Then, the substituents are written in the positions in which they appear to the observer, i.e. the substituents which are at left and right of the observer are written at left and right, respectively, and the other two substituents which appear above and below are written at above and below positions, as shown in Fig. 11.1c). Further, we can simplify Fig. 11.1c) by removing the plane of paper shown in it and write the structure of the molecule as shown in Fig. 11.1d), which is nothing but the **Fischer projection formula** for the compound shown in Fig. 11.1a). Note that the chiral centre is not shown in Fischer projection formula and it is assumed to be located at the point of intersection of the horizontal and vertical lines.

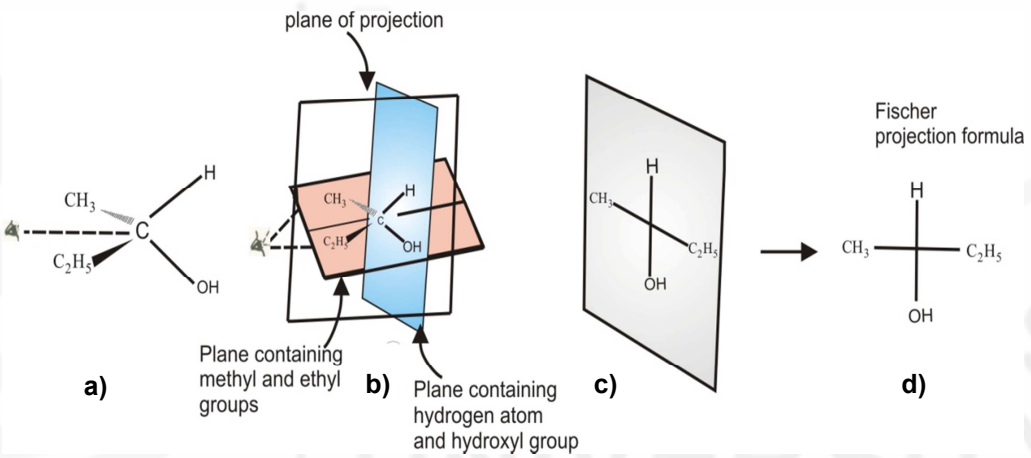


Fig. 11.1: Writing Fischer projection formula for a molecule: a) perspective drawing of a molecule having one chiral carbon atom; b) two substituents each in horizontal and vertical planes at right angles to each other; c) representation of molecule in plane of paper; and d) the Fischer projection formula.

Similarly, for one of the isomers of tartaric acid, shown in Fig. 11.2a), the Fischer projection formula can be written as shown in Fig. 11.2b).

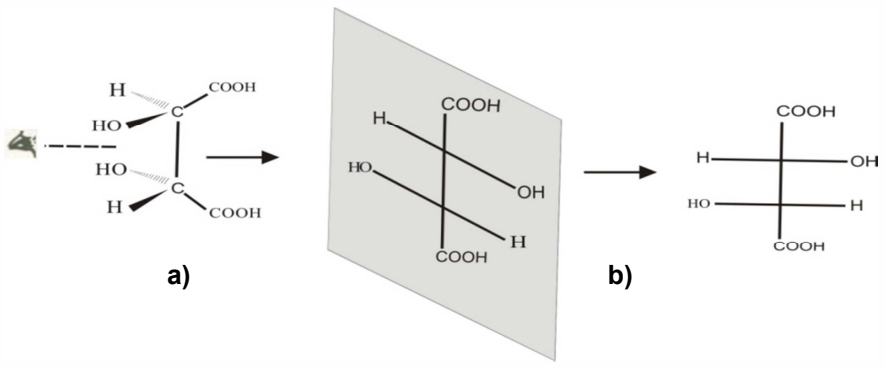
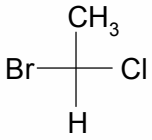


Fig. 11.2: a) An isomer of tartaric acid and b) its Fischer projection formula.

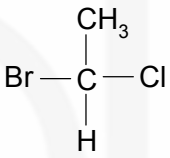
The Fischer projection formula or Fischer projections are very useful in case of molecules having may chiral centres linked together to form a continuous chain. You will realise the importance of these projection formulae in a later course when you will write the structures of carbohydrates.

Let us now learn the reverse of what have done above, i.e. write the three-dimensional structures of a molecule from its Fischer projections. For this, we have to reverse the process we have just described. **Always remember that in a Fischer projection formula, the vertical lines represent the bonds that point away from you and the horizontal lines represent the bonds that point towards you.** Let us start with a molecule having the Fischer projections as given below,

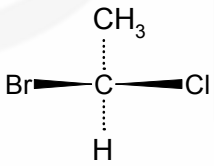


The three-dimensional structure for this molecule can be written by using the following steps:

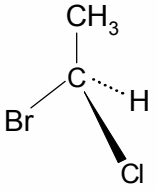
i) Write a carbon atom at the intersection of the horizontal and vertical lines in Fischer projection, as shown below.



ii) Since thevertical lines represent the bonds away from the observer and the horizontal lines represent the bonds towards the observer, we can write the structure of the molecule shown in step i) as,

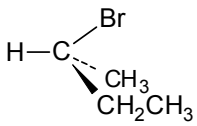


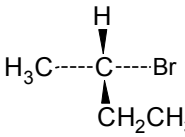
This can be translated into the perspective formula by viewing the molecule in such a way that the two substituents (say, CH_3 and Br) parallel to the planeof the paper. In such a situation, H will appear behind the plane of the paper and Cl will appear projecting in front of the plane of the paper leading to the perspective drawing of the molecule as follows:

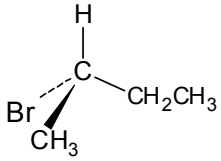


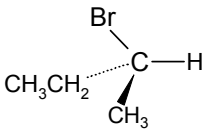
which leads to the following three-dimensional structure of the molecule.

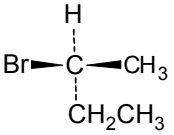
Different representations of (+)–2–bromobutane.

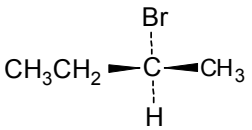


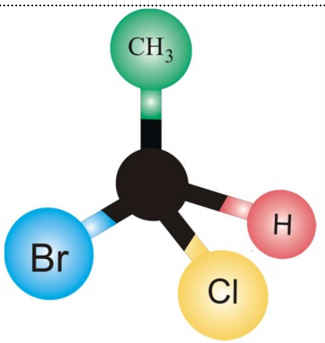






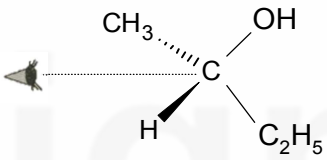




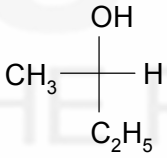


How to interconvert Fischer Projections while maintaining the Configuration

Since there are many ways in which a given molecule can be oriented depending upon which two substituents are chosen to point towards the observer; hence, several different Fischer projections can be written for the same molecule. Let us go back to Fig. 11.1 and instead of viewing the molecule as shown in Fig. 11.1a), now let us view the molecule in such a way that the substituents CH_3 and H point towards the observer. Thus, the substituents will now appear as shown below.

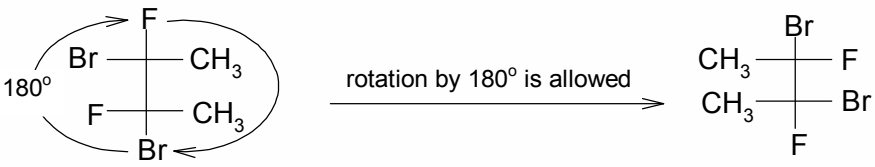


For this orientation of the molecule, the Fischer projection formula can be written as,



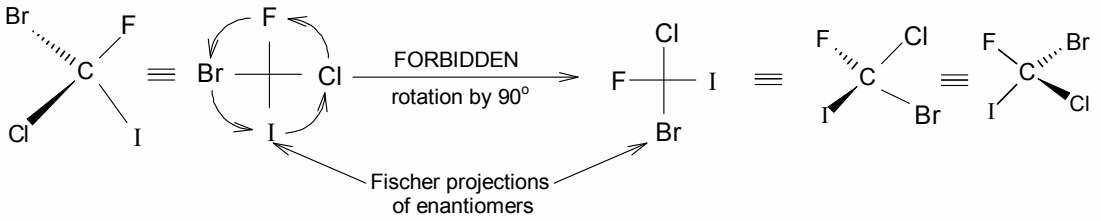
which is another Fischer projection formula for the same molecule as shown in Fig. 11.1a). Because various Fischer projections are possible for a given molecule, you should have a clear understanding of writing different correct Fischer projections for a given molecule without going back and forth to the three-dimensional model. Therefore, you should be able to write different Fischer projections for the same molecule form its given Fischer projection formula. For this, there are some rules to be followed. These rules are as given below.

1. Rotation of the given Fischer projection formula by 180^0in the plane of the paper yields another Fischer projection of the *same molecule*, i.e.,



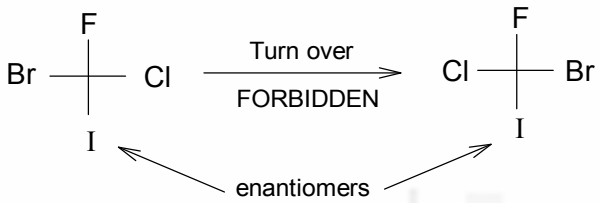
In other words, rotation of the Fischer projection in the plane of paper by 180° does not alter the configuration.

2. Rotation of a Fischer projection formula of a compound in the plane of the paper by 90° yields the Fischer projection formula of its enantiomer. It means that such a rotation leads to change in the configuration at the chiral centre. This is illustrated in the following example.



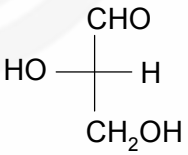
It is better to verify this rule with the help of the models.

3. Fischer projection formula may **not** be lifted out of the plane of the paper and turned over as shown below.

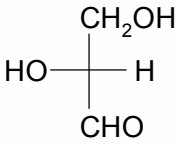


Thus, turn over leads to the Fischer projection formula of the enantiomer. Thus, this operation on the Fischer projection changes the configuration at the chiral centre.

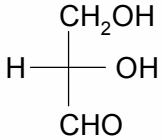
4. Interchange of two pairs of substituents leads to another Fischer projection of the same isomer. Hence, no change in configuration is observed by this operation. Let us understand this by the following example. If we have a molecule represented by the following Fischer projection,



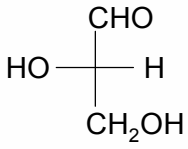
Interchange of one pair of substituents (i.e., –CHO and–CH_2OH) leads to the following Fischer projection.



Another interchange of second pair of substituents leads to the Fischer projection as follows:



This structure when rotated by 180°, yields



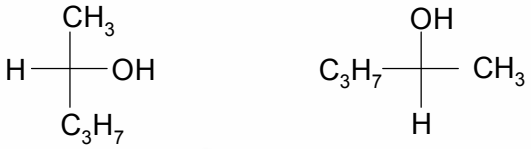
which is nothing but the same isomer we started with.

In the next section, you will learn about the specification of the configuration at a given chiral centre. Before that check your knowledge of Fischer projections, by answering the following SAQ.

SAQ 1

Study each of the following pairs of Fischer projections carefully and decide whether they represent the same isomer or an enantiomeric pair.

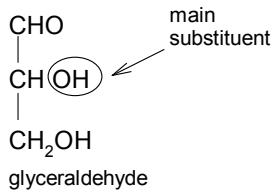
a)



b)

c)

d)



There is also a convention that the longest carbon chain forms the vertical back bone of the Fischer projections with the most highly oxidised carbon (if any) at the top; and then the substituents are projected horizontally.

Do not confuse *d* and *l* with D and L. The lower-case *d* and *l* were used in many places in older literature to specify the direction of rotation (synonymously with '+' and '–'). But D and L are used to specify the configuration at the chiral centre.

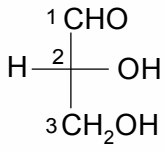
11.3 CONFIGURATIONAL NOTATIONS

The existence of enantiomers poses special problem of their nomenclature. As the enantiomers differ from each other in their direction of rotation, prefixes *d* and *l* were used earlier to designate the dextrorotatory and levorotatory isomers, respectively. But it was reaslised that the sign of rotation does not tell about the absolute configuration of the compound. Thus, to describe the structure of a compound completely, it was necessary to specify the configuration at each chiral centre.

One of the earliest attempts to specify the configuration is that of Fischer which dates back to 1891. According to this system, the configuration at a

particular carbon atom is designated by selecting a main chain in the molecule in the sense of the rules which are used for nomenclature. The molecule is then oriented vertically in such a way that the carbon atom numbered 1 in the chain is at the top. Then, the main substituent attached to the chiral centre is looked for. For example, in glyceraldehyde, it is an – OH group. If in the Fischer projections of the compound the main substituent group is on the **right,** then the molecule is said to have D configuration and when this main substituent is on the **left,** then the molecule is said to have L configuration.

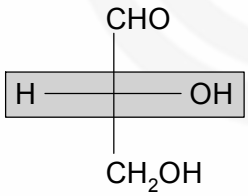
Rosanoff (1906) suggested that a particular configuration be assigned to (+)-glyceraldehyde. The Fischer projection corresponding to this configuration is given below.



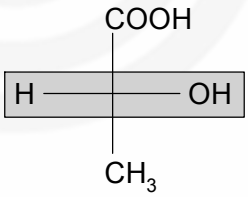
Thus, according to this system of designation of configuration as D or L, the carbon chain in (+)- glyceraldehyde can be numbered and oriented as shown above. Here, the substituent on the chiral centreis hydroxyl (–OH) group. Since, it is on the right side, hence, (+)-glyceraldehyde has D configuration. Similarly, the enantiomer of (+)-glyceraldehyde, i.e. (–)-glyceraldehyde will have L configuration. Thus, we can designate the two enantiomers as D-(+)-glyceraldehyde and L-(–)-glyceraldehyde. Also, all compounds having an arrangement of atoms similar to that at the chiral centre of (+)-glyceraldehyde at the corresponding carbon atom are members of the D family. Similarly, we can state for the L family. Some examples of compounds belonging to D and L families are shown below:

The D, L system is useful in specifying the configurations for carbohydrates and amino acids.

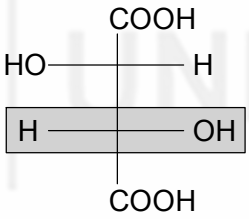
D-family



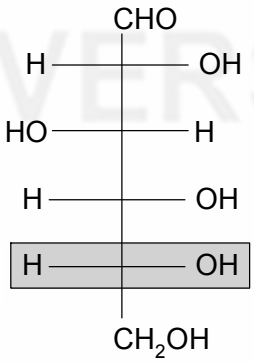
D-(+)-glyceraldehyle



D-(–)-lactic acid

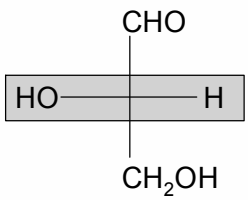


D-(–)-tarteric acid

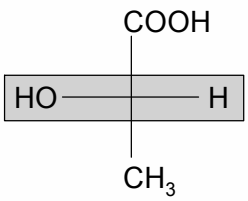


D-(+)-glucose

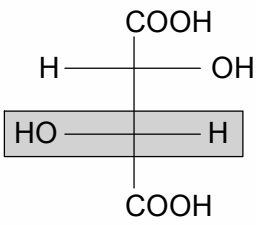
L-family



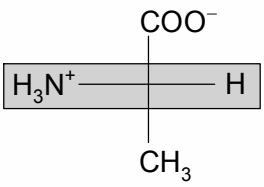
L-(–)-glyceraldehyle



L-(+)-lactic acid

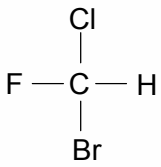


L-(–)-tarteric acid



L-(+)-alamine

The D, L system can be applied only when the main chain and the main substituents can be unambiguously chosen; hence, in some cases, it is not possible to assign the configuration by this system. For example, the molecules of the type cannot be assigned configuration according to this system.



Also, there are cases when it is difficult to assign the configuration unambiguously to the molecules containing more than one chiral centre.

Thus, a more systematic way of denoting configurations was needed. The system that emerged is called the *R, S* convention and is discussed below.

In the light of the fact that **the configuration of a chiral centre in a compound is not changed unless at least one bond at the chiral centre is broken,** chemists on the basis of the experimental evidences realised that the configurations of various optically active compounds can be related to each other even without knowing their absolute configurations. Thus, **relative configurations** of a large number of compounds could be determined.

11.3.1 *R/S* System

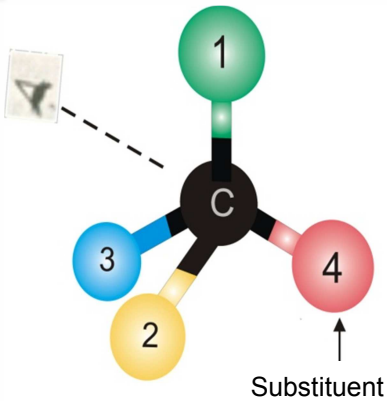
The *R/S* system of designating configuration is based on the actual three-dimensional formula of the compound to be named. In this system, the configuration at the chiral centre is assigned by assigning the order of precedence to the groups attached to the chiral centre according to the specific set of rules.

These rules have been already listed as Cahn-Ingold-Prelog priority rules in Unit 10. According to this system, the configuration of a given chiral centre can be assigned using the following steps:

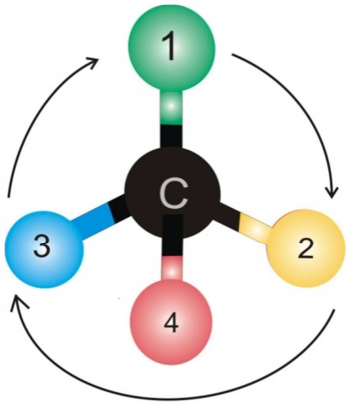
1. Identify the four substituents attached to the carbon atom for which the configuration is to be assigned.

2. Arrange these substituents in the decreasing order of priority as 1 > 2 > 3 > 4 which is determined by Cahn-Ingold-Prelog rules.

3. View the molecule in such a way that the substituent of lowest priority is away from observer.



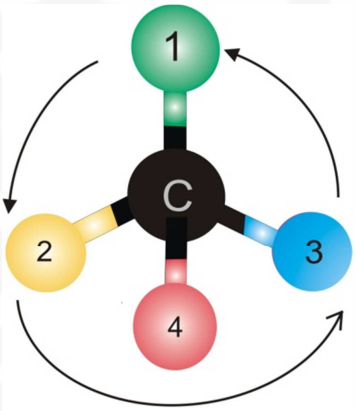
4. When the molecule is viewe d in the way as suggested in step 3, the remaining substituents 1, 2 and 3 appear as spokes of a wheel, with the carbon atom at the centre of the wheel, as shown below.



Clockwise;
therefore *R*

Now, trace a path starting from the substituent of highest priority to the substituent next in order of priority, i.e., from 1 to 2 to 3. If this path is in clockwise direction, as in the case of arrangement shown above, then the chiral centre is said to have the *R* configuration (*R* from *rectus,* a Latin word meaning: **right**).

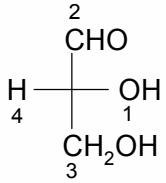
If this path from 1 to 2 to 3 has an anticlockwise direction, then the chiral centre is said to have the *S* configuration (*S* from *sinister*, a Latin word meaning: **left**),i.e.



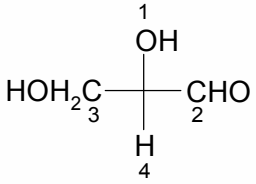
Anticlockwise
therefore *S*

Since, the assignment of *R* or *S* configuration to the molecule requires a specific orientation of the molecule in space, you should be able to write the three-dimensional orientation of a molecule from its Fischer projections and *vice-versa*.

Let us now take the example of D-(+)-glyceraldehyde and see how the configuration at the chiral centre of a molecule can be assigned starting from its Fischer projection. The Fischer projection formula of D-(+)-glyceraldehyde can be written as follows:

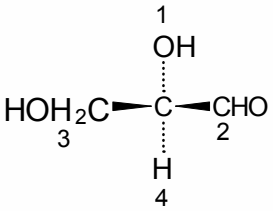


The four substituents attached to the chiral centre have the order or priorities as shown by the numbers 1>2>3>4. Now, the molecule is to be viewed in such a way that the substituent of lowest priority i.e. having number 4 in the priority, which is a hydrogen in this case, is away from the viewer. In other words, in the Fischer projection formula, this substituent should find a place at the bottom end. Thus, we have to transform the above Fischer projection into another Fischer projection as shown below:

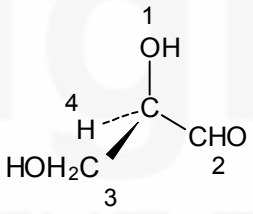


This new Fischer projection corresponds to the following perspective drawing.

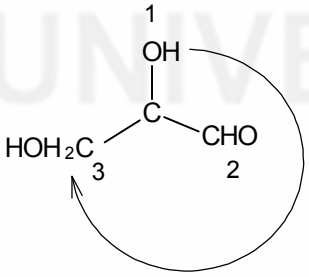
Use models to understand the transformations from perspective drawing to the assignment of configuration.



The molecule is then projected in such a way that H is at the back.



Then, by overlooking this H, path from $1 \rightarrow 2 \rightarrow 3$ is traced as illustrated below.

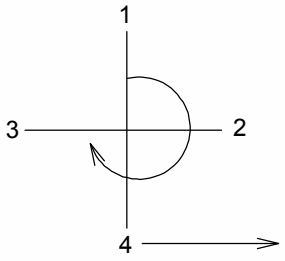


Since, this path is clockwise, hence, D-(+)-glyceraldehyde is assigned *R* configuration.

There is another way which allows the assignment of configuration without having to visualise the three-dimensional structure of the molecule. Let us study it.

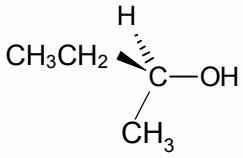
A simple way to assign *R* or *S* Configuration using Fischer Projections

It is a short cut method and requires that the Fischer projection is written in such a way that the substituent of lowest priority is at bottom. Then, this substituent is neglected and the configuration is assigned by tracing the path from 1 to 2 to 3, as stated before.



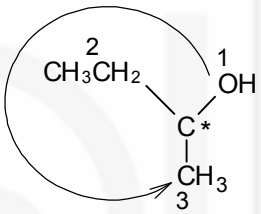
neglect it and trace the path from 1 to 2 to 3. Since, this path is in clockwise direction, hence the configuration is *R*.

Similarly, in case of (+)-2- butanol,



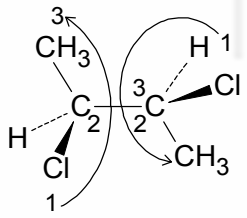
(+)-2-butanol

the order of priority of substituents is $\underset{1}{OH} > \underset{2}{CH_3CH_2} > \underset{3}{CH_3} > \underset{4}{H}$. If the molecule is viewed in such a way that the H is at the back, then the other substituents appear as shown below:



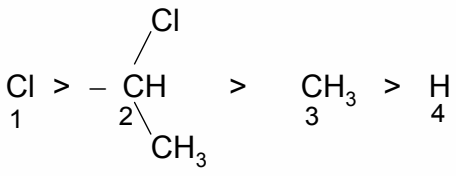
Now,trace the path from 1 to 2 to 3 which is anticlockwise in this case. Hence, the configuration of the carbon atom marked by asterisk (*) is *S*.

In the compounds containing more than one chiral centre, the configuration is specified at each of these centres. For example, in case of 2,3-dichlorobutane,



2,3-dichlorobutane

the priorities of substituents at the C-2 and C-3 chiral centres are



Focusing our attention on C-2 carbon, the path from substituents 1 to 2 to 3 has anticlockwise direction; hence, it has *S* configuration. Similarly, at C-3

carbon also, the path from 1 to 2 to 3 is in anticlockwise direction. Hence, it also has *S* configuration. Thus, this isomer of 2,3-dichlorobutane is named as (2*S*,3*S*)-2,3-dichlorobutane.

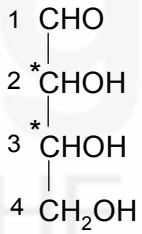
With the determination of absolute configuration of (+)-tartaric acid, the absolute configuration of its enantiomer (−)-tartaric acid was also established. The (−)-tartaric acid and (+)-glyceraldehyde were known to have the same relative configuration. Thus, the absolute configuration of (+)-glyceraldehyde was also established; and the configuration assigned earlier to (+)-glyceraldehyde arbitrarily was found to be correct.

It is not difficult to decide whether a molecule has *R* or *S* configuration, if the actual arrangement of the groups about the chiral centre is known. But, how to determine the actual arrangement of the groups? Until 1951, the absolute configuration of any optically active compound was not known. In 1951, Bijvoet determined the absolute configuration of (+)-tartaric acid using a sophisticated modification of X-ray diffraction called **anomalous dispersion.** Then, the absolute configurations of all other compounds whose configurations had been related to (+)-tartaric acid were also revealed.

11.3.2 *Erythro*- and *Threo*-Nomenclature

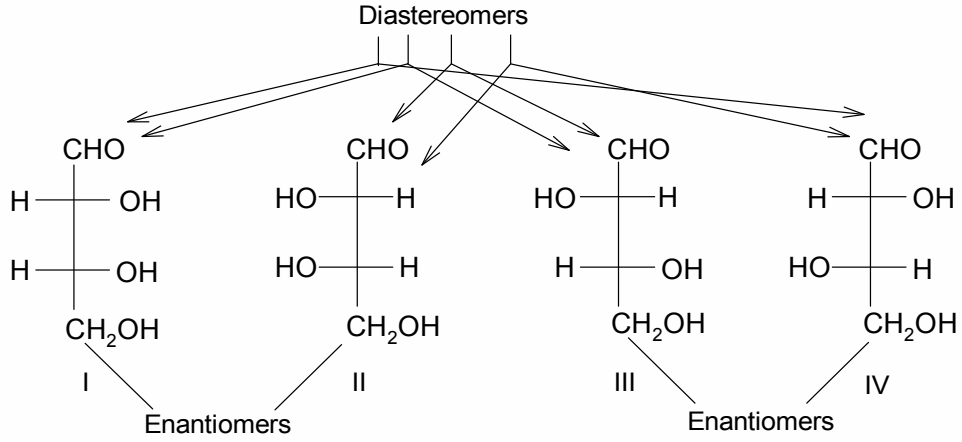
This is another way of designating diastereoisomers. It is very useful in case of carbohydrates. With the increase in the carbon chain length in carbohydrates, the number of stereocentres increases and this leads to increased number of stereoisomers. The number of possible stereoisomers is given by n^2 where n is the number of stereocentres present in a molecule. Hence, for a molecule having two stereocentres, 2^2 or four stereoisomers are possible.

Let us understand this with the example of the aldotetrose, 2,3,4-trihydroxybutanal.



2,3,4-Trihydroxybutanal

It is called an aldotetrose as it has an aldehyde (−CHO) functional group and a chain of four carbon atoms. It has two stereocentres at C−2 and C−3 which are shown below by asterisk (*) mark in its four possible stereoisomers.

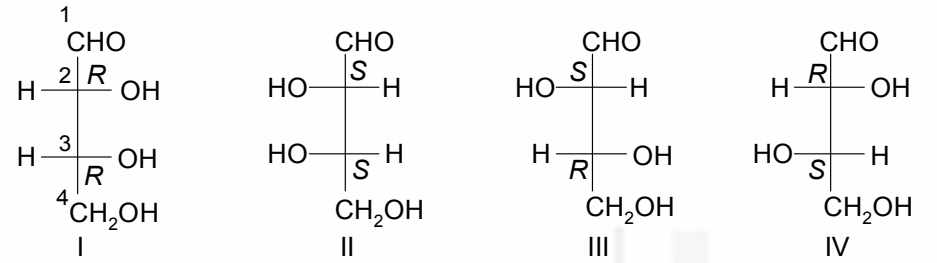


You can see that stereoisomers I and II are enantiomers. Similarly, stereoisomers III and IV form another enantiomeric pair. But stereoisomers I

and III as well as I and IV are diastomers. Also, II and III are diastereomers and II and IV are another pair of diastereomers.

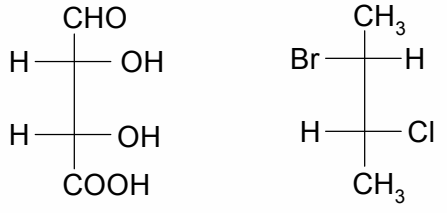
In stereoisomers I and III, the hydroxyl group at carbon number 3 is on the right hand side in the Fischer projections shown above. Hence, these stereoisomers belong to D-series. But in stereoisomers II and IV, the hydroxyl group at carbon number 3 is on the left hand side in the Fischer projection and therefore, these stereoisomers as classified as belonging to L-series.

The stereoisomers I and II are, thus, called D-Erythrose and L-Erythrose, respectively. Note that in *erythro*– stereoisomers, the substituents in the Fischer projection are on the *same side*. On the other hand, in stereoisomers III and IV, which are called D-threose and L-threose, respectively the substituents are on the *opposite side* in the Fischer projection. This is shown below in the names of these stereoisomers.



In the structures of these isomers, the absolute configuration of each stereocentre (i.e. carbon numbers 2 and 3) is specified as *R* or *S* as the case is. Please also remember that (–) and (+) signs in the names of these stereoisomers indicate their directions of optical rotations. You can see that the enantiomeric relationship of D-erythrose and L-erythrose is evident by their (2*R*, 3*R*)and (2*S*, 3*S*) configurations, respectively. Similar relationship can also be seen between the other pair of enantiomers (III and IV). On the similar lines, we can interpret for the configurations at C–2 and C–3 for various pairs of diastereoisomers mentioned above.

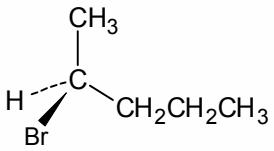
The erythro and threo designations can be extended to other molecules also in which two adjacent stereo centres are present and in their diastereomers, the substituents on these centres are present on the same side or on the opposite sides in the Fischer projection. This is illustrated in the following examples.

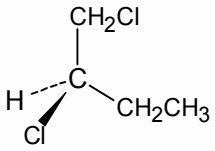


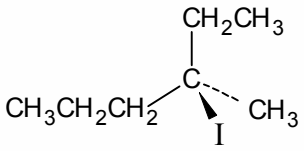
To determine the configuration, one must have a pure sample of the compound. But this is not usually the case and most often in chemical reactions, one gets a mixture of enantiomers. In the next section, we will study in detail about these mixtures and their separation into enantiomers. But, before that answer the following SAQs.

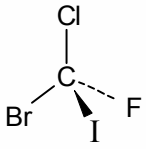
SAQ 2

Assign the configuration as *R* or *S* to each of the following compounds:

a) 

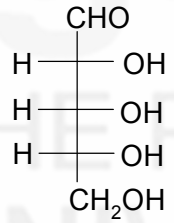
b) 

c) 

d) 

SAQ 3

The structure of D-(–) ribose is given below:



i) Indicate whether it is an *erythro*– or a *threo*–stereoisomer.

ii) Draw its enantiomer and classify the enantiomer as *erythro*– or *threo*– stereoisomer.

11.4 RACEMIC MIXTURES AND THEIR RESOLUTION

A mixture containing an equal amount of each enantiomer of compound is called a **racemic mixture** or a **racemic modification** or a **racemate.** A racemic mixture is indicated by the (±)-sign or just by the racemic prefixed to the name of the compound.

The physical properties of a racemic mixture are different from those of the pure enantiomers. For example, the melting point of the either enantiomer of 2-hydroxypropanoic acid (lactic acid) is 326 K but the racemic 2-hydroxypropanoic acid (lactic acid) has a melting point of 291 K. Also, since a racemic mixture contains equal amounts of enantiomers, optical rotation of

one enantiomer is cancelled by an equal and opposite rotation of the other enantiomer. Hence, a racemic mixture is **optically inactive** although its constituents are **optically active.**

A racemic mixture can be obtained from a pure enantiomer by a process called **racemisation.** It can also be obtained by simply mixing two enantiomers in equal amounts. Racemic mixtures may also result from chemical reactions. One such kind of reactions is the *nucleophilic substitution reaction.* You will study about these reactions in detail in a later course. But to give you an idea about how a racemic mixture results from them, one such reaction is illustrated in the box.

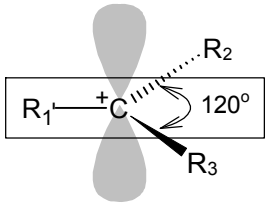
A **substitution reaction** can be defined as the reaction in which one group is substituted by another group. For example, in the reaction below,

$$CH_3 - I \quad + \quad {}^{-}OH \quad \rightarrow \quad CH_3 - OH \quad + \quad I^{-}$$

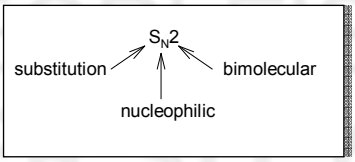
(substrate) (nucleophile) (product) (leaving group)

the iodide group is substituted by the hydroxide group. When the incoming group($^{-}$OH group in this case) is a **nucleophile,** (means seeking a nucleus; obviously an electron rich species), then, the reaction is called **nucleophilic substitution reaction.**

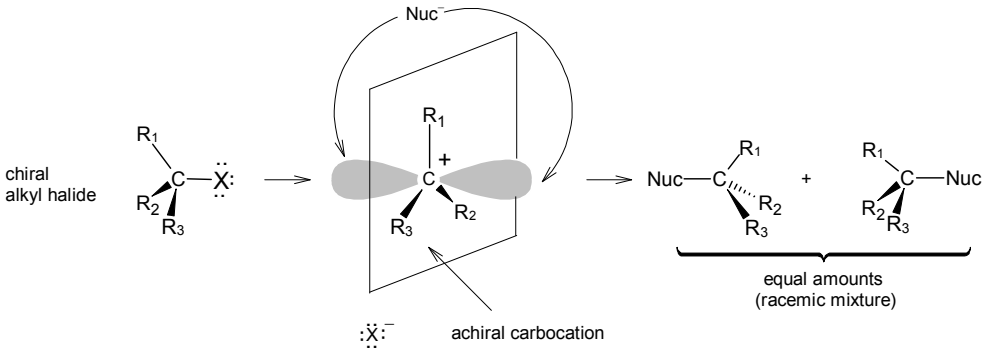
The nucleophilic substitution reactions can be **unimolecular** or **bimolecular,** depending upon the number of molecules involved in the rate-determining step of the reaction. When the rate-determining step involves a single molecule, the reaction is called a *unimolecular substitution reaction* and it denoted as S_N1. The S_N1 reactions involve a positively charged carbon atom as an intermediate which is called a **carbocation.** Such a carbocation is shown below.



a carbocation



This carbocation being planar, can be attacked by the incoming group or nucleophile from either side leading to the formation of both the enantiomers. If the attack is equally favourable from both the sides, then



the enantiomers are formed in equal amounts and the product obtained is a racemic mixture.

Once a racemic mixture is obtained, the next step is to separate this mixture into its pure components. The separation of a racemic mixture into the enantiomers is called **resolution.** The first resolution was that of tartaric acid by Pasteur in 1848. Tartaric acid was obtained as a by-product of wine making and was found almost always as its dextrorotatory 2*R, 3R* stereoisomer. Occasionally, an optically inactive sample of tartaric acid was obtained.

One day Pasteur was viewing the crystals of sodium ammonium double salts of (+)-tartaric acid and inactive tartaric acid. He found that the crystals of the double salt of (+)-tartaric acid were hemihedral, (see Fig. 11.3 a)). But the crystals of the double salt of inactive acid were not the crystals of just one type, but a mixture of **two** types and these two types of crystals were mirror images of each other [(see Fig. 11.3 a) and b)]. He separated the two types of crystals with a pair of tweezers. These two types of crystals showed *equal* and *opposite optical rotation.*Thus, the inactive sample of tartaric acid was actually a **racemic mixture.** Pasteur had thus performed the first resolution by human hands! Before this,the levorotatory form of tartaric acid was not known. It is now known that the double salt of racemic tartaric acid forms two types of crystals, as shown in Fig. 11.3 a) and b), only at temperatures below 299K. Had the temperature of Pasteur's laboratory been above this temperature, he would have obtainedthe crystals of the type shown in Fig. 11.3 c) and he would not have made this discovery!

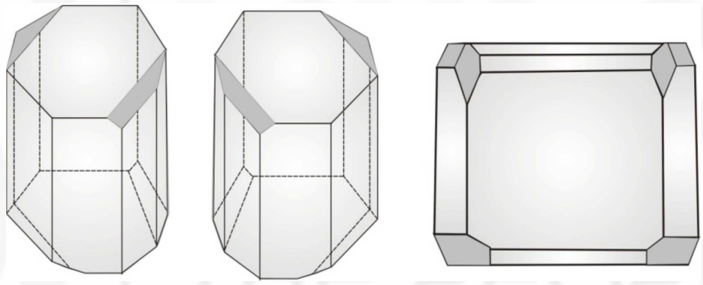


Fig. 11.3: a) Dextrorotatory hemihedral crystals of sodium ammonium tartarate; b) Levorotatory hemi hedralcrystals of sodium ammonium tartarate; c) Holohedral crystals of racemic sodium ammonium tatarate that crystallises at a higher temperature.

Resolution by ordinary physical methods like crystallisation, distillation, chromatography etc. is not possible because the physical properties of the two components, except the direction of rotation, are identical. Almost all methods of resolution make use of the fact that only under the influence of another chiral reagent,the enantiomers can be made to behave differently.

Hence, the enantiomeric mixture is treated with a chiral substance to convert it into a mixture of diastereomers. Since the diastereomers have different physical properties, they can be separated using physical methods. The enantiomers are then regenerated from each diastereomer. The general scheme for resolution involving the formation of diastereomers is depicted in Fig. 11.4.

The advantage of acid-base properties is also taken in obtaining the diastereomers. For example, if we want to resolve an acid A which is present as a mixture of the enatntiomers (+)-A and (–)-A as shown in Fig. 11.4 a); then

we choose either of the enantiomers of base B, which is, say, (+)-B in this case. When the base (+)-B is added to the racemic mixture of acid A, diastereomers of the type (+)-A(+)-B and (–)-A(+)-B, as shown in Fig. 11.4 b), are obtained. These diastereomers can then be seperted using physical methods, [see Fig. 11.4 c)].

The individual enantiomers of acid A are then regenerated from each of the above diastereomers by treatment with a mineral acid, Fig. 11.4 d).

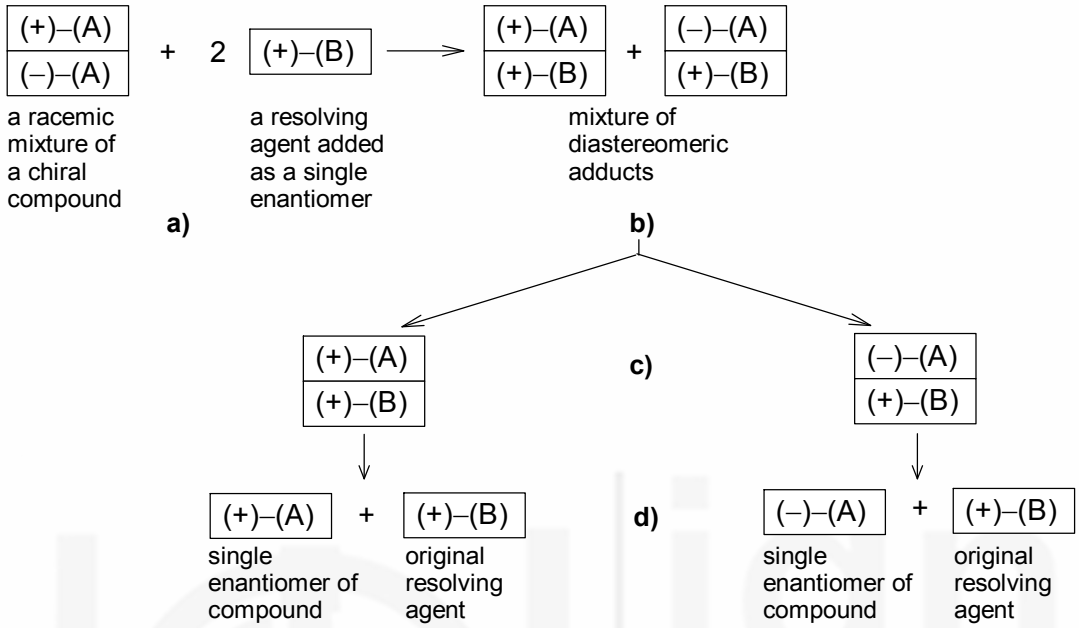
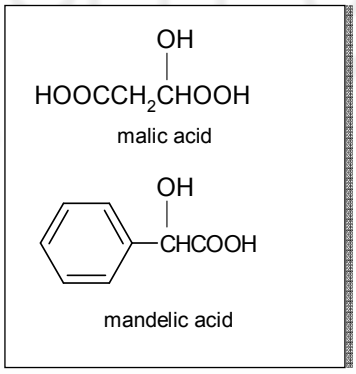
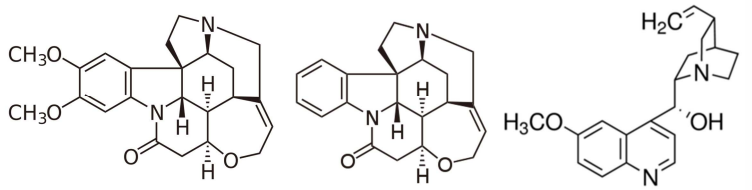


Fig. 11.4: a) Racemic mixture of enantiomers; b) Mixture of diastereomers obtained; c) Diastereomers seperated; and d) Enantiomers regenerated from diastereomers.

Similarly, we can resolve a racemic mixture of a base using a chiral acid.

The chiral reagents which are used for resolving a racemic mixture are called **resolving agents.** A number of resolving agents are available, many of them are naturally occurring acids and bases.For example, chiral bases such as brucine, strychnine and quinine are used for resolution. On the hand, chiral acids such as (+)-tartaric acid, (–)-malic acid and (–)-mandelic acid are used for resolution or racemic bases.





Analogous methods of resolution of compounds containing other functional groups have also been developed.

Chromatographic methods for resolution using chiral adsorbents have also been developed. In such methods, one of the enantiomers gets adsorbed on the chiral adsorbent more strongly than the other leading to their partial separation. The drawback with chromatographic resolution is that it is not quantitative.

As pointed our earlier, the resolution is effective only under a chiral influence. Such an influence can also be exerted using enzymes. The enzymes are highly selective with regard to stereochemistry of the compounds with which they interact. Hence, they can perform the resolution by metabolising only one enantiomer and rejecting the other. For example, the racemic ammonium tararate when fermented using yeast or a mold (*Penicillium glaucum),* showed that the dextrorotatory isomer is consumed faster by the mold leaving behind the pure levorotatory isomer. A disadvantage of the resolutions of this type is that the more reactive enantiomer is usually not available and we get **only one** enantiomer at the end of the resolution.

Pure enantiomers can also be obtained using synthetic methods, without the necessity of resolution. The study of such methods is beyond the scope of this course.

SAQ 4

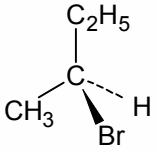
Why are racemic mixtures optically inactive?

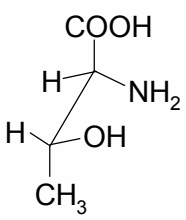
11.5 SUMMARY

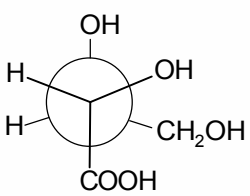
- The spatial arrangement of the atoms (or groups) in a molecule is known as the configuration.
- Fischer projection formulas are used for representing the molecules in the two-dimensional plane of the paper.
- Several Fischer projections can be written for a particular stereoisomer.
- A chiral compound can be assigned an absolute configuration as either *R* or *S* using the Cahn-Ingold-Prelog sequence rules.
- The *erythro*– and *threo*– nomenclature is also used for designating the configuration, especially in case of carbohydrates.
- Racemic mixtures can be resolved into optically active compounds via the formation of diastereomers.

11.6 TERMINAL QUESTIONS

1. Draw Fischer projection formulae for the following compounds:

   a) 

   b) 

   c) 

2. a) Write the stereoisomers for tartaric acid (i.e., 2,3-dihydroxybutanedioic acid).

   b) Assign the configuration as *R* or *S* to the chiral centres in each of the stereoisomers in part a).

c) Which of the isomers of part a) are optically active?

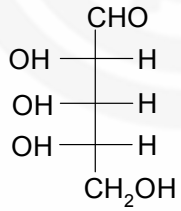
3. The resolution of 1-phenylethylamine using (–) malic acid, yielded the less soluble diastereomeric salt having the configuration (*R*)-*1*-phenylethylammonium (*S*)-malate. The other diastereomeric salt being more soluble remained in the solution. What is the configuration of this more soluble salt?

4. Substituted chiral ethanoic acid having the formula DHTC–C(=O)–OH, in which two hydrogens of the CH_3 group have been substituted by deuterium, D, and tritium, T, can exist as enantiomers. Write the three dimensional structures for its *R* and *S* isomers.

11.7 ANSWERS

Self-Assessment Questions

1. a) Same compound , Ist interchange –CH_3 and –OH
   IInd interchange –H and –C_3H_7
   b) Same compound, Ist interchange –COOH and –OH
   IInd interchange –OH and –H.
   c) enantiomers, using rule 3.
   d) enantiomers as they are interconvertible by rotation of 90^0, (rule 2).
2. a) *S* b) *R* c) *R* d) *S.*
3. i) *Erythro*
   ii)

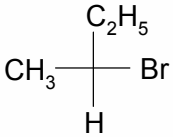


   Erythro isomer

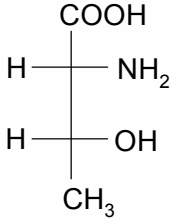
4. Since racemic mixtures contain equal amounts of the two enantiomers, the optical rotation caused by one enantiomer is cancelled by the optical rotation of the other enantiomer.

Terminal Questions

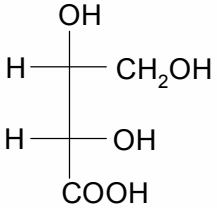
1. a)

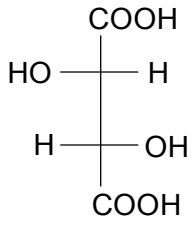


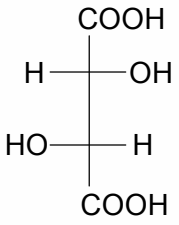
b)

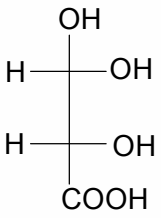


c)



2. a) i) 

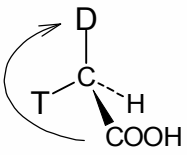
ii) 

iii) 

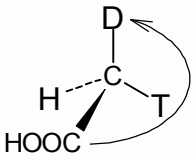
b) i) 2*S,* 3*S* ii) 2*R,* 3*R* iii) 2*R,* 3*S*

c) i) and ii) are optically active but iii) being a *meso* compound, is optically inactive.

3. (*S*)-1-phenylethylammonium (*S*)-malate.

4. 

R isomer



S isomer

UNIT 12

STEROCHEMISTRY–III: CONFORMATIONAL ISOMERISM

Structure

12.1 INTRODUCTION

After studying cofigurational isomerism in Units 10 and 11, it will be interesting for you to learn about another category of stereoisomerism known as *conformational isomerism*. In contrast to the configurational isomers resulting from the different spatial arrangements of groups around a rigid framework, whether a double bond or a cyclic structure or an asymmetric centre, conformational isomers are obtained by simple rotation of sigma (σ) bonds and are therefore interconvertible.

In this unit, you will study how these conformational isomers are represented. Two such ways are Newman and sawhorse projections which will be explained in the beginning of the unit. Then, the conformations of simple alkanes such as ethane and butane will be discussed in detail and the stabilities of their various conformations will be explained.

It will also be very interesting to know about the conformations of cyclic systems such as cyclohexane which have carbon atoms joined to each other in a ring. For cyclohexane, several conformations resulting by the rotation about C–C bonds will be described and their relative stabilities will be discussed.

Expected Learning Outcomes

After studying this unit, you should be able to

- define the term conformation;
- draw Newman and sawhorse representations of a given compound;
- illustrate the possible conformations of simple straight chain hydrocarbons such as ethane and butane and compare the relative stabilities of various conformations; and
- draw the possible conformations of cyclohexane and compare their relative energies and stabilities.

12.2 CONFORMATIONAL ISOMERS: NEWMAN AND SAWHORSE REPRESENTAIONS

The various spatial arrangement obtained by rotation about the single bonds are called **conformations.** Among the different conformations of a molecule, the stable ones are known as **conformers** or **conformational isomers.** The simplest molecule which shows these conformations is ethane.

Before starting the study of conformations of various molecules, let us learn how to represent these conformations, which are again three-dimensional spatial arrangement of a molecule, in two-dimensions.

You have already learnt about the Fischer projections for representing the *configuration* of a compound. Two types of representations, namely, *Newman projections* and *sawhorse projections* are used to represent the conformations. We will first study the Newman projections.

Newman Projections

For writing the Newman projections of a molecule, it is viewed along the carbon-carbon bond as shown for ethane in Fig. 12.1a).

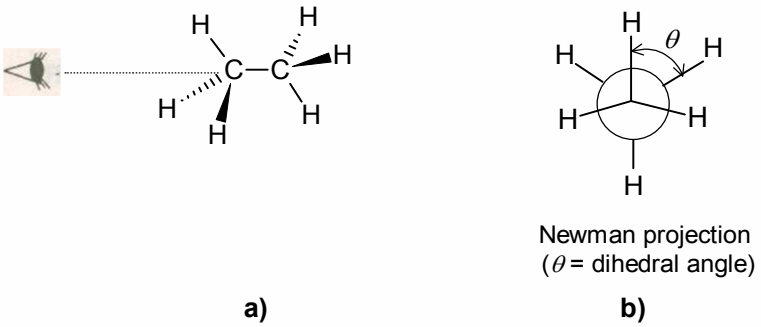


Fig. 12.1: a) Wedge and dash drawing of ethane; solid wedges show the bonds above the plane of paper and dash lines represent the bonds behind plane of the paper whereas the ordinary lines represent the bonds in plane of the paper. b) Newman projections of ethane.

Here, the ethane molecule is shown in wedge and dash drawing. In drawing the Newman projection, the carbon atom nearer to the observer is represented by a point and the three groups attached to it are shown by three lines emerging from this point, [Fig. 12.1b)]. The rear carbon is shown by a circle and the three substituents attached to this carbon are shown by three lines emerging form the edge of the circle. The angle, θ, between the H–C–C plane and the C–C–H plane of an H–C–C–H unit is called the **dihedral angle.**

Let us now understand how to write the sawhorse projections.

Sawhorse Projections

In this representation, the carbon-carbon single bond is represented by a line which is oriented diagonally backward, i.e., the left hand carbon projects towards the viewer and the right-hand carbon projects away from the viewer. This is illustrated in sawhorse projections for ethane in Fig. 12.2. Analogues to the Newman projections, here also the substituents on each carbon are shown by lines joined to the respective carbon atoms.

Remember that the four substituents attached to the carbon atoms in ethane are arranged in tetrahedral fashion.

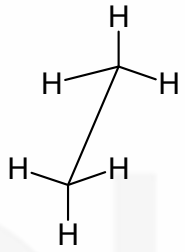


Fig. 12.2: Sawhorse projection of ethane.

We now know how to represent a molecule in Newman or sawhorse projections. These projection formulae are useful in studying the conformations of simple molecules. Let us now study the conformations of ethane. Here, you can check your understanding about representation of conformations by answering the following SAQs.

SAQ 1

In a Newman projection, how are two carbon atoms of the C–C bond represented?

SAQ 2

In a sawhorse projection, how are the left hand and the right hand atoms projected.

12.3 CONFORMATIONS OF ETHANE

A number of different conformations are possible for ethane molecule depending upon the value of the dihedral angle, θ. Fig. 12.3 shows the variation with dihedral angle for potential energy of various conformations of ethane.

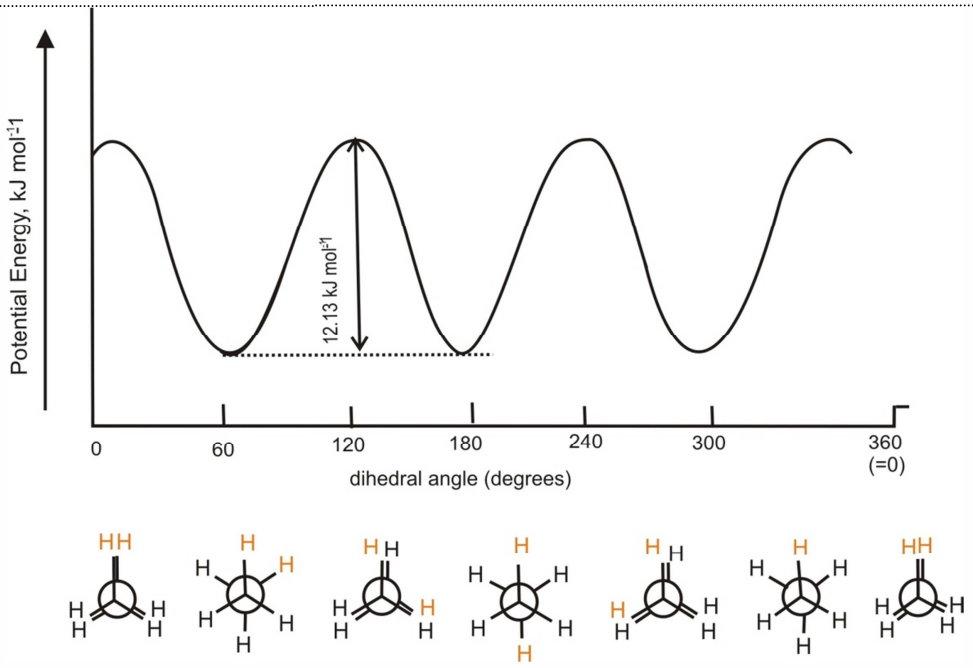
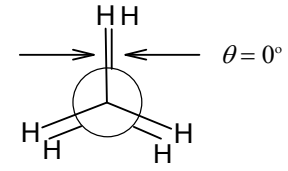
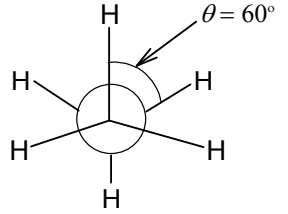


Fig. 12.3: Variation of potential energy with dihedral angle. Here, to make it easy to visualise the dihedral angle, the two hydrogens on the two carbons are shown in the different colour.



eclipsed conformation of ethane



staggered conformation of ethane

While comparing the stability of various conformations, remember that the conformation having the least potential energy is the most stable conformation. Thus, ethane has one conformer which is the staggered conformation.

When the dihedral angle is 0°, then the hydrogens on the carbon atoms are parallel and the conformation is known as **eclipsed conformation.** The other limiting possibility is when the dihedral angle is 60°; this conformation is called **staggered conformation.** Fig. 12.3 shows that there is an energy difference of12.13 kJ mol^{-1} between the eclipsed and staggered conformations, with the staggered conformation having the *lower* energy. This can be explained in terms of the maximum separation of bonded electron pairs in the staggered conformation which leads to minimum repulsion between them. On the other hand, in the eclipsed conformation, the C–H bonds are closer and hence, there is a repulsion between the electrons forming these bonds. Thus, the staggered conformation is more stable than the eclipsed conformation.

The energy difference of 12.13 kJ mol^{-1} between these two conformations is very small as compared to the kinetic energy of the molecule due to molecular motions and even at low temperatures, a molecule can pass from one staggered conformation to another staggered conformation (although in between it has to pass through an eclipsed conformation) at the rate of about 10^{11} times per second! Thus, the interconversion of conformations is very rapid; nevertheless it is not strictly 'free' in the sense that there is an energy barrier of 12.13 kJ mol^{-1} to be overcome. Hence, the ethane molecule spends most of its time in its staggered forms, passing only transiently through its eclipsed forms.

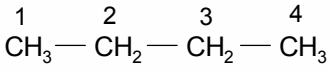
Before you proceed to study the conformations of another alkane, namely butane, answer the following SAQ.

SAQ 3

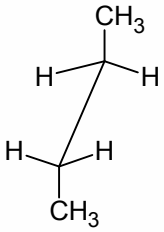
Draw the eclipsed and staggered conformations of ethane in sawhorse representation.

12.4 CONFORMATIONS OF BUTANE

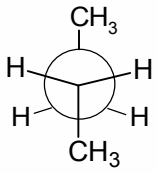
The sawhorse and Newman projections of butane are represented below.



Butane

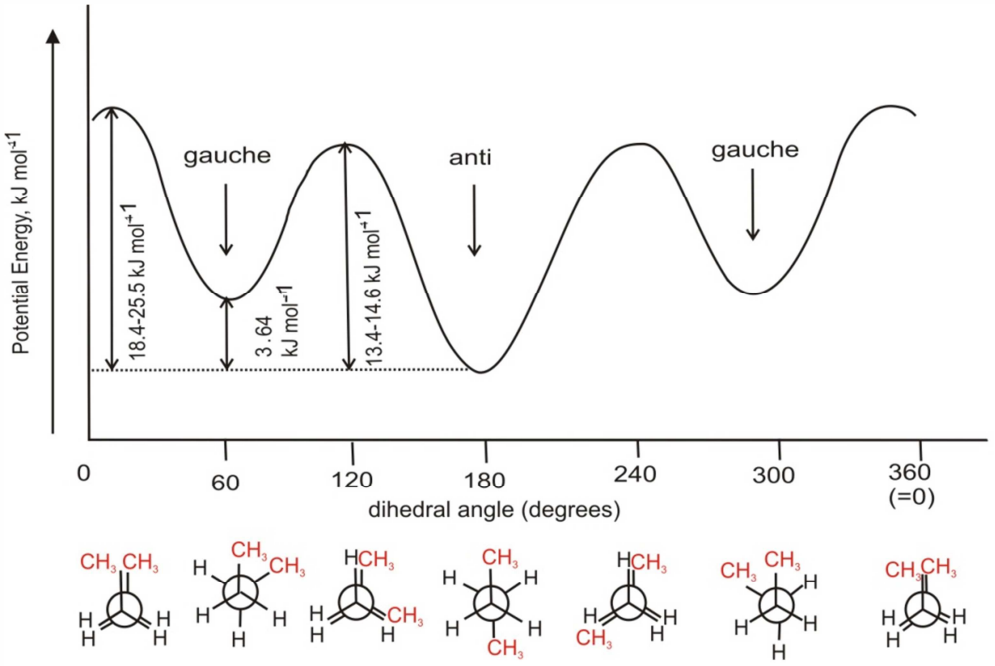


Sawhorse projection



Newman projection

Similar to the case of ethane, various conformations of butane are possible due to rotation of the C–C bond formed by the carbon atoms numbered as 2 and 3. These are shown in Fig. 12.4.



Butane has two conformers; namely, anti and gauche conformations. The anti-conformer is more stable as compared to the gauche, as shown in Fig. 12.4.

Fig. 12.4: Potential energy variation for various conformations of butane.

As the above figure shows, when the dihedral angle is zero, the conformation is called **eclipsed conformation.** As the dihedral angle increases to 60°, we get another conformation which is called **gauche or skew conformation.** Further rotation of the C_2–C_3 bond yields another **eclipsed conformation** when the dihedral angle is 120°. Note in this conformation, **CH_3 and H are eclipsed** whereas in the earlier eclipsed conformation **two methyl groups were eclipsed.** Hence, this eclipsed conformation has a little lower energy than the earlier eclipsed conformation.

When the two methyl groups are maximum apart, i.e. when the dihedral angle is 180^0, then the conformations is known as **anti conformation.** Note that this is the most stable conformation of butane because it has the lowest energy

The analysis of molecular conformations and their relative energies is called **conformational analysis**.

value. On further rotation, another set of **eclipsed** and **gauche** conformations results. The difference in energy between the **anti** and **gauche** conformations is about 3.64 kJ mol^{-1}. At room temperature, butane is a mixture of 72% anti and 28% gauche conformations.

Similar to ethane, in this case also, the interconversion of these conformations is rapid and if one wants to separate them, one has to make the interconversion slow by working at very low temperatures of about 43 K.

Hassel and Barton received Nobel Prize in Chemistry in 1969 for their contribution in the field of conformational analysis.

The study of conformations or **conformational analysis** is helpful in explaining the specificity of reactions; particularly, the reactions observed in living systems where such a specificity is exhibited by virtue of the particular conformations of the compounds.

At this stage, you can check your understanding about conformations of simple straight chain alkanes, namely butane by answering the following SAQ.

SAQ 4

a) Write sawhorse projections for the gauche conformations of butane.

b) What is the value of dihedral angle in these conformations?

c) What relationship do these two **gauche** conformations have with each other?

12.5 CONFORMATIONS OF CYCLIC SYSTEMS

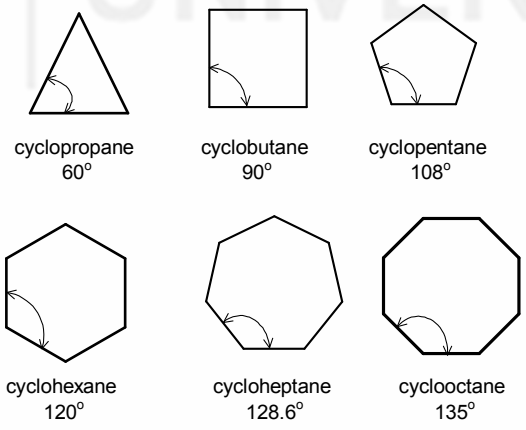
During the nineteenth century, it was believed (erroneously, as we shall see in the subsequent discussion) that the cycloalkanes are planar. According to the German chemist Baeyer, the internal bond angles for cycloalkanes should be the same as those of the corresponding regular polygons. This is shown below:

The bond angle in a polygon having n sides is given by

$$\left(\frac{2n-4}{n}\right)\times 90°.$$

For example, in cyclopropane having $n = 3$,

$$\left(\frac{2\times 3-4}{3}\right)\times 90° = 60°$$



In order to explain the fact that the cyclic compounds having rings containing fewer than five or more than six carbon atoms were less abundant in nature, he suggested that the stability of such compounds could be related to the tetrahedral bond angle of 109.5°. The deviation from this angle could cause a strain in the molecule leading to its decreased stability. This type of instability is called **angle strain.**

Thus, according to this explanation, as the deviation from the tetrahedral value decreases, the stability should increase. Thus, the stability should increase from cyclopropane < cyclobutane < cyclopentane. As the deviation in angle from the tetrahedral angle of 109.5° is minimum in case of cyclopentane, Baeyer predicted it to be the most stable. Cyclohexane and higher cycloalkanes according to him would be less stable than cyclopentane because the angles of larger polygons deviate more and more from the ideal tetrahedral angle of 109.5°.

The experimental values of heat of combustion per methylene group showed that the energies for the first three cycloalkanes are in the following order:

Cyclopropane > cyclobutane > cyclopentane

This order is consistent with the predictions of the Baeyer strain theory. But in case of cyclohexane, the heat of combustion is less indicating its greater stability. Further increase in the ring size does not affect the heat of combustion much, indicating a constant value of about 652.7 kJ mol^{-1} per methylene group in contradiction to the prediction of Baeyer Strain theory that with the increase in ring size, angle strain must increase.

Let us now understand what was wrong with Baeyer's theory.

Baeyer's theory failed because of the assumption that the cycloalkanes are *planar*. Of course, cyclopropane has to be planar because three carbons must lie in a single plane. But other larger cycloalkanes are **not planar and are puckered.** Puckering of rings relieves the angle strain. You will study about this in detail in case of cyclohexane in the following discussion.

General equation for combustion of alkanes is

$$C_nH_{2n+2} + \left(\frac{3n+1}{2}\right)O_2 \rightarrow$$

alkane oxygen

$$n\,CO_2 + (n+1)H_2O + \text{heat}$$

carbon dioxide water

The heat released on complete combustion of one mole of a substance is called its **heat of combustion**.

The heat of combustion data is useful in determining the relative energies of various molecules.

The higher the heat of combustion per methylene group, the lower will be the stability.

12.5.1 Conformations of Cyclohexane

If you make a model of cyclohexane containing 6 sp^3 hybrid carbon atoms forming a regular hexagon, you will realise that in this molecule, in addition to the angle strain, the hydrogens on the adjacent carbon atoms have the eclipsed arrangement as depicted in Fig. 12.5.

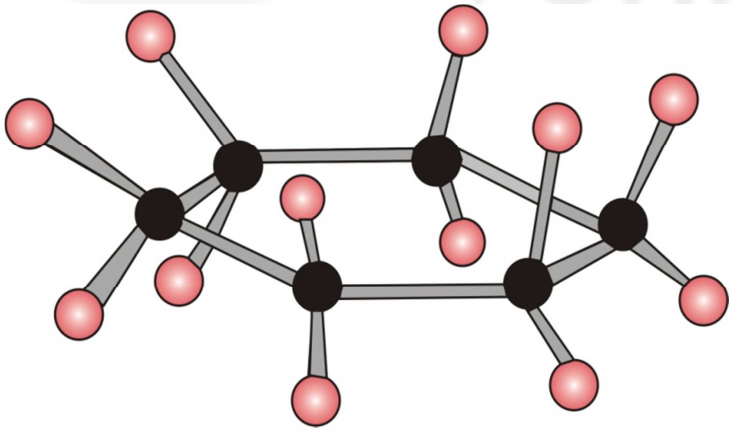
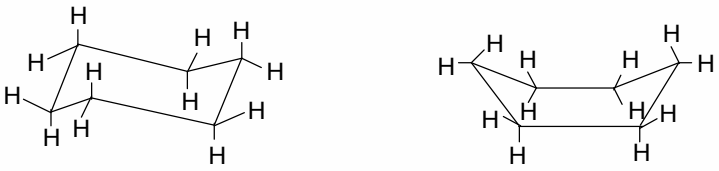


Fig. 12.5: Strained planar conformation of cyclohexane showing eclipsed hydrogens.

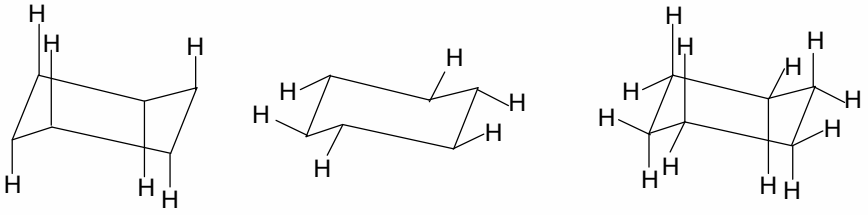
Sachse in 1890 pointed out that two nonplanar models of cyclohexane are possible which are free from angle strain. There are called **chair** and **boat conformations** and are shown in Fig. 12.6.



Chair conformation Boat conformation

Fig. 12.6: Chair and Boat conformations of cyclohexane.

There are two types of hydrogens in the chair form of cyclohexane, see Fig. 12.7. The six hydrogens which are *above* and *below* the plane of the carbon ring are called **axial** hydrogens. Note that the axial bonds are alternately directed up and down on the adjacent carbon atoms. The second set of hydrogens is called **equatorial** hydrogens and are located approximately along the equator of the molecule.



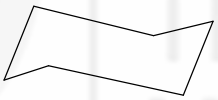
axial C–H bonds equatorial C–H bonds axial and equatorial bonds together

Fig. 12.7: Axial and equatorial bonds in the chair conformation of cyclohexane.

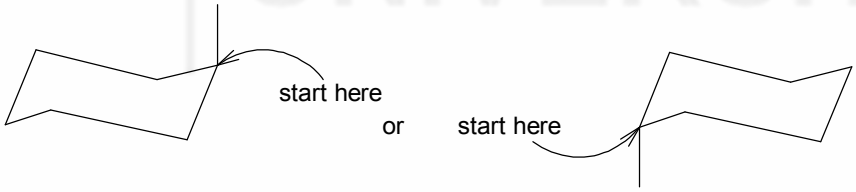
Given below are the steps to enable you to represent the axial and equatorial bonds correctly on the chair conformation of cyclohexane.

Steps

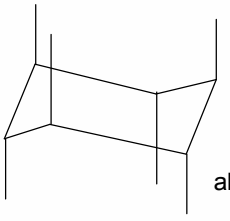
1) Draw the chair conformation of cyclohexane as



2) Draw one axial bond as shown below,

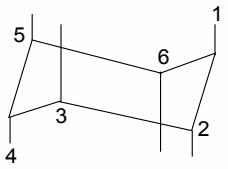


and then draw bonds alternately up and down as represented below.

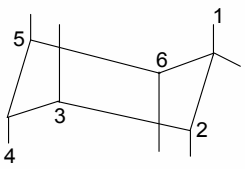


all axial bonds are parallel to each other

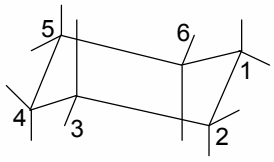
3) Draw equatorial bonds keeping in mind the tetrahedral arrangement at the carbon atoms. Draw an equatorial bond at C-1 in such a way that it is parallel to the carbon-carbon bond between C-2 and C-3 and also between C-5 and C-6.



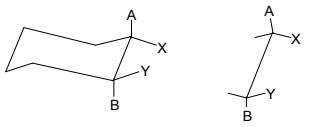
Place equatorial bond at C-1 so that it is parallel to the bonds between C-2 and C-3; and between C-5 and C-6



Then, complete the other equatorial bonds as shown below.

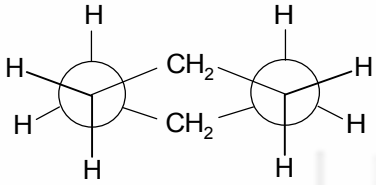


complete set of axial and equatorial bonds



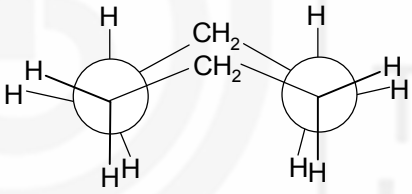
Chair cyclohexane drawings resemble sawhorse projections of staggered conformations of alkanes.

You can notice the sawhorse representation of the bonds in the above chair conformation. This *staggered* nature of bonds can also be visualised in the Newman projections of the chair conformation of cyclohexane as shown below:



staggered arrangment of bonds in chair conformation of cyclohexane

However, a similar representation of the boat form of cyclohexane shows the *eclipsed* bonds.



eclipsed bonds in boat conformation give it torsional strain

If the distance between two non-bonded atoms is less than the sum of their van der Waals radii, there is repulsive interaction between the two atoms. This is known as *van der Waals repulsion.*

Further, in the boat conformation, the two hydrogens at the bow and stern of the boat, called **flagpole hydrogens**are 183 pm apart. This distance is significantly lesser than the sum of their van der Waals radii (240 pm) and it results in a repulsion between them. These van der Waals repulsions increase the energy of the boat form as compared to the chair form by about 27 kJ mol^{-1}.

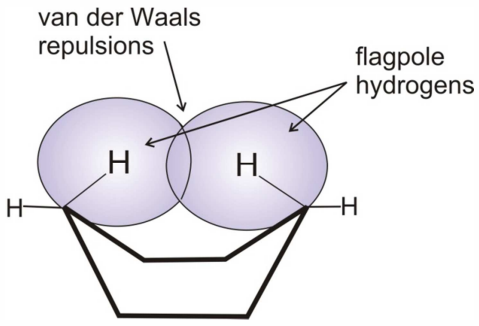
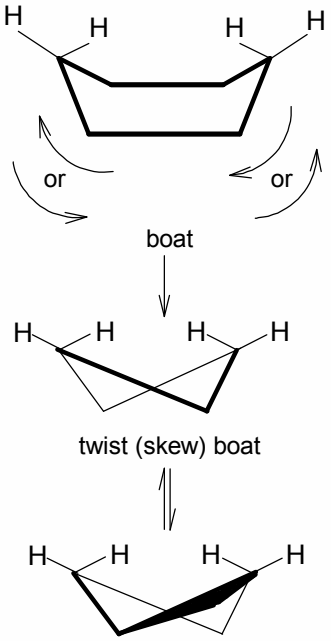


Fig. 12.8: van der Waals repulsions between flagpole hydrogens.

A portion of the strain due to the flagpole interactions in the boat conformation is relieved in the **twist boat** (or **skew boat)** conformation, which is obtained by slightly twisting the boat conformation as shown below:

The conversion of a boat into a twist-boat cyclohexane



The twist boat form is more stable than the boat conformation but less stable than the chair conformation by about 2.51 kJ mol^{-1}. As the chair conformation is the most stable form, most of the molecules of cyclohexane exist in the chair form. The available experimental data indicate that no more than one or two molecules per thousand exist in the skewboat conformation.

A chair conformation is also convertible into another chair conformation by the process known as **ring flipping.** This interconversion, as shown in Fig. 12.9, occurs via the intermediate half-chair and skew-boat conformations.

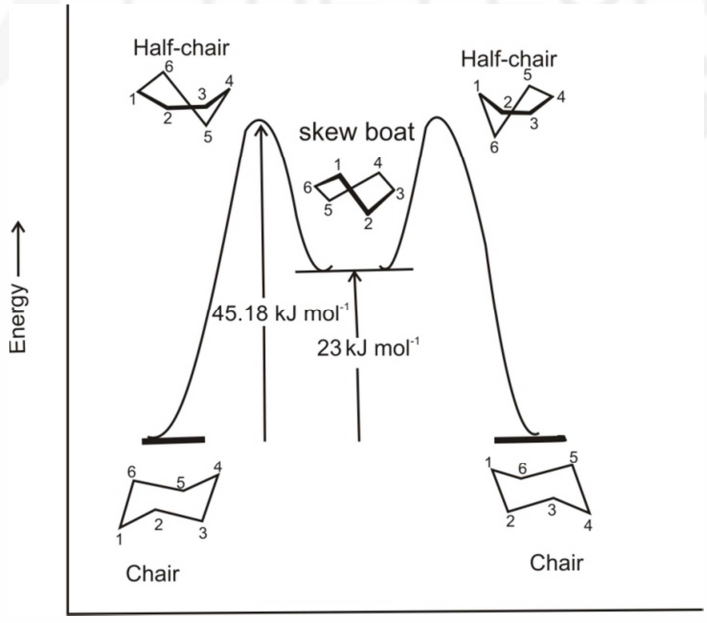


Fig. 12.9: Energy profile associated with ring flipping.

The energy profile for such an interconversion is shown in Fig. 12.9. The ring flipping requires an energy of 45.18 kJ $mol^{-1}$and even at room temperature, this interconversion is very fast.

An important consequence of the ring flipping is that the axial substituents in the original chair conformation become equatorial in the flipped chair conformation and *vice-versa*. **Note that this inversion does not involve any bond breaking or bond forming.**

A detailed energy profile for various conformations of cyclohexane is shown in Fig. 12.10. Note that the boat form is transition state for the interconversion of skew-boat conformations.

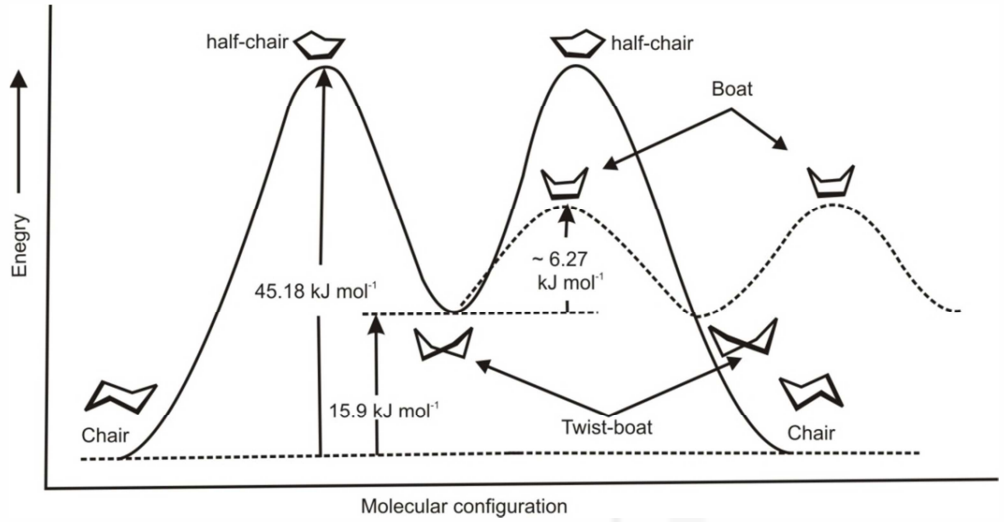
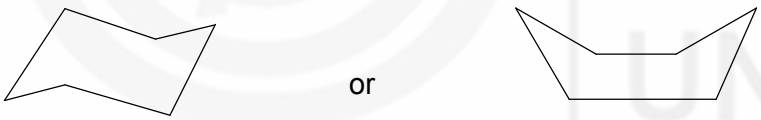


Fig. 12.10: Relative energies for various conformations of cyclohexane.

Using your knowledge of conformations of cyclohexane systems, answer the following SAQ.

SAQ 5

Which of the following would be more stable and why?



a) b)

12.6 SUMMARY

In this unit, we learnt that

- Isomerism is the phenomenon of an existence of two or more compounds having the same molecular formula.
- Various types of isomerism are possible, the important ones are structural isomerism and stereoisomerism.
- Structural isomerism can be further sub-divided into chain isomerism, position isomerism and functional group isomerism.
- Stereoisomerism can be further classified as conformational isomerism or configurational isomerism.

- Stereoisomers differ from each other in the arrangement of their atoms in space.
- Rotation about carbon-carbon single bond leads to conformational isomers.
- Newman and sawhorse projections are used to represent the conformations of a molecule.
- The staggered conformation of ethane is more stable than its eclipsed conformation.
- The most stable conformation of butane is *anti-* conformation and its least stable conformation is *eclipsed* conformation. The other conformation of butane is gauche or skew conformation which have stability in between the *anti-* and the *eclipsed* conformations.
- The order of stabilities of various conformations of butane is as follows:

  Anti >gauche >eclipsed

- Many conformations are possible for cyclohexane. The chair conformation of cyclohexane is more stable than its boat conformation.
- Of the three conformations of cyclohexane, namely, chair, boat and skew-boat, the chair conformation is the most stable one.
- Ring flipping is the interconversion of one chair form of cyclohexane into another chair form. It occurs via the intermediate half-chair and skew-boat conformations.

12.7 TERMINAL QUESTIONS

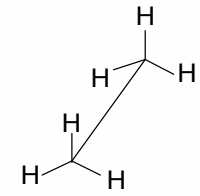
1. Draw the Newman projection for the staggered conformation of ethane.
2. Why is the staggered conformation of ethane more stable than its eclipsed conformation?
3. Name the most stable conformation of butane and draw its sawhorse projection.
4. Explain ring flipping. What are the intermediate conformations involved in it?

12.8 ANSWERS

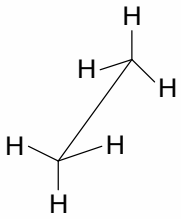
Self-Assessment Questions

1. In Newman projection, carbon atom nearer to the observer is represented by a point and the rear carbon is shown by a circle.
2. In sawhorse projection, the left hand-carbon projects towards the viewer and the right-hand carbon projects away from the viewer.

3. The Sawhorse projections of eclipsed and staggered conformations of ethane are as follows:

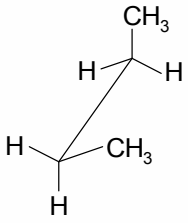


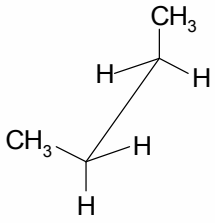
eclipsed conformation



staggered conformation

4. a) Two gauche forms of butane in sawhorse projections are as follows:



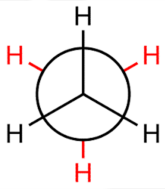


b) 60^0

c) They are enantiomeric in nature.

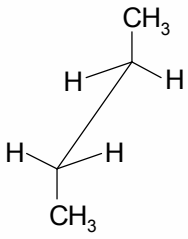
5. a) The chair form is more stable due to staggered arrangement of bonds. The bonds are eclipsed in the boat conformation. There is also van der Waals repulsion between the flagpole hydrogens in the boat form.

Terminal Questions

1. 

2. The staggered conformation of ethane is more stable than its eclipsed conformation due to the maximum separation of bonded electron pairs in it which leads to minimum repulsion between them.

3. Anti conformation of butane



sawhorse projection

4. The interconversion of one chair conformation of cyclohexane into another chair conformation is called ring flipping. For diagram, refer to Fig. 12.9. Half-chair and skew boat conformations are intermediated between the two chair conformations.

UNIT 13

STRUCTURE–REACTIVITY RELATIONSHIPS

Structure

13.1 INTRODUCTION

In last few units, i.e. Units 10 to 12, you studied in detail about some basic concepts and *stereoisomerism* which included *configurational* and *conformational isomerisms*. In this unit, you will study about the effect of molecular structure on the reactivity of the molecules. The *reactivity* of one substance towards another is measured by the rate at which the two substances react and the amount of the products formed.

Not all molecules are equally reactive. But, what makes some organic molecules more reactive than others? To find an answer to this question, we should have some idea of the nature of reactions that the organic molecules undergo. A large number of reactions that the organic molecules undergo can be readily understood as simple analogies of *acid-base reactions.* Therefore, it is important for us to know the basic features of acid-base reactions.

We will begin this unit with a discussion on various ways in which the acids

and bases can be defined. Then, the concept of acid-base, equilibrium will be discussed. Here, you will also study that the position of the acid-base equilibrium is a measure of molecular reactivity; further it is influenced by many factors. Although, the functional groups present in a molecule are of key importance in determining the molecular reactivity, it has been observed that various compounds containing the same functional groups differ in their reactivities. Thus, in addition to the presence of the functional groups, the nature and arrangement of atoms attached to the functional groups also control the molecular reactivity. These effects which are associated with the change in molecular structure, are called **structural effects.** These effects are also called **electronic effects** because a change in the structure of molecules also affects the distribution of electrons present in them. In this unit, you will study various electronic effects such as *inductive effect, resonance effect* and *steric effect, hyperconjugation* and their influence on molecular reactivity.

Finally, you will study an interesting equilibrium involving a proton shift from one atom of a molecule to another, called **tautomerism.**

Expected Learning Outcomes

After studying this unit, you should be able to

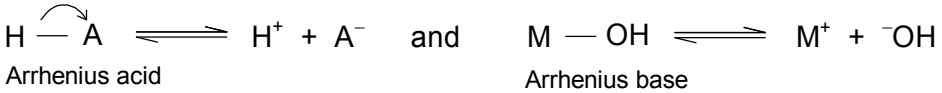
- ❖ define acids and bases;
- ❖ classify the given compounds as acids or bases according to Brönsted – Lowry and Lewis definitions;
- ❖ define pK_a of an acid;
- ❖ predict the relative acidities and basicities of compounds from their pK_a values;
- ❖ list various factors affecting the strengths of acids and bases;
- ❖ explain the effect of structural changes on the acidic and basic behaviour of organic molecules;
- ❖ predict the relative reactivity of the molecules on the basis of inductive effect, resonance effect, hydrogen bonding and hyperconjugation etc.; and
- ❖ define tautomerism and give examples of various kinds of tautomerism.

Arrhenius received Nobel Prize in Chemistry in 1903.

13.2 WHAT ARE ACIDS AND BASES?

There are various ways of defining acids and bases. According to Arrhenius (1884), a Swedish chemist, an *acid* is a substance which ionises in aqueous solution to produce hydrogen ions (H^+), also known as *protons.* And, a *base* is a substance which ionises to produce hydroxide (^-OH) ions. Thus, Arrhenius theory assumes a simple dissociation such as,

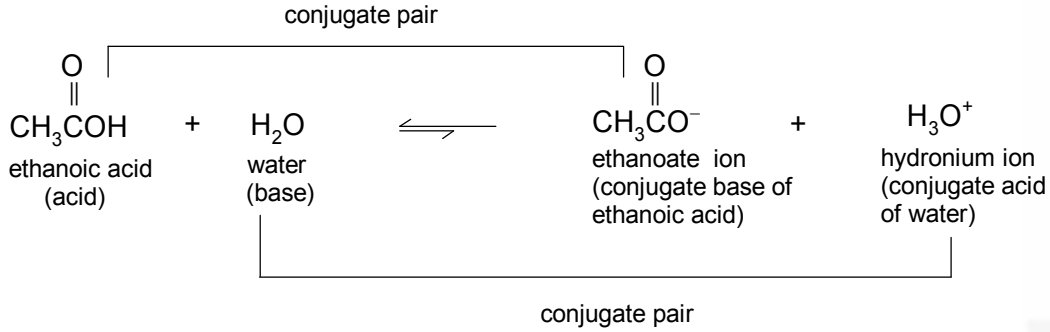
Note that during dissociation, the covalent bond between H - A is broken and the electrons forming this bond shift on A as shown by the curved arrow.



Arrhenius acid Arrhenius base

Thus, HCl is an acid and NaOH is a base because on dissociation they yield H^+ and ^-OH ions, respectively. Thus, the strength of these acids and bases is related to the degree of their dissociation. The mineral acids such as HCI, HI, HBr, H_2SO_4 and HNO_3 are strong acids because they are almost completely dissociated in aqueous solutions. Similarly, the strength of a base will also depend upon its degree of dissociation.

An alternative theory of acids and bases was devised independently by Brönsted and Lowry in 1923. According to the Brönsted-Lowry approach, **an acid is a proton donor and a base is a proton acceptor.** Since under ordinary reaction conditions a free proton cannot exist as a separate entity, when an acid in the Brönsted -Lowry sense is considered, a base must be present to accept the proton from the acid. Consider the following example.

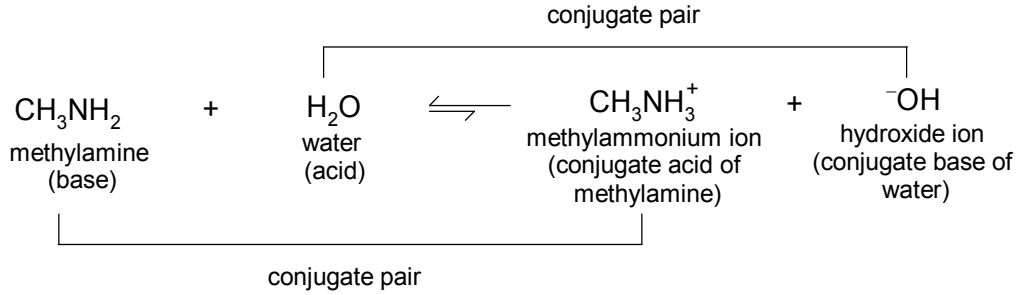


The Brönsted acids are also called **protic acids** because they react by the transfer of a *proton.*

The word **conjugate** has its origin from the Latin word *conjugatus* which means *joined together.*

Here, the ethanoic acid is an **acid** because it donates a proton to water which is a **base** because it accepts the proton. Similarly, the ethanoate ion, which is formed by the loss of a proton from ethanoic acid, functions as a ***base*** because it can accept a proton to become ethanoic acid again. Thus, ethanoate ion is called the ***conjugate base*** of ethanoic acid. Similarly, the hydronium ion is the ***conjugate acid*** of the base, water. This pair of a base and its conjugate acid or an acid and its conjugate base is also called ***conjugate acid-base pair.***

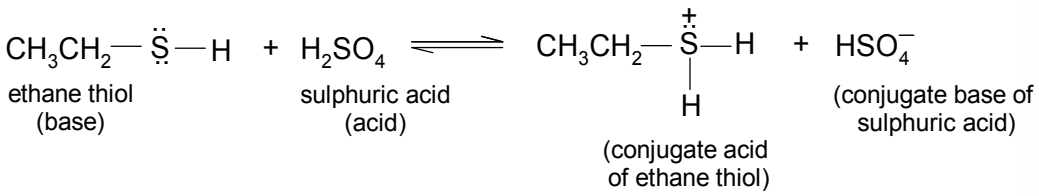
Let us now consider an acid-base reaction involving methylamine which acts as a **base** and water which acts as an **acid** in this case, as shown below:



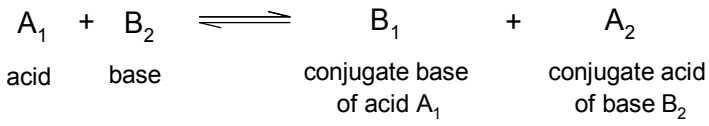
Note that water can act *both as an acid as well as a base*. It acts as an acid by donating a proton to yield the ^-OH ion which is its conjugate base. It can also act as a base by accepting a proton to yield a hydronium ion which is its conjugate acid.

Although, we have illustrated both the above examples using water as one of the components, the scope of Brönsted-Lowry definition of acids and bases is

not limited to aqueous solutions, as is the case in Arrhenius definition. The Brönsted-Lowry concept of acids and bases is more general and applies to any type of solvent. One such example is shown below:



Thus, according to this concept the general form of an acid-base reaction can be written as,

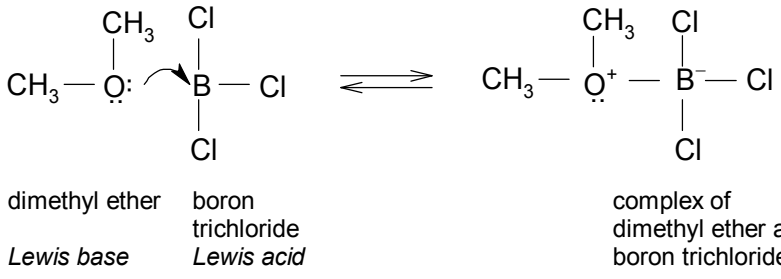


where $A_1 - B_1$ and $A_2 - B_2$ are conjugate acid-base pairs.

The acid-base theory was further broadened by Lewis in 1938. He proposed that the *acids are the electron-pair acceptors* and *the bases are the electron-pair donors.* Hence, according to this idea any molecule or ion which can accommodate an electron pair is an acid. For example, a proton, H^+, is a Lewis acid because it can accept an electron pair.

A proton is only one of a large number of species that may act as a Lewis acid. The electron deficient species such as $AlCl_3$, BF_3, BCl_3, $ZnCl_2$, Mg^{2+} and carbocations are also Lewis acids. The electron deficient atoms in these species accept the electrons to complete their valence shell octets.

Similarly, any molecule or ion which has an unshared pair of electrons to donate can act as a base. Thus, dimethyl ether acts as a Lewis base towards boron trichloride which acts as a Lewis acid. This acid-base reaction is represented below:



Note that the curved arrow shows the movement of a pair of electrons *from* their source *to* their destination.

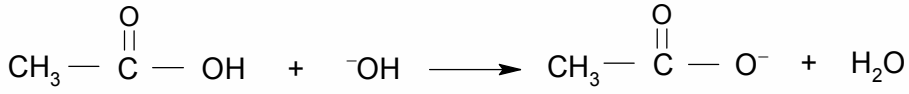
You will agree that the bases are much the same in both the Lewis and the Brönsted-Lowry definitions because a Brönsted-Lowry base must possess a pair of electrons in order to accept a proton.

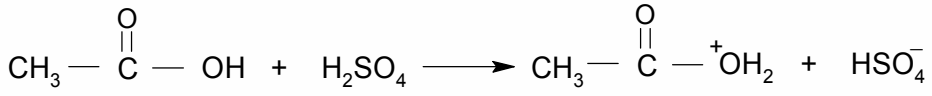
Having identified a substance as an acid or a base according to the above criteria, let us study how to determine the strength of an acid or a base.

Before that check your understanding of the above concepts by answering the following SAQ.

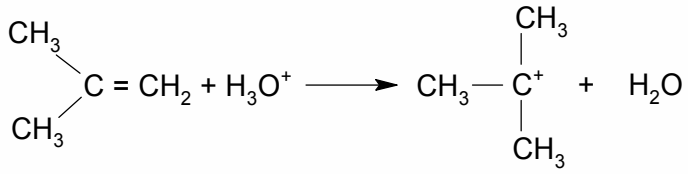
SAQ 1

Label the conjugate acid and the conjugate base in each of the following reactions.

a) 

b) 

c) $(CH_3)_3\overset{+}{N}H + CH_3O^- \longrightarrow (CH_3)_3N: + CH_3OH$

d) 

13.3 STRENGTHS OF ACIDS AND BASES

It is not possible to determine the strength of an acid or a base in absolute terms. Therefore, these strengths are always expressed in relative terms. The *relative strengths* of acids are determined by the extent to which they transfer a proton to a standard base. The standard base, which is commonly used for such comparisons, is water. Hence, for an acid HA, the proton transfer can be represented by the following equilibrium:

$$HA + H_2O \rightleftharpoons :A^- + H_3O^+$$

The equilibrium constant, K_{eq}, for the above equilibrium can be written as,

$$K_{eq} = \frac{[:A^-]\,[H_3O^+]}{[HA]\,[H_2O]} \qquad \ldots(13.1)$$

where the quantities in brackets are the molar concentrations (expressed as moles dm^{-3}) of the species at equilibrium.

For dilute solutions, the concentration of water is large and is almost constant. Hence, the above expression for equilibrium constant can be rewritten in terms of a new constant, K_a, called the **acidity constant**, as given below:

$$K_{eq}[H_2O] = K_a = \frac{[:A^-]\,[H_3O^+]}{[HA]} \qquad \ldots (13.2)$$

The dissociation of an acid HA in solvents other than water can be generalised as,

$$HA + \text{solvent} \rightleftharpoons H^+ - \text{solvent} + :A^-$$

The expression for acidity constant can then be written as follows:

$$K_a = \frac{[H^+ - \text{solvent}]\,[:A^-]}{[HA]} \qquad \ldots(13.3)$$

Taking - log of Eq. 13.2 and rearranging, we get

$-\log K_a = -\log [H_3O^+] + \log \frac{[HA]}{[:A^-]}$

By definition,

$-\log K_a = pK_a$

and

$-\log [H_3O^+] = pH$

Hence,

$pK_a = pH + \log \frac{[HA]}{[:A^-]}$

This expression relating the pK_a and pH is also known as **Henderson-Hasselbalch equation**.

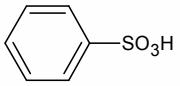
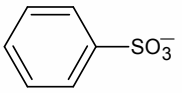
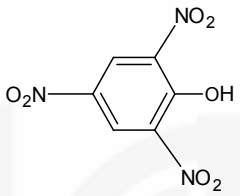
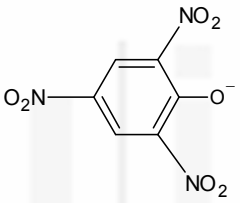
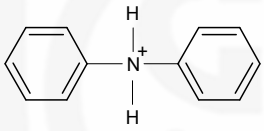
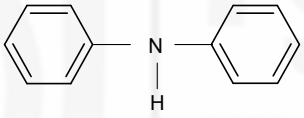
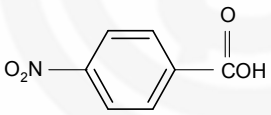
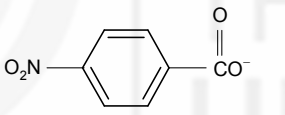
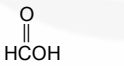
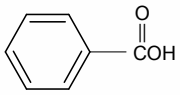
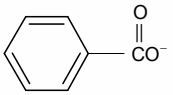
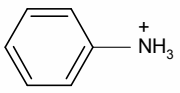
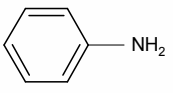
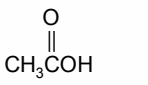
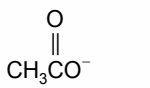
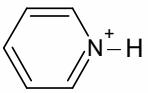
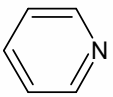
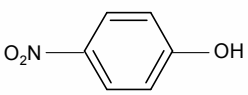
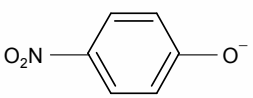
Thus, when $[HA] = [:A^-]$, then $pK_a = pH$.

The acidity constants of different acids have magnitudes ranging from 10^{14} to 10^{50}. In order to avoid writing a wide range of powers of 10, K_a is generally expressed in terms of pK_a, where

$$pK_a = -\log_{10} K_a \qquad \ldots(13.4)$$

Table 13.1 shows the pK_a values for a variety of acids along with their conjugate bases.

Table 13.1: pK_a Values

Acid	Conjugate base	pK_a
H_2SO_4	HSO_4^-	– 9
HCl	Cl^-	– 7
H_3O^+	H_2O	– 1.7
HNO_3	NO_3^-	– 1.3
		– 0.6
		0.25
		0.8
		3.4
		2.7
		4.2
		4.6
		4.8
		5.2
		7.2

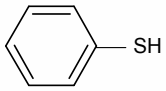
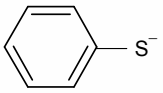
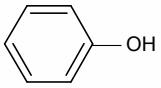
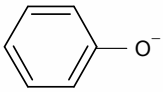
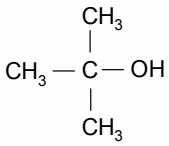
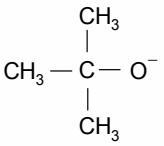
Acid	Conjugate base	pK_a
		7.8
NH_4^+	NH_3	9.4
$(CH_3)_3NH^+$	$(CH_3)_3N$	9.8
		10.0
CH_3CH_2SH	$CH_3CH_2S^-$	10.5
$CH_3NH_3^+$	CH_3NH_2	10.6
CH_3OH	CH_3O^-	15.5
H_2O	OH^-	15.7
CH_3CH_2OH	$CH_3CH_2O^-$	17
		19
$CHCl_3$	$^-CCl_3$	25
$HC \equiv CH$	$HC \equiv C^-$	26
NH_3	$^-NH_2$	36
$CH_2 = CH_2$	$CH_2 = CH^-$	36
CH_4	$^-CH_3$	49

Table 13.1 shows that the acids which are listed at the top are strong acids. For strong acids such as H_2SO_4, the proton transfer to the base (i.e., water) is almost complete and equilibrium lies towards the right. Thus, the stronger acids have larger K_a values. Therefore, it follows from Eq. 13.4.that the stronger the acid, the smaller the pK_a value. Thus, as Table 13.1 shows, the sulphonic acids and carboxylic acids are much more acidic as compared to phenol and alcohols.

The **stronger** the acid, the **weaker** is its conjugate base and *vice-versa*.

Remember that the conjugate base of a strong acid will be a weak base and the conjugate base of a weak acid will be a strong base. Similarly, we can generalise for conjugate acids.

Note that Table 13.1 lists the pK_a values for protic acids or Brönsted acids only. A similar Table for the relative acidities of Lewis acids is not feasible because in these acids it is not possible to have a standard base as reference. But, an approximate order of the strengths of various Lewis acids is as given below:

BF_3	>	$AlCl_3$	>	$FeCl_3$	>	$SbCl_3$	>	$ZnCl_2$	>	$HgCl_2$
Boron trifluoride		Aluminium chloride		Ferric chloride		Antimony chloride		Zinc chloride		Mercuric chloride

Lewis acids such as boron trifluoride and aluminium chloride are important acid catalysts for certain organic reactions.

The Table of pK_a values can be used to predict the feasibility of an acid-base reaction. **In general, an acid will transfer a proton to the conjugate base of any acid that is below it in the pK_a Table. Also, the larger the difference**

between the pK_a values (i.e., acidities) of the acid and the conjugate acid of the base, the more favourable will be the proton transfer from the acid to the base.

Many organic reactions are initiated by protonation or deprotonation of a reactant, therefore, the pK_a values are also helpful in choosing the appropriate acidic or basic reagents required for a particular reaction.

Similar to acids, an equilibrium for bases in water can be written as,

$$:A^- + HOH \rightleftharpoons HA + {}^-OH$$

The equilibrium constant for such an equilibrium can be expressed as,

$$K_{eq} = \frac{[HA]\,[{}^-OH]}{[:A^-]\,[HOH]} \qquad \ldots(13.5)$$

where the quantities in brackets are molar concentrations of the respective species at equilibrium.

In the expressions for K_a and K_b, the concentration of water is generally omitted and hence, K_a and K_b, have units of moles dm^{-3}.

The self-ionisation of water can be represented as,

$H_2O + H_2O \rightleftharpoons H_3O^+ + {}^-OH$

Since, the reaction is carried out in aqueous solution, water is acting both as a solvent as well as an acid; hence, its concentration can be taken as almost constant. Thus, we can write Eq. 13.5 in terms of the basicity constant, K_b, as

$$K_{eq}\,[H_2O] = K_b = \frac{[HA]\,[{}^-OH]}{[:A^-]} \qquad \ldots(13.6)$$

The two constants K_a and K_b are related to each other as shown below:

$$K_a \,.\, K_b = \frac{[:A^-]\,[H_3O^+]}{[HA]} \,.\, \frac{[HA]\,[{}^-OH]}{[:A^-]}$$

$$= [H_3O^+]\,[{}^-OH] = K_w = 10^{-14}\ \text{moles}^2\ \text{dm}^{-6}$$

where K_w is the self-ionisation constant of water. Hence,

$$pK_a + pK_b = 14$$

Therefore, if we know the pK_a of acid HA, the pK_b of the base :A$^-$ can be obtained by using the above relation.

The concentration of the species H_3O^+ and ${}^-OH$ in pure water is very low and is equal to 10^{-7} moles dm^{-3}. Therefore, the self-ionisation constant, K_w, of water is defined as,

$K_w = [H_3O^+][{}^-OH]$

$= 10^{-7} \times 10^{-7}\ \text{moles}^2\ \text{dm}^{-6}$

$= 10^{-14}\ \text{moles}^2\text{dm}^{-6}$

It is customary to express the strengths of organic bases not as K_b values but in terms of the K_a and pK_a values because it allows a single continuous scale for both acids and bases. The acidities of the bases can be compared by comparing pK_a of their conjugate acids. As has been stated above the stronger the acid, the weaker will be its conjugate base and *vice-versa*. In other words, the stronger the acid, the lower the pK_a, but, the stronger the base, the higher is the pK_a. This is also evident from Table 13.1 that whereas the acidity of the acids *decreases* from top to bottom, the basicity of the conjugate bases *increases* from top to bottom. You can see that ${}^-NH_2$, which comes almost at the bottom of this Table, is a very strong base (see Table 13.1). A comparison of the pK_a values from Table 13.1 shows the following order of the basicities for some of the bases.

$${}^-CH_3 > {}^-NH_2 > RO^- > {}^-OH > RCOO^-$$

Note that the organic compounds which act as bases can be regarded as alkyl derivatives of either water or ammonia; for example, alcohols (R – O – H), ethers (R – O – R′) and amines RNH_2, R_2NH and R_3NH. The basic character of these compounds can be attributed to atoms such as nitrogen and oxygen which contain at least one lone pair of electrons.

Having discussed the strengths of acids and bases, let us now study the factors affecting the strength of acids and bases. But before proceeding to the study of next section which deals with these factors, answer the following SAQ.

SAQ 2

An acid HX has pK_a = 20 and another acid HY has pK_a = 10.

a) Which of these two acids is stronger?

b) If $Na^+ X^-$ salt is added to acid HY, does any acid base reaction take place? Explain.

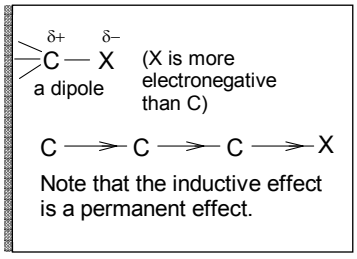
13.4 FACTORS AFFECTING THE STRENGTHS OF ACIDS AND BASES

The strengths of acids and bases depend upon many factors. It was mentioned before, that apart from the presence of functional groups, structural variations in molecules also influence their acidic or basic properties. We will now focus our attention on some effects which arise due to structural changes in the molecules. A change in molecular structure can affect the reactivity of the molecule by changing the *electron distribution* of the system, in which case it is called an **electronic effect.** Another possibility is that two or more groups or atoms may come close enough in space so that the London interactions between them become significant. The effects arising from such interactions are called **steric effects.**

We will begin our discussion with the study of an electronic effect, known as **inductive effect.**

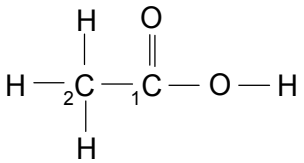
13.4.1 Inductive Effect

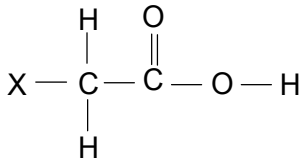
You are already familiar with the fact that when two different atoms form a covalent bond, the shared pair of electrons is pulled more by the more electronegative atom. This unequal electron distribution results in partial separation of charge and we get a dipole in which one atom has a partial positive charge and another atom (the more electronegative one) has a partial negative charge. Such a polarisation of a bond can be felt by adjacent groups also. This phenomenon of the transmission of charge through a chain of atoms linked together by sigma bonds is called **inductive effect.**



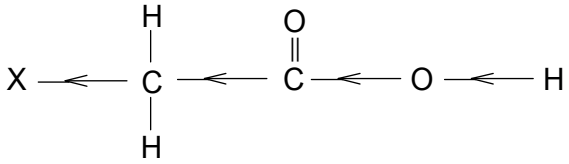
Note that the inductive effect is a permanent effect.

Let us now analyse how inductive effect causes a change in the acidity or basicity of a molecule. Let us take the example of ethanoic acid whose structure is shown below.

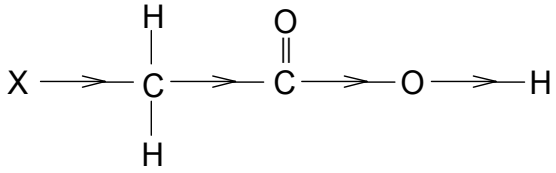

ethanoic acid
pK_a 4.76


substituted
ethanoic acid

If we substitute one of the hydrogen atoms on the C-2 carbon atom with a substituent X, then, the nature of the substituent group may effect the electron density of the O–H bond resulting in a change in the acidity of the molecule. Depending upon whether the substituent X is electron-withdrawing or electron donating, the electron density will decrease or increase, respectively. If the electron density at the bond formed between O and H atoms *decreases,* then, the loss of H as H^+ ion is facilitated resulting in the *increased acidity* of the molecule.

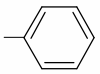
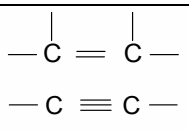


On the other hand, an *increase* in the electron density at the bond between O and H atoms will make the proton release difficult, thereby, *decreasing* the acidity.



The electron-withdrawing substituents are said to have -*I* effect and the electron-donating substituents are said to have +*I* effect. Some examples of the substituents belonging to these two categories are listed in Table 13.2.

Table 13.2: Inductive effect of various functional groups

Electron-donating substituents (+ *I*)	**Electron-withdrawing substituents (– *I*)**		
– O^-	– F	– CO_2H	
– CH_3	– Cl	– CO_2R	
	– Br		
	– I	— C ≡ N	
	– OR	– NO_2	
	– OH	– SO_2	
			
	– SR		
	– SH		

The effect of some of these substituents on the acidity of the substituted acids in terms of their pK_a values is shown in Table 13.3.

Table 13.3: pK_a values for some substituted acids determined in water at 298 K

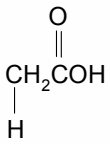
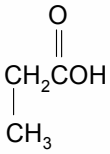
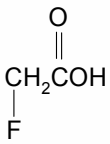
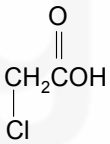
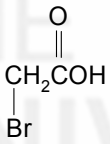
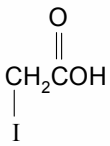
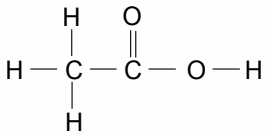
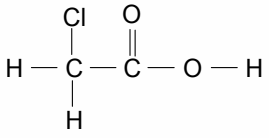
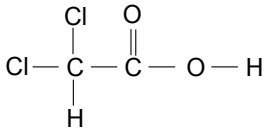
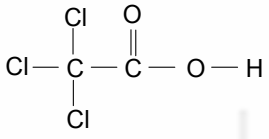
Acid	Structure	pK_a
Ethanoic acid		4.76
Propanoic acid		4.87
Fluoroethanoic acid		2.59
Chloroethanoic acid		2.86
Bromoethanoic acid		2.90
Iodoethanoic acid		3.17

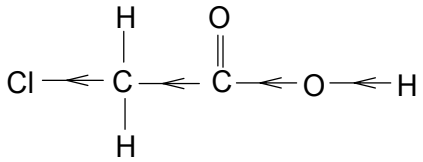
Table 13.3 shows the decreased acidity for propanoic acid (larger pK_a value) as compared to the ethanoic acid. Note that the propanoic acid has a methyl group in place of H in ethanoic acid. The methyl group is electron-donating in nature and, therefore, has a $+I$ effect which results in the decrease in the acidity of propanoic acid. But the acidity increases when the electron-withdrawing substituents such as F, Cl, Br and I are present. Note that the increase in acidity is in accordance with the electronegativity of these elements.

The inductive effect of these substituents is further enhanced with the increase in the number of these substituents. This is represented in Table 13.4.

Table 13.4: Effect of increase in the number of chlorine substituents on acidity of ethanoic acid

Acid	Structure	pK_a
Ethanoic acid		4.76
Monochloroethanoic acid		2.86
Dichloroethanoic acid		1.30
Trichloroethanoic acid		0.65

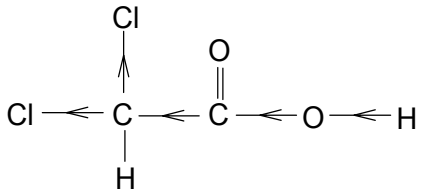
In monochloroethanoic acid, one of the three hydrogen atoms in ethanoic acid has been replaced by an electron-withdrawing chlorine atom. Hence, the electron pair constituting the C – Cl bond is drawn closer to the chlorine atom. This effect is transmitted through other atoms forming σ bonds to the OH bond of the  group. This results in a shift of the electrons constituting the O – H bond towards oxygen atom as shown below:



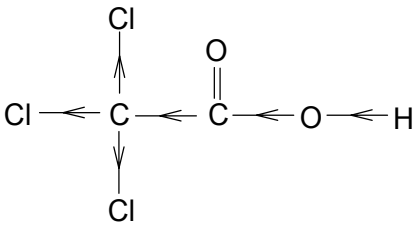
monochloroethanoic acid

Such an electron withdrawal by chlorine atom, thus, facilitates the departure of the proton and hence, increases the acidic character of monochloroethanoic acid as compared to ethanoic acid.

In the dichloro- and trichloroethanoic acids, the presence of second and third chlorine atoms results in more electron withdrawal and hence the shared pair of electrons shifts away from hydrogen of the O — H bond.



dichloroethanoic acid



trichloroethanoic acid

Thus, the inductive effect of chlorine atoms would further increase the acidity of these compounds as compared to ethanoic acid or chloroethanoic acid. Therefore, we can arrange these acids in the increasing order of their acidities as follows:

ethanoic acid < chloroethanoic acid < dichloroethanoic acid < trichloroethanoic acid

The position of electron-withdrawing substituents in a molecule also influences its acidic character. This is shown by the pK_a values of isomeric monochlorobutanoic acids given in Table 13.5.

Table 13.5: Effect of position of substituent on acidity

Acid	Structure	pK_a
Butanoic acid	$CH_3CH_2CH_2COH$ (O)	4.82
2-Chlorobutanoic acid	CH_3CH_2CHCOH (O, Cl)	2.86
3-Chlorobutanoic acid	CH_3CHCH_2COH (O, Cl)	4.05
4-Chlorobutanoic acid	$CH_2CH_2CH_2COH$ (O, Cl)	4.52

It can be seen that although in each of these acids a chlorine atom has replaced a hydrogen atom but they show different acidities. Note that as the distance of the electron-withdrawing chlorine atom from the reaction site (i.e., the O – H of the COOH group) increases, the acid strength decreases. Thus, the influence of the inductive effect on acid strength is greatest when the electron-withdrawing chlorine atom is present on the carbon next to the carboxylic group and it diminishes quickly with increase in the distance. This effect is almost negligible after the fourth carbon atom in the chain.

A similar electron withdrawal occurs when a positively charged group is present in a molecule. A positive centre such as $(CH_3)_3\overset{+}{N}-$ (trimethyl ammonium) or $-\overset{+}{N}H_3$ (ammonium), eases the departure of proton by withdrawing electrons and hence, increases the acidic character of the molecule. This is illustrated in the example given below:

CH_3COOH	$(CH_3)_3\overset{+}{N}-CH_2COOH$	$(CH_3)_3\overset{+}{N}CH_2CH_2CH_2CH_2COOH$
pK_a 4.76	pK_a 1.83	pK_a 4.27

Note that here also with the increase in the distance between the positively charged group and the carboxyl group, the inductive effect decreases.

If the presence of a positively charged group increases the acidity of a molecule, then a negatively charged group should decrease the acidity. Consider the dissociation of propanedioic acid, as given below:

$$HOOCCH_2COOH \overset{K_{a_1}}{\rightleftharpoons} HOOCCH_2COO^- + H^+$$

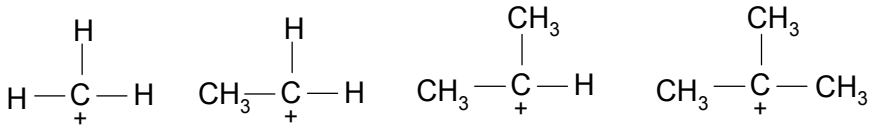
propanedioic acid
$pK_{a_1} = 2.83$

Always remember that K_{a_1} is larger than K_{a_2} for a dicarboxylic acid. Therefore, for these acids pK_{a_1} has a lower value than pK_{a_2}.

where K_{a_1} is the first dissociation constant.

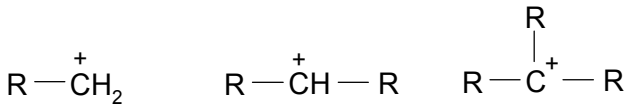
Here, a proton is lost from one of the two carboxyl groups of the molecule. The dissociation constant for this dissociation is called the first dissociation constant and is represented by K_{a_1}. Further dissociation of the anion obtained in the above dissociation is difficult because it involves the removal of the proton from a negatively charged species. Therefore, this step has a pK_a value equal to 5.69. This is called pK_{a_2} because K_{a_2} represents the second dissociation constant.

From the above discussion, we can say that the substituents having -I effect increase the acidity while the substituents having +I effect decrease the acidity. On this basis, let us now analyse the stability of carbocations which are reactive intermediates formed during the chemical reactions. You are already familiar with the shape of the carbocations which you studied in Unit 11 under the stereochemistry of S_N1 reactions. Look at the following examples of carbocations:



methyl carbocation | primary carbocation | secondary carbocation | tertiary carbocation

The carbocations are classified by the degree of alkyl substitution at the positively charged carbon atom as primary, secondary or tertiary carbocations, as shown below:



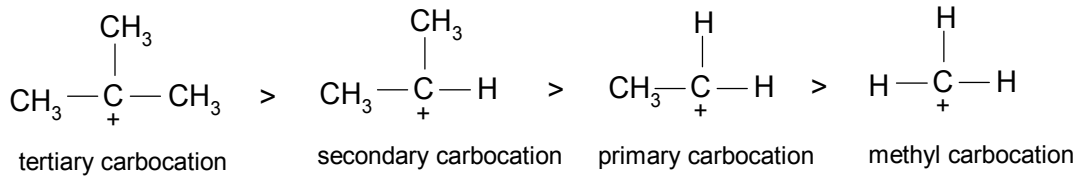
a primary carbocation | a secondary carbocation | a tertiary carbocation

Carbocations contain a positively charged carbon atom.

where R is the alkyl group.

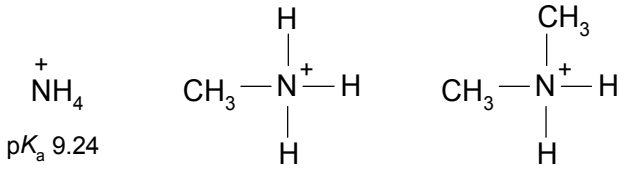
Since the alkyl groups are electron donating in nature, the +I effect increases with the increase in the number alkyl groups. Thus, the increase in the number of alkyl groups in a carbocation helps in the dispersal of its positive charge. Therefore, a tertiary carbocation is more stable than a secondary carbocation

ion which is, in turn, more stable than a primary carbocation. Hence, we can arrange the above carbocations in the following order of their stabilities:



Since the substituents having $+I$, effect decrease the acidity, their presence should also increase the basicity. This is what is actually observed when the hydrogen atoms of ammonia are successively replaced by methyl groups to give methylamine and dimethylamine whose basicities increase with the increase in the number of methyl groups, as shown below by the pK_a values of **their conjugate acids**.

The basicity of tertiary amines will be discussed in sub-Sec. 13.4.5.



Till now, you have been studying the inductive effect of various substituents on the acidities and basicities of molecules. In fact, the inductive effect influences the electron density of the H – A bond. Another factor which affects the release of protons from the acid HA is the stability of the anion, A^-, formed by the loss of proton from the acid HA. You will be studying about this in the next section.

As this stage, it would be helpful to answer the following SAQ.

SAQ 3

a) Arrange the following compounds in the decreasing order of their acid strengths. Also, give reasons in support of your answer.

   i) CH_3COOH, $NCCH_2COOH$, $NCCH_2CH_2CH_2COOH$

   ii) CH_3COOH, HOOCCOOH, $^-OOCCOOH$

b) Arrange the following compounds in the decreasing order of their base strength. Support you answer with reasons.

   i) Aniline, *N*-methylaniline, *N,N*-dimenthylaniline

   ii) NH_3, NH_2CH_3, NH_2OH

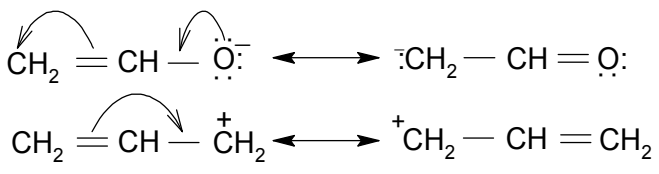
13.4.2 Resonance Effect

One of the factors which stabilises the A^- anion with respect to the acid HA, is *resonance effect.* Let us first revise the basic ideas about resonance which you have learnt earlier in Unit 8, Block 2 of this course and then we will discuss the effect of resonance on the acidity and basicity of molecules.

Resonance

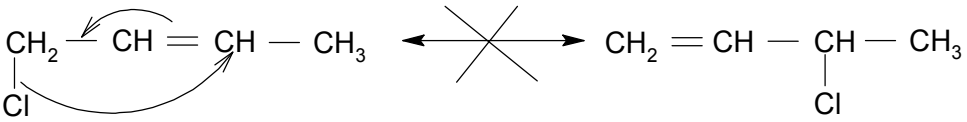
You are already familiar with the fact that some covalent molecules or ions cannot be represented satisfactorily by a single Lewis structure. Therefore, for such species, more than one Lewis structure is possible. These Lewis structures are called **resonance structures** or **resonance contributors** and the actual molecule or ion is said to be a **resonance hybrid** of these resonance structures. Since we will be dealing with the resonance structures of various molecules in explaining their reactivity, we should be able to write all the possible resonance structures of a molecule. For this purpose, certain rules are to be followed. These rules are as listed below:

1. Only nonbonding electrons and electrons constituting the multiple bonds change locations from one resonance contributor to another. The electrons forming single covalent bonds are not involved. This is shown in the examples below:

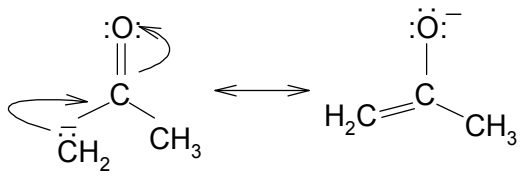


Note that a double headed arrow (↔) is used to represent the resonance contributors. It should be clear to you that it does not mean that the resonance contributors are in rapid equilibrium but it implies that the actual molecule has one structure which has the contribution from various resonance contributors.

2. The nuclei of various atoms in different resonance contributors are in the same position. Hence, the structures which are shown below are not resonance structures because the location of the chlorine atom is different in them. These are, in fact, position isomers.

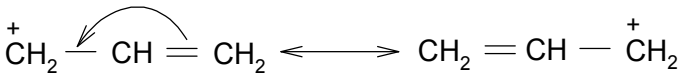


3. All resonance contributors must have the same number of paired and unpaired electrons. This is illustrated below:



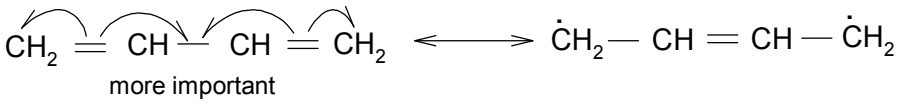
Here, it is important to understand that the individual resonance structures do not exist in reality and the actual compound is not a mixture of the various resonance contributors, but it is a **weighted average** of these structures. When we use the words *weighted average*, it is implied that some resonance structures are more important than the others and therefore, contribute more to the hybrid structure. But, how to know which structure is more important than the others. To evaluate the relative importance of various resonance structures, their stabilities are compared by considering each structure as a separate entity or species. In other words, we assume each resonance structure to be real. Thus, the most stable structures are the most important ones. Given below are some guidelines to enable you to assess the relative importance of resonance structures.

1. *Identical resonance structures are equally important and contribute equally towards the actual structure of a molecule.* For example, the following resonance structures contribute equally to the actual structure of the molecule.



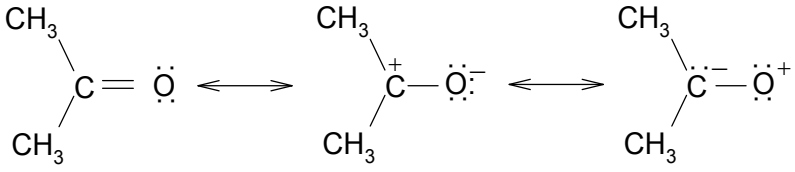
2. *Resonance contributors having greater number of bonds are more important.* Thus, in the following resonance structures, the one on the left hand side is more important.

Single headed arrow (or) denotes movement of an electron.



more important

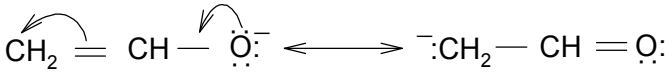
3. *Resonance contributors with little or no charge separation are more important than those having the large separation of charge.* Therefore, among the three resonance structures shown below, the first one is the most important.



most important

4. *In case of resonance contributors having separation of charge, the resonance contributor having the negative charge on the more electronegative atom is more important.*

   Hence, in the following two resonance structures, the one in which the more electronegative oxygen atom carrying the negative charge is more important.



more important

5. *Resonance structures in which the atoms of elements from the second period of the periodic table have eight electrons around them are more important than those in which these atoms have less than eight electrons.*

6. *Resonance structures that help in delocalisation of charge or of unpaired electrons are important.*

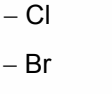
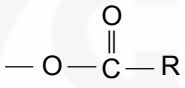
You will study about resonance energy of benzene in Unit 19.

Having understood how to assign the relative importance to various resonance structures, let us now consider why resonance structures are important in deciding the stability of a molecule. Since the resonance structures of a molecule are symbolic representations of the additional bonding associated with the orbital overlap, *the greater the number of important resonance structures, the greater is the stability of the actual molecule.* This stabilisation

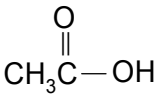
due to resonance is measured in terms of the **resonance energy** which is the energy difference between the actual molecule and its best resonance structure.

Table 13.6 lists various groups which donate or withdraw electrons due to resonance. Groups which donate electrons by resonance are called +*R* groups. Some examples of the +*R* groups being the hydroxy (–OH), amino ($-NH_2$), alkoxy (–OR), halogens (–X) and alkylamino (–NHR and $-NR_2$) groups. On the other hand, the groups which withdraw electrons by resonance are called –*R* groups. The examples of –*R* groups are nitro ($-NO_2$), cyano (–C ≡ N), carbonyl (>C = O), and sulphonic ($-SO_3H$) groups.

Table 13.6: Resonance effects of various groups

Electron-donating + *R* groups	**Electrons-withdrawing – *R* groups**
– F	– C ≡ N
– Cl	
– Br	– SO_2^-
– I	– NO_2
– O^-	
– OR	
– OH	
	
– N <	
– SR	
– SH	
– CH_3	

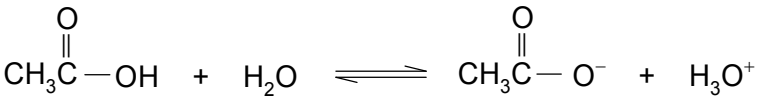
Let us now study how resonance affects the acidity and basicity of various molecules. Consider the pK_a values for ethanoic acid and ethanol as given below:



ethanoic acid
pK_a 4.76

CH_3CH_2OH
ethanol
pK_a 17

Consider the dissociation of these compounds as shown below:

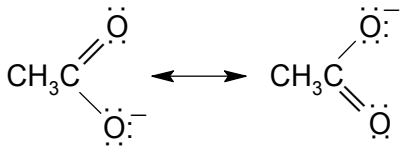


ethanoate ion

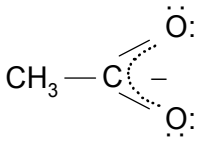
$CH_3CH_2OH + H_2O \rightleftharpoons CH_3CH_2O^- + H_3O^+$

ethoxide ion

We find that the anion of ethanoic acid can be represented as a resonance hybrid of the following two resonance structures.



Since these two structures are equivalent, they contribute equally to the actual structure which can be represented as shown below:



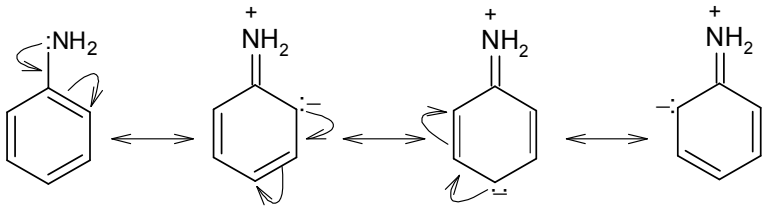
Thus, we can say that in the ethanoate anion, the charge is not localised on any one of the oxygen atoms but is distributed equally, or is delocalised, over both the oxygen atoms. This dispersal of charge resulting from the delocalisation stabilises this anion. But, the delocalisation of charge reduces the availability of electrons, thereby resulting in the decrease in the basicity of the anion. Hence, the equilibrium lies in the forward direction resulting in the dissociation of the acid.

Similar resonance stabilisation is not possible for the ethoxide ion because such a stabilisation is possible only if the system has π electrons. Because of the absence of stabilisation by resonance for the ethoxide anion, ethanol is less acidic as compared to ethanoic acid.

Resonance structures discussed in this section involve π electrons and in some cases nonbonded electrons. In the next section, you will study hyperconjugation which involves π and σ electrons.

The acidity of phenols can also be explained using the resonance phenomenon about which you will study in later course. In that course, you will also study the effect of resonance on the reactivity of aromatic compounds.

Similar to acidity, the basicity of compounds is also affected by the resonance. For example, in case benzenamine (aniline), in addition to the electron withdrawing nature (-I effect) of the aryl group, the following resonance structure are possible.



benzenamine (aniline)

These resonance structures clearly show that the nonbonding electrons of the nitrogen atom are delocalised over the aromatic ring. Thus, the electron density at the nitrogen atom decreases which results in the lower basicity of aniline as compared to ammonia.

You can check your knowledge of resonance by answering the following SAQ.

SAQ 4

Draw resonance structures for the following species to rationalise the facts given with them.

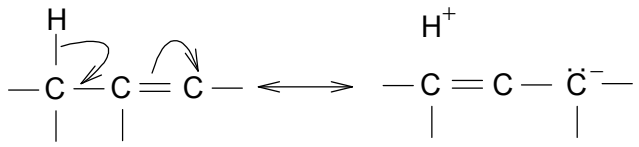
a) $H_2C = \overset{+}{\underset{\cdot\cdot}{O}} - H$ is the conjugate acid of methanal (formaldehyde) and has a substantial positive charge on carbon.

b) In acetonitrile oxide, $H_3C - C \equiv \overset{+}{N} - \ddot{O}:^{-}$, the inner carbon acquires a positive charge.

We will now study a special case of resonance which is known as hyperconjugation.

13.4.3 Hyperconjugation

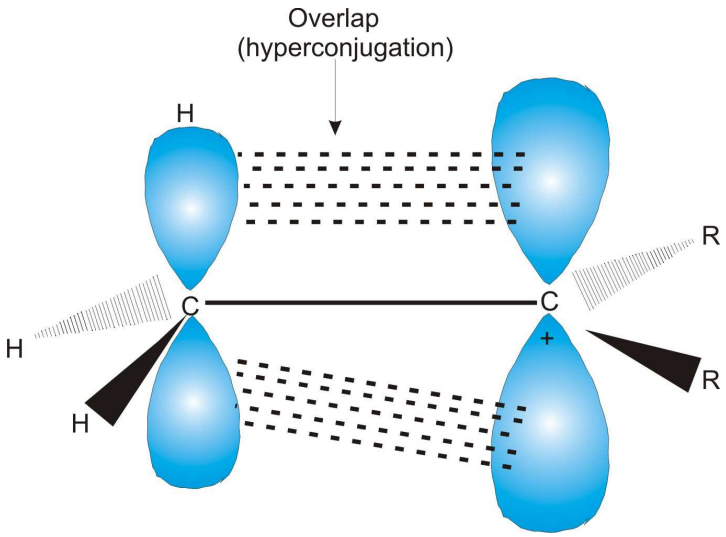
Hyperconjugation involves the overlap of bonding electrons from adjacent *sigma* (σ) bonds with the unoccupied *p* orbital. The resulting shift of electrons of C – H sigma bond and adjacent *pi* electrons is as shown below:



Hyperconjugation involving hydrogen is the most common.

This is also known as $\sigma - \pi$ conjugation.

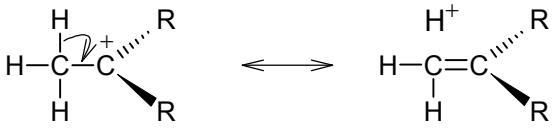
This type of delocalisation leads to a situation where there is *no bond* between the hydrogen and the carbon atom of the molecule. Therefore, it is also known as **no-bond resonance.** Remember that the proton does not leave its position and since the nuclei or the atoms do not change their positions, therefore, the hyperconjugation becomes similar to resonance. Hyperconjugation also results in the delocalisation of charge, as you will now study in case of carbocations. The stability of carbocations has been earlier explained on the basis of inductive effect of the alkyl groups. Let us consider again a primary carbocation, such as the one shown below in Fig. 13.1.



For hyperconjugation to occur, the substituent next to the positively charged carbon must have a filled σ orbital available to overlap with vacant *p* orbital of the carbon atom carrying the positive charge.

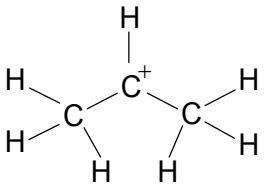
Fig. 13.1: The hyperconjugation in a carbocation.

It is clear from the above structure that the electrons forming the α–C–H bond can overlap, or spill over, into the empty *p* orbital of the carbon atom carrying the positive charge. The resulting hyperconjugation can be represented as illustrated below:

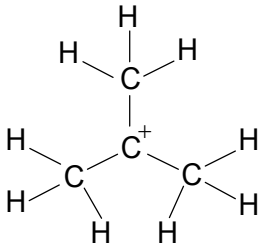


The C – H bond adjacent to the >C=C< or a carbocation is referred here as α-C–H bond.

Note that hyperconjugation produces some additional bonding between the electron-deficient carbon and the adjacent carbon atom. Hence, hyperconjugation results in the stabilisation of carbocation by delocalising the positive charge. Obviously, the more the number α–C–H bonds which can participate in hyperconjugation, the more stable will be the carbocation. You can see that in case of the primary carbocation shown above, there are three such α–C–H bonds. Let us now examine the secondary and the tertiary carbocations.



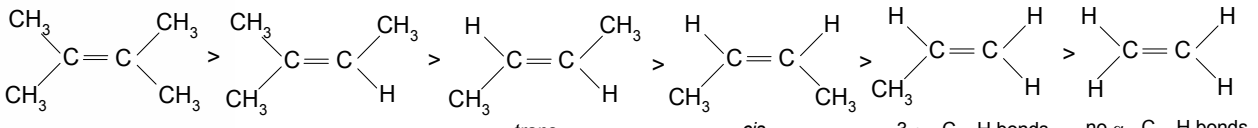
secondary carbocation
6 α-C–H bonds



tertiary carbocation
9 α-C–H bonds

The secondary carbocation has 6 α–C–H bonds which can participate in hyperconjugation whereas the tertiary carbocation has 9 α–C–H bonds. Certainly, more delocalisation of charge is possible in case of a tertiary carbocation than in a secondary carbocation which is in turn more than that possible in a primary carbocation. Therefore, the tertiary carbocation is more stable than the secondary carbocation which is more stable than the primary carbocation.

Hyperconjugation has also been used to explain the relative stabilities of substituted alkenes. Consider the following order of stability of some alkenes.



12 α - C – H bonds
tetrasubstituted

9 α - C – H bonds
trisubstituted

trans –
6 α - C – H bonds
disubstituted

cis –

3 α - C – H bonds
monosubstituted

no α - C – H bonds
no hyperconjugation
unsubstituted

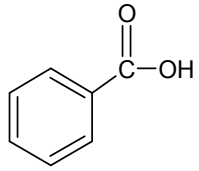
You can see that in an alkene, the more the number of α–C–H participate in hyperconjugation, the higher is its stability.

In spite of the fact that hyperconjugation can be used to explain many otherwise unconnected phenomena, it is controversial as it involves the formation a weaker *pi* bond at the expense of a strong *sigma* bond.

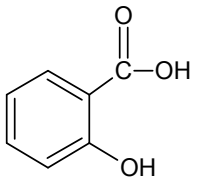
In addition to the resonance, another factor which contributes to the stability of the anion, A^- , is hydrogen bonding which you will now study.

13.4.4 Hydrogen Bonding

You are already familiar with the concept of hydrogen bonding from your study of earlier classes. If you analyse the pK_a values of benzenecarboxylic acid and 2-hydroxybenzenecarboxylic acid, as given below, then you will conclude that



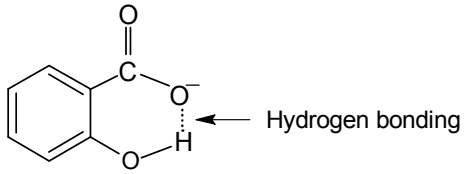
benezenecarboxylic acid
pK_a 4.2



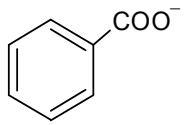
2-hydroxybenezenecarboxylic acid
pK_a 2.98

Hydrogen bonding stabilises the anion by delocalising the charge.

2-hydroxybenzenecarboxylic acid is much more acidic than benzenecarboxylic acid. This is because the anion formed from 2-hydroxybenzenecarboxylic acid is stabilised by hydrogen bonding, as shown below:



Similar stabilisation is not possible for the benzenecarboxylate anion; therefore, benzenecarboxylic acid is less acidic than 2-hydroxybenezecarboxylic acid.



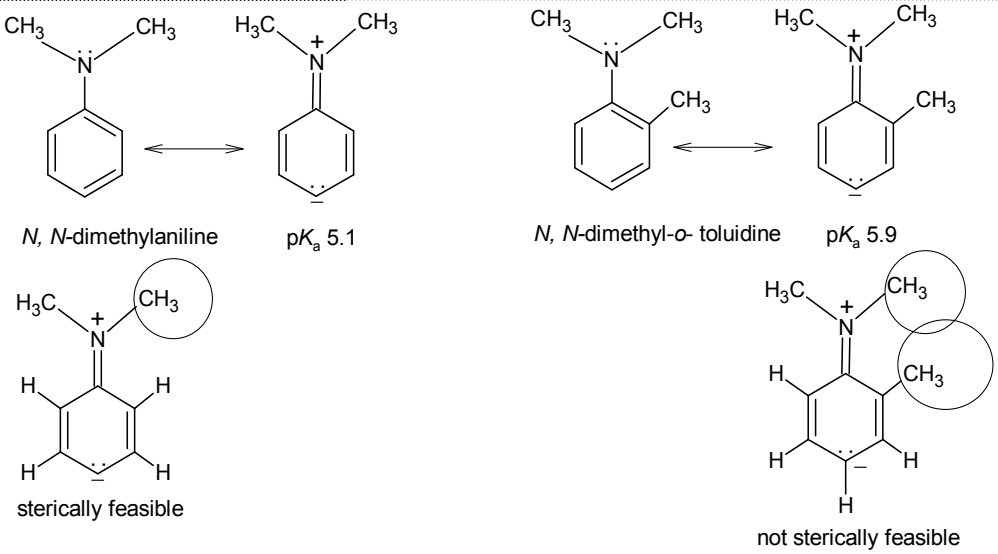
benzenecarboxylate anion

In the next section, you will study the steric effect on molecular reactivity.

13.4.5 Steric Effect

The effect arising from the spatial interactions between the groups is called the **steric effect**. You have already studied the effect of such interactions on the stability of geometrical isomers, (in Unit 10 where you studied that the *trans*- isomer is more stable than the *cis*- isomer) and conformational isomers, (in Unit 11 where you studied that the staggered conformation of ethane is more stable than its eclipsed conformation). As the acid-base behaviour or the molecular reactivity is related to the availability of the electrons, steric factors may also influence the molecular reactivity. For example, they can inhibit the delocalisation of charge, as is observed in case of *N,N*-dimethyl-*o*-toluidine. The delocalisation of the nonbonded electron pair on nitrogen, as shown in the structure of *N,N*-dimethylaniline in Fig. 13.2 a), requires that the *p*-orbital of nitrogen and those of the aromatic ring should be coplanar. Such coplanarity is inhibited in the case *N,N*-dimethyl-*o*-toluidine due to the presence of the *ortho* methyl group, as shown in Fig. 13.2 b). Therefore, in this molecule the electron pair is not delocalised but is available for bonding with the proton which makes this molecule more basic than *N,N*-dimethylaniline. This type of steric effect is known as *steric inhibition of resonance.*

Remember that the *steric hindrance* affects the molecular reactivity not by increasing or decreasing the electron availability but due to spatial congestion. Therefore, it is different from electronic effects.



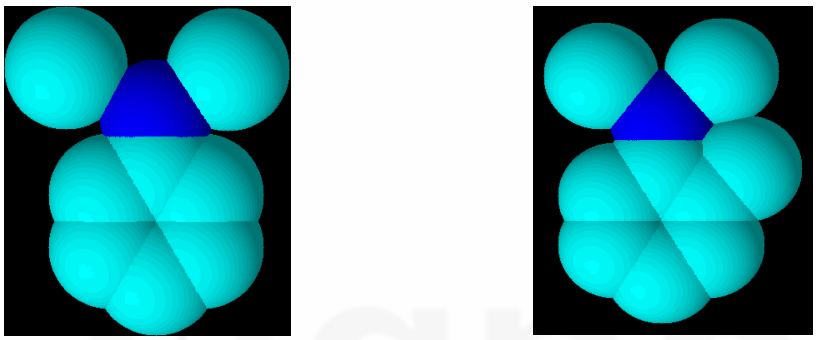
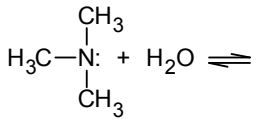
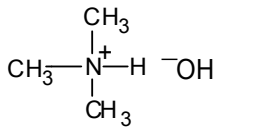


Fig. 13.2: a) Delocalisation of nonbonded electrons on nitrogen in aromatic ring in *N,N*-dimethylaniiline, b) Such a delocalisation is not possible in *N,N*-dimethyl-*o*-toluidine.





The most common steric effect is, however, the *steric hindrance* where the presence of the bulky groups makes the approach of the reagent to the reaction site difficult. Such steric hindrance can account for the lower basicity of tertiary amines as compared to secondary amines. The three alkyl groups attached to the nitrogen atom of the tertiary amine give rise to steric hindrance and interfere with the solvation of its conjugate acid. Thus, as shown in Fig. 13.3, the trimethylammonium cation, i.e. the conjugate acid of trimethylamine, is sterically the most hindered.

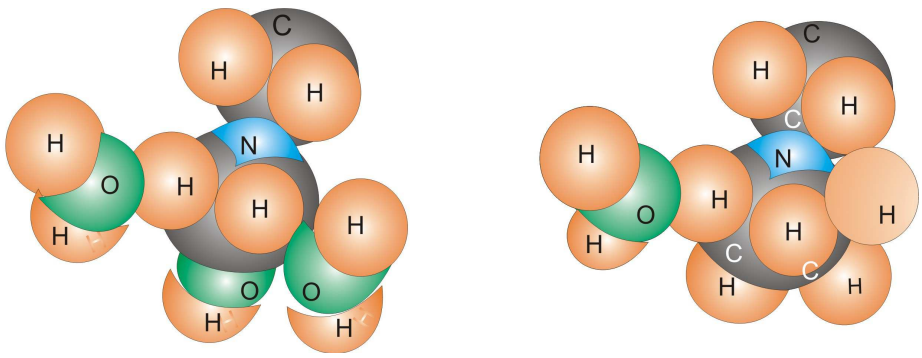


Fig. 13.3: A comparison of the solvation of trimethylammonium and methylammonium ions.

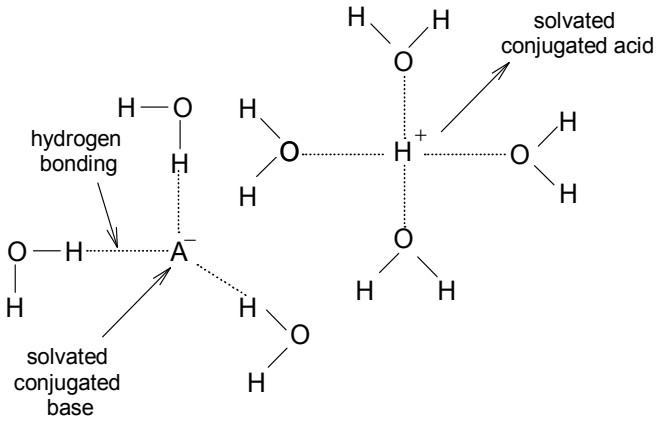
It is, thus, least stabilised by solvation, leading to the lower basicity of trimethylamine in water as compared to dimethylamine and methylamine.

However, in the gas phase or nonaqueous media, the electron-donating inductive effect of a methyl group makes trimethylamine the most basic among methylamines.

Let us now study what is solvation and the role of solvent on the reactivity of the molecules.

13.4.6 Solvent

The presence of a solvent in acid-base reactions leads to the solvation of the ionised species which are the conjugate acid and the conjugate base when we are dealing with Brönsted acids and bases. Solvation refers to the interaction of the dissolved species and solvent molecules wherein several solvent molecules surround the dissolved species by forming a **solvent shell** or **solvent cage** around it, as shown below:



The greater the solvation, the greater is the delocalisation of the charge on the species. Thus, increased solvation increases the dissociation of an acid or a base by increasing the stability of the ions.

These interactions are particularly important when water is used as a solvent where the hydrogen bonding plays an important role in solvating the anions. The high dielectric constant of water also helps in the dissociation of the acids. Thus, the ionisation and the acidity of a substance increases with the increase in the dielectric constant of the solvent. This is illustrated in Table 13.7.

Table 13.7: Effect of solvent on pK_a of ethanoic acid at 298 K

Solvent	pK_a
Benzene	almost unionised
82% Dioxane – 18% Water	10.14
70% Dioxane – 30% Water	8.32
45% Dioxane – 55% Water	6.31
20% Dioxane – 80% Water	5.29
Water	4.76

Thus, as the percentage of water in the solvent system increases, the pK_a value of the acid decreases.

Water is a peculiar solvent as it can behave both as an acid as well as a base. But its use has a limitation in the sense that some organic compounds are not soluble in it.

Having discussed the various aspects of acids and bases, let us now focus our attention on an internal acid-base process called tautomerism.

13.5 TAUTOMERISM

In contrast to resonance structures, tautomers are real compounds and are capable of independent existence.

The term *tautomerism* designates a rapid and reversible interconversion of isomers which are related to each other with the actual movement of electrons as well as that of one or more atoms. Such isomers are called **tautomers.** Thus tautomerism is a chemical reaction and is to be differentiated from resonance in which the nuclei do not move. It is, therefore, represented by the equilibrium sign (⇌) between the tautomers. Tautomers which differ from each other only in the location of a hydrogen atom and a double bond are called **proton tautomers.** Table 13.8 shows some examples of proton tautomers.

Table 13.8: Some examples of Proton tautomers

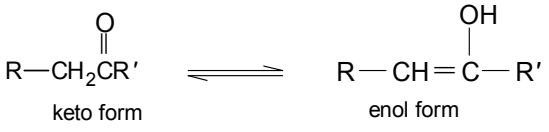
R, H, –O, –N; :O: ‖ —C— CH—	⇌	:ÖH | —C= C—	Keto-enol tautomerism occurs with all carbonyl-containing functional groups (esters, amides, etc).
Carbonyl*		Enol	
—N̈ ‖ —C— CH— |	⇌	N̈H | —C= C— |	
Imine		Enamine*	
:O: ‖ :N— CH— |	⇌	:ÖH | :N= C—	
Nitroso		Oxime*	
:O: ‖ N⁺— CH— | :Ö⁻	⇌	HÖ: \ N= C— ⁺ :Ö⁻	
Nitro*		*aci*-Nitro	
:N≡ C— CH— |	⇌	HN̈= C= C— |	
Nitrile*			

The word *enol* has its origin from *ene+ol.* In *keto-enol tautomers,* the *keto* form is usually the more stable form and, therefore, it predominates at equilibrium.

The mechanism of *enolisation* involves solvent mediated proton transfer steps rather than a direct intramolecular jump of the proton from carbon to oxygen.

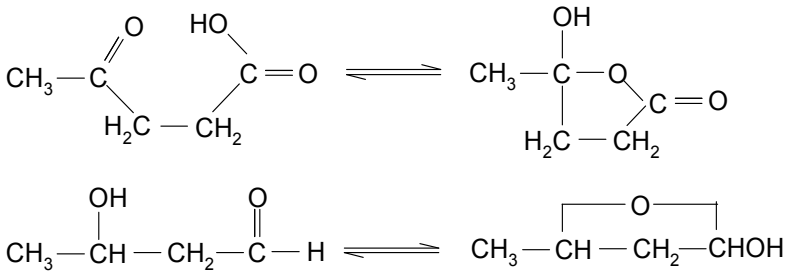
(* = more stable tautomer)

A particular example of tautomerism involving the ketones as carbonyl compounds is called keto-enol tautomerism and is represented below:

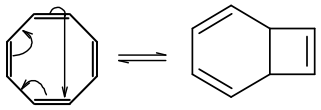


The keto-enol tautomerism is of enormous importance as you will study later in another course on Organic Chemistry.

Proton tautomerism in some cases leads to the formation of a ring in one of the tautomers. Such a tautomerism is called as **ring-chain tautomerism** and is illustrated below:



Another kind of tautomerism, known as **valence tautomerism** involves a shift in interatomic distances within a molecule, without the separation of any atom from the rest of the molecule, as an intermediate stage. This kind of tautomerism occurs as a result of movement of valence electrons of the molecule. An example of valence tautomerism is shown below:



Cyclooctatetraene

The valence tautomerism may appear similar to resonanace but remember that the two are different. The difference is that the valence tautomerism involves making and breaking of σ and π bonds while, in resonance only the π electrons or the nonbonding electrons shift and the σ framework of the molecule is not disturbed. Some other differences between tautomerism and resonance are as follows:

i) Tautomerism may involve a change in the hybridisation of atoms which may result in a change in the shape of the molecule. While in resonance there is no such change in the hybridisation and geometry of the molecule.

ii) The tautomers have a physical reality while the resonance structures are imaginary.

iii) Tautomerism involves an equilibrium between two or more tautomers. On the other hand, the resonance implies that the actual structure of the molecule is the *weighted average* of various resonance contributors and not a mixture of them.

13.6 SUMMARY

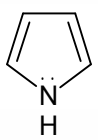
In this unit, you studied that

- Many reactions of organic compounds can be classified as acid-base reactions. Therefore, the study of acids and bases is important for understanding the organic reactions.
- According to Brönsted-Lowry definition, an acid is a proton donor and a base is a proton acceptor.

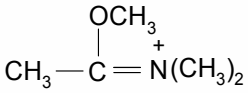
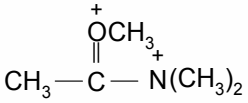
- Lewis definition classifies acids as electron pair acceptors and bases as electron pair donors.
- The acidities of Brönsted acids can be expressed in terms of their pK_a values.
- A strong acid has a weak conjugate base and a weak acid has a strong conjugate base and *vice-versa*.
- Structural changes can bring about marked differences in the acidic and basic behaviour of a molecule which can be explained on the basis of inductive effect, resonance effect, hyperconjugation and hydrogen bonding.
- The inductive effects operate through *sigma* bonds and decrease rapidly with increase in the distance between the substituent and the reaction site. As a consequence of the fact that inductive effect increases with the number of substituents present, a tertiary carbocation is more stable than a secondary carbocation which is, in turn, more stable than a primary carbocation.
- Resonance stabilisation of its anion (or the conjugate base) favours dissociation of the acid.
- The steric effect operates due to the presence of the bulky groups near the reaction site which prevent the approach of the reagent to the reaction site. The steric requirements for Brönsted acids are usually negligible because of the small size of the proton but are important in case of Lewis acids.
- Tautomerism involves a rapid and reversible inter-conversion of isomers which are related to each other with the actual movement of electrons as well as of one or more atoms.
- In addition to the structural changes mentioned above, solvent also plays an important role in the acid-base equilibrium.

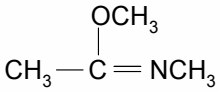
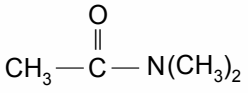
13.7 TERMINAL QUESTIONS

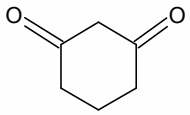
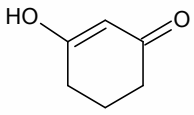
1. Compare the acidic nature of 2,2,2-trifluoroethanol and ethanol.
2. Explain the difference between pK_{a_1} (4.16) and pK_{a_2} (5.61) of butanedioic acid.
3. Draw resonance structures for the following:

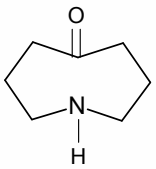
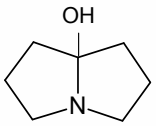
   i) chlorobenzene ii) acetonitrile iii) pyrrole, 

4. Ethylamine and aniline react with aq. HCl. Write the equations for these reactions.
5. Are the following pairs of compounds tautomers or resonance forms?

a)  and 

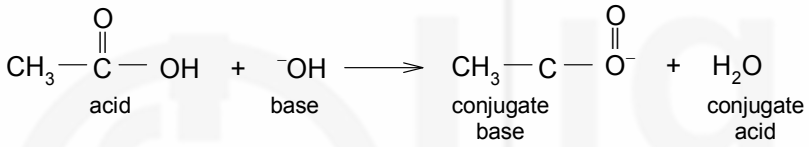
b)  and 

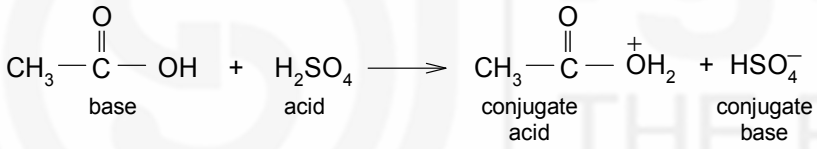
c)  and 

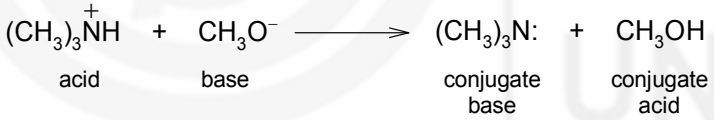
d)  and 

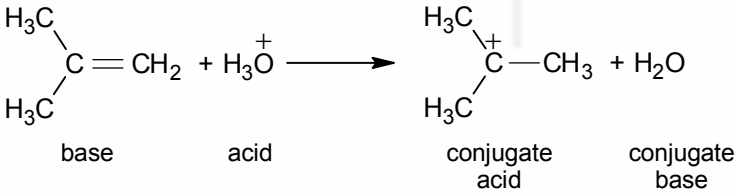
13.8 ANSWERS

Self-Assessment Questions

1. a) 

b) 

c) 

d) 

2. a) Acid HY having the lower pK_a value is stronger than acid HX having higher pK_a value.

b) Since HY is stronger acid, therefore, Y^- is the weaker base as compared to X^-. Thus, in an acid-base reaction between Na^+X^- and HY which is shown below:

$$Na^+ X^- + HY \rightleftharpoons HX + Na^+ Y^-$$

The stronger base X^- will abstract the proton from the acid HY and the equilibrium will lie towards the right to yield HX and $Na^+ Y^-$.

3. a) The compounds in the decreasing order of acidities can be arranged as follows:

i) $NCCH_2COOH > NCCH_2CH_2CH_2COOH > CH_3COOH$.

Since the –CN group has *–I* effect, it increases the acidity of $NCCH_2COOH$ and $NCCH_2CH_2CH_2COOH$ as compared to ethanoic acid. But the *–I* effect of the –CN group decreases with the distance; therefore, $NCCH_2CH_2CH_2COOH$ is less acidic than $NCCH_2COOH$.

ii) $HOOCCOOH > CH_3COOH > {}^{-}OOCCOOH$

1 2 3

The COOH group is *–I* type. Hence, it increases the acidity in case of HOOCCOOH as compared to CH_3COOH. But, in case of ${}^{-}OOCCOOH$, the removal of a proton is difficult because it is a negatively charged species. Hence, it is less acidic as compared to CH_3COOH.

b) i) The basicities decrease in the following order:

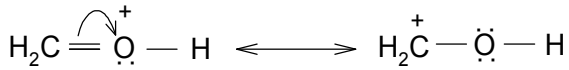
N,N-dimethylaniline > *N*-methylaniline > aniline

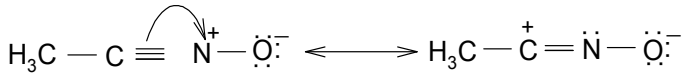
As the methyl group is electron donating, it has *+I* effect which increases the basicity in case of *N*-methylaniline as compared to aniline. The basicity further increases in *N,N*-dimethylnaniline due to the increase in the number of methyl groups.

ii) The decreasing order of basicitiies is as shown below:

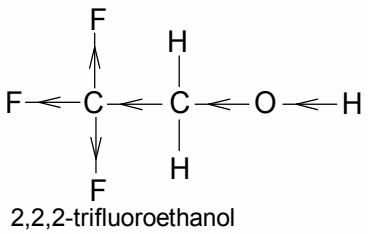
$CH_3NH_2 > NH_3 > NH_2OH$

Since the methyl group has *+I* effect, it increases the basicity of CH_3NH_2 as compared to NH_3. But, the substitution of an – OH group in NH_3 decreases the basicity of NH_2OH as compared to NH_3 because – OH group has *– I* effect.

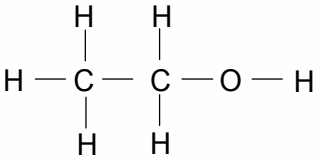
4. a) 

b) 

Terminal Questions

1. 

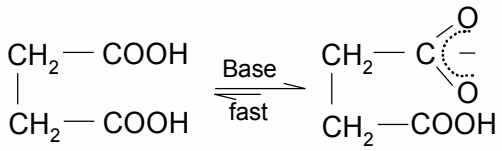
2,2,2-trifluoroethanol



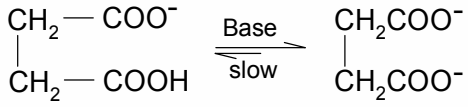
ethanol

The three strong electron-withdrawing fluorine atoms (*-I* groups) increase the acidity of 2,2,2-trifluoroethanol as compared to ethanol.

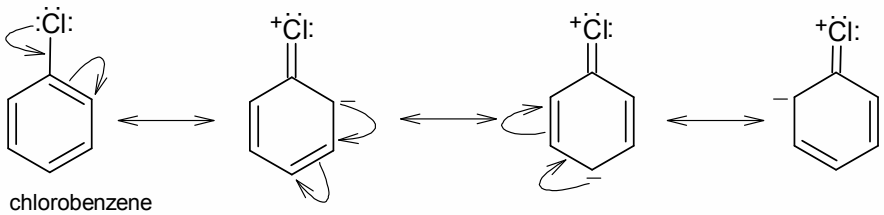
2. The first inonisation is fast because this anion is resonance stabilised.



The anion formed in the first step slows down further ionisation because it is difficult to remove a proton from a negatively charged species.

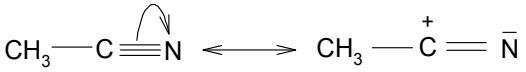


3. i)



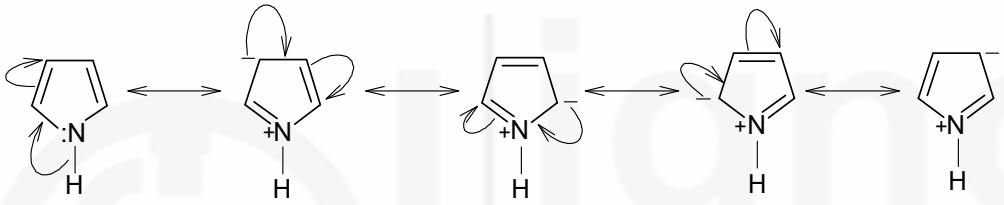
chlorobenzene

ii)



acetonitrile

iii)



pyrrole

4. $C_2H_5NH_2 + HCl \rightleftharpoons C_2H_5\overset{+}{N}H_3Cl^-$

ethylamine

$C_6H_5NH_2 + HCl \rightleftharpoons C_6H_5\overset{+}{N}H_3Cl^-$

aniline

5. Only a) shows resonance structures; b), c) and d) are tautomers.

UNIT 14

REACTIONS AND REACTIVE INTERMEDIATES

Structure

14.1 INTRODUCTION

The organic reactions involve stepwise progress of reactions as the reactants are converted into products. The organic products find applications in medicine, industry, textiles, household appliances, defense, space research, etc., in fact, practically in every sphere of modern life. An understanding of the detailed description of the reactions involved helps in utilising and modifying the processes as per the requirement. It is essential to learn some of the fundamental concepts that form common guidelines for the prediction of fate of many such reactions. You will like to recall some of the fundamental concepts of organic reactions like, the inductive effect, resonance and hyperconjugation dealt in detail in Unit 13 of this course.

In the present unit some concepts specific to organic reactions and generally applied to a number of organic reactions are considered. We start with the ways cleavage of bond takes place in organic molecules i.e. homolysis and heterolysis, followed by the common reaction types. The two types of reagents

used in many organic reactions taking place by heterolytic mechanism are nucleophiles and electrophiles. These are discussed in detail. Lastly a good account of the most common reaction intermediates has been given. A study of all these fundamental concepts would be helpful in understanding the progress of a number of organic reactions based on functional groups that are to be dealt in forthcoming courses.

Expected Learning Outcomes

After studying this unit you should be able to:

- describe the heterolytic and homolytic ways of bond cleavage in organic molecules,
- define the terms, nucleophile and electrophile with examples,
- differentiate a nucleophile from a base and nucleophilicity from basicity,
- define and categorise a reaction as substitution, addition, elimination, or polymerisation, and
- describe the formation, structure, stability and reactivity of carbocations, carbanions and free radicals as reactive intermediates.

14.2 CLEAVAGE OF BONDS

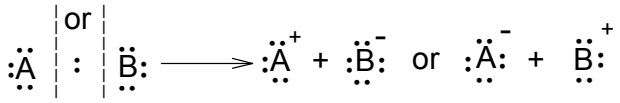
There are two general features that characterise the reactions of organic compounds. One of these is the relative slowness of most organic reactions compared to many familiar inorganic reactions. For example, the reaction between hydrochloric acid and sodium hydroxide is instantaneous, whereas the esterification of acetic acid by ethyl alcohol takes hours and occurs only if the reaction mixture is heated with a catalyst such as sulphuric acid. Even then the reaction hardly ever goes to completion. The other characteristic feature of organic reactions is that, in general, the greater part of the reacting molecule remains relatively unchanged during the course of a reaction. Thus you may recall that most organic reactions occur at the site of functional groups, which leave the rest of the molecule intact. For example, in the reaction between bromoethane and aqueous sodium hydroxide, the hydrocarbon part of the molecule, i.e., CH_3CH_2 is retained as such and the bromo functional group is replaced by the hydroxy group. This reaction can be written as follows.

$$CH_3CH_2 — \boxed{Br} + NaOH \rightarrow CH_3CH_2 — \boxed{OH} + NaBr$$

The slowness and the relative stability of the molecule in reactions are due to the type of bonding that exists in organic compounds. We know that atoms in organic compounds are covalently bonded. When reactions involving organic compounds take place, one or more of these bonds may be broken and atoms (or groups) originally attached may be replaced by other atoms (or groups) or may be lost altogether. The type of mechanism followed by the reaction is determined by the way the bond breaks. The cleavage of a covalent bond may take place in one of the ways discussed in the following subsections.

14.2.1 Bond Heterolysis

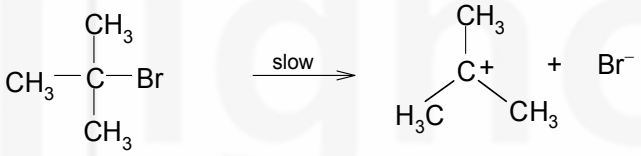
When a bond breaks in an unsymmetrical way, such that both the bonding electrons remain with either of the fragments, then it is called **bond heterolysis**. Heterolysis is made up of two words viz., *hetero* meaning different, *lysis* meaning cleavage or breaking.



Bond heterolysis

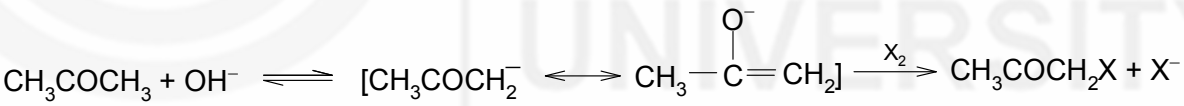
In heterolytic cleavage of a bond the resulting species are charged. Depending upon the site of cleavage, either of the resulting species can be positively or negatively charged as shown above.

If the species resulting from heterolytic cleavage has a carbon atom bearing positive charge, then it is called a **carbocation** or **carbonium** ion. For example, the hydrolysis of 2-bromo-2-methylpropane to 2-methyl-2-propanol follows a two step mechanism, the first step being the slow heterolytic cleavage forming a carbocation. This step is given below.



2-bromo-2methylpropane **(cabocation)**

On the other hand, reaction of propanone with halogens in the presence of a base proceeds by a different mechanism as shown below.



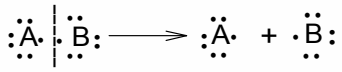
We see that here we get a species having a carbon atom bearing a negative charge; such a species is called a **carbanion**.

In bond heterolysis, which fragment would carry the pair of bonding electrons is determined by the electronegativity of the atoms and gives rise to a negatively charged ion. Since, carbon has very low electronegativity, very often, in the event of heterolytic cleavage, it loses its share in the bond and becomes a part of the positively charged fragment. Therefore, while carbocations are very common as intermediates, carbanions are rare. You would learn about these in Section 14.5 dealing with intermediates and also in the units dealing with nucleophilic and electrophilic substitution reactions in detail. As these reactions involve charged species, these are said to follow **ionic** or **polar mechanism**.

The other type of bond cleavage is observed in reactants, which are nonpolar in nature. It is explained in the next subsection.

14.2.2 Bond Homolysis

If a bond cleaves in a symmetrical way, such that either fragment of the molecule gets one electron, then it is referred to as **bond homolysis**.



Bond homolysis

The word homolysis is also made up of two words *homo* and *lysis*; *homo* means same and *lysis* means cleavage or breaking. For example, in photochlorination of methane, which is a multistep reaction, the first step is homolysis of Cl_2 molecule. The reaction and the first step are shown below.

$$CH_4 + Cl_2 \xrightarrow{h\nu} CH_3Cl + HCl$$

$$Cl : Cl \rightarrow Cl^{\cdot} + Cl^{\cdot}$$

The resulting species have got an unpaired electron each and are referred to as **free radicals**. Chlorine free radical, same as chlorine atom, has got seven valence electrons. Thus chlorine radical is a neutral species. In fact, it is true of any free radical. The homolytic cleavage or fission is observed with non-polar molecules and it is also in contrast to the heterolytic cleavage where polarity of the molecules is one of the conditions. Further, due to the presence of unpaired electrons, free radicals are very reactive. Reactions involving the formation of free radicals are said to follow **free radical mechanism**. You will read more about free radicals as reactive intermediates in Section 14.5. In the next section you will learn about the common types of reagents.

Now to assess your understanding of bond cleavage, try to answer the following SAQs.

SAQ 1

Choose a correct option in the following:

One of the conditions for heterolysis in a molecule is that

i) the bond involved should be polar in nature.

ii) the bond involved should be nonpolar.

iii) the groups involved should have at least one halogen atom.

iv) the bond breaking should involve a C—C bond.

SAQ 2

Which of the following statements is not correct for homolytic reactions?

i) The reaction should be carried out in presence of light.

ii) The reacting species may not be polar in nature.

iii) The resulting species get an unpaired electron each.

iv) The free radicals formed after homolysis are polar in nature.

14.3 TYPES OF REAGENTS

In the previous section, we have tried to focus our attention only on a single molecule and attempted to visualise the process of bond breaking. You would have noticed that organic reactions often involve two reactants: one is the organic molecule, which is referred to as the **substrate** and the other is called the **reagent**. You may recall the reaction between bromoethane and sodium hydroxide, the former is a substrate and the latter is a reagent. Since, these reagents bring about changes in organic molecules, it is important to know more about their types and their nature.

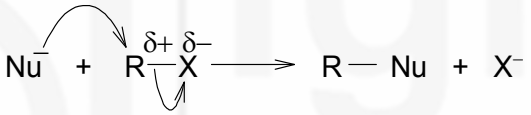
On the basis of their electronic structure, reagents can be broadly classified into two types discussed in the following subsections.

14.3.1 Nucleophiles

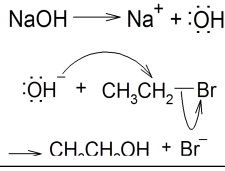
Nucleophiles are electron rich reagents possessing at least one nonbonded pair of electrons. These are attracted towards an electron deficient site in the substrate. Nucleophiles are **'nucleus loving'** and tend to **donate** electrons. Most of the nucleophiles are negatively charged or negatively polarized species. However, a few of them are also neutral molecules with at least one lone pair. These may be represented as 'Nuc' or 'Nu' in the abbreviated form. A reaction initiated by a nucleophile is called **nucleophilic reaction**. A nucleophilic reaction is represented in the following manner:

Electrons always flow from nucleophile to electrophile:

Nucleophile : Electrophile



You would recall that as per convention, movement of an electron pair is depicted by the use of a curved arrow. For example, the reaction between bromoethane and sodium hydroxide can be represented as:



A list of nucleophiles with corresponding nucleophilic atoms is given in Table 14.1. A nucleophile with a negative charge is stronger than its conjugate acid. For example, OH^- is a stronger nucleophile than H_2O and NH_2^- than NH_3.

Table 14.1: List of some common nucleophiles

Nucleophilic atom	Nucleophile
Halogen, X=F, Cl, Br, I	X^-
Oxygen	OH^-, RO^-, $RCOO^-$, H_2O^-, ROH^-, RCOOH
Sulphur	HS^-, RS^-, H_2S, RSH, R_2S
Nitrogen	NH_3, RNH_2, R_2NH, R_3N, N_3, H_2N^-
Carbon	CN^-, $RC \equiv C^-$, RLi, RMgX

Carbon, nitrogen, oxygen, sulphur or a halogen atom in a nucleophile provides the nonbonded pair of electrons. The strength of a nucleophile depends upon a number of factors like the nature of the electron donating atom, its position in the periodic table, its polarisability, size and the nature of the solvent, etc. The relative strength of nucleophiles is measured in terms of their nucleophilicities. As nucleophiles donate electrons, these are bases according to Lewis definition. Different nucleophiles would have different basic strength, i.e., basicity. It is reasonable to expect that strong bases are good reagents for

nucleophilic substitution reactions. This is generally true but there are some deviations also. For example, the iodide ion (I^-) is a good nucleophile but a very weak base. It is worthwhile to understand the difference between the two closely related terms, viz., **nucleophilicity and basicity**.

Basicity and Nucleophilicity

You would recall from Unit 13 that it is not possible to determine the strength of an acid or a base in absolute terms. Therefore, these strengths are always expressed in relative terms. Basicity is a measure of a reagent's ability to accept a proton in an acid-base reaction. It pertains to the acid-base equilibrium, which is characterised by equilibrium constant, K_b. The acid-base equilibrium in case of a nucleophile can be written as follows.

$$Nu^- + H^+ \leftrightharpoons Nu - H$$

It is customary to treat this as acid dissociation equilibrium with equilibrium constant, K_a, which is characterised as pK_a.

$$Nu - H \leftrightharpoons Nu^- + H^+$$

The magnitude of pK_a serves as an index of basicity. The basicities of two nucleophiles are compared in terms of the pK_a values of their respective conjugate acids. A higher value of pK_a indicates a weaker conjugate acid or a strong base, i.e., a strong nucleophile. A list of pK_a values of the conjugate acids of common nucleophiles is given in Table 14.2. You can again recall the list of acids and the conjugate bases given along with their pK_a values in Unit 13 of this course.

$pK_a = -\log K_a$

Table 14.2: Common nucleophiles with pK_a values of conjugate acids

Nucleophile	Conjugate acid	pK_a
I^-	HI	–10
Br^-	HBr	–9
Cl^-	HCl	–7
CN^-	HCN	9.2
RS^-	RSH	10-11
R_3N	R_3NH^+	10-11
R_2NH	$R_2NH_2^+$	11
OH^-	H_2O	15.7
$CH_3CH_2O^-$	CH_3CH_2OH	16
$RCGCN^-$	RCH_2CN	25
$HC \equiv C^-$	$HC \equiv CH$	25
NH_2^-	NH_3	38
$CH_2 = CH^-$	$CH_2 = CH_2$	44
CH_3^-	CH_4	48
$(CH_3)_2CH^-$	$(CH_3)_2CH_2$	51

The increasing order of basicity of some reagents is,

$$I^- < Br^- < Cl^- < ROH < H_2O < C \equiv N^- < \underbrace{OH^- < OR^-}_{\text{Strong bases}}$$

Let us recall here the two important structural features affecting the basicity of a molecule. These are given in the following paragraphs.

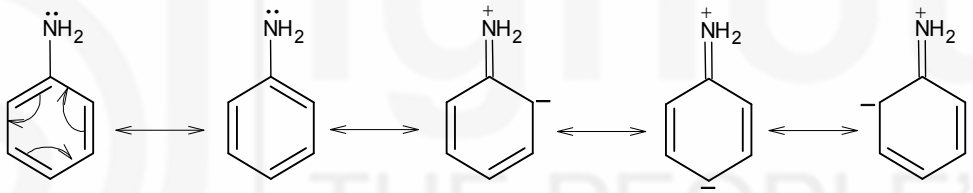
i) **Inductive effect**: In general, the substituents having $+I$ effects, i.e., electron releasing effect increase basicity. For example, in the case of amines an alkyl group on nitrogen increases basicity by dispersing the positive charge in the cation, which is stabilised relative to the free amine.

$$CH_3 \rightarrow \ddot{N}H_2 + H_2O \rightleftharpoons CH_3 \rightarrow \overset{+}{N}H_3 + \overset{-}{O}H$$

Therefore, base strength increases in the series,

$$NH_3 < CH_3NH_2 < (CH_3)_2NH$$

ii) **Resonance**: Resonance affects the base strength of an amine. For example, cyclohexylamine is a far stronger base than is aniline. The reason is that the availability of lone pair in case of aniline will be reduced due to the delocalization of the lone pair over the ring as shown in the resonance structures below.



Resonance structures of aniline

In contrast to basicity, nucleophilicity is a measure of a reagent's ability to cause substitution at a carbon atom. The relative nucleophilicities of a series of reagents are determined by their relative rates of reaction in a substitution reaction, e.g., in the substitution reaction with bromoethane,

$$OH^- + CH_3CH_2 - Br \longrightarrow CH_3CH_2 - OH + Br^-$$

the increasing order of nucleophilicity of some reagents is,

$$H_2O < ROH < Cl^- < Br^- < O\overline{H} < O\overline{R} < I^- < C \equiv \overline{N}$$

The order of nucleophilicity can be rationalized in terms of polarisability and solvation of nucleophiles and the nature of the solvent. Steric considerations are also associated with nucleophilicity. These aspects would be taken up in the units pertaining to nucleophilic substitution reactions in detail in the other courses.

14.3.2 Electrophiles

Electron deficient reagents, which tend to accept electrons and are "**electron loving**" are called electrophiles. These reagents attack electron rich centres or

nucleophiles and form a bond during the reaction. A general reaction can be depicted in the following manner.

$$Nu^- + E^+ \longrightarrow Nu^- - E$$

You will study a number of electrophilic substitution reactions that occur in case of aromatic compounds. For example, nitration of benzene to form nitrobenzene is given in subsection 14.4.1 under electrophilic substitution reactions.

Since, electrophiles can accept an electron pair or get attracted towards a negative centre, they also act as **Lewis acids**. Electrophiles are of two types, **positively charged** and **neutral**. A list of electrophiles is given in Table 14.3.

Table 14.3: List of some electrophiles

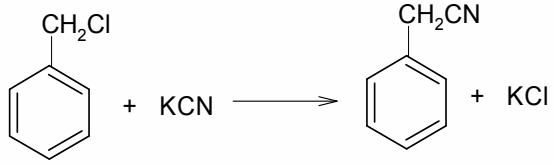
Positively charged	Neutral
H^+, M^+, MX^+	$:CCl_2, I-Cl$
Br^+, Cl^+	RCOCl
NO_2^+, NO^+, NH_4^+	$R-CO-O-COR$
H_3O^+	CO_2, SO_3
$Ar\overset{+}{N}_2, R_3C^+, R\overset{+}{C}=O$	$BF_3, ZnCl_2, AlCl_3, FeCl_3$

You will be able to appreciate the role of the reagents discussed above after studying and understanding the types of organic reactions discussed in the next section. As you will see a number of reactions are named on the basis of these reagents. Before proceeding further, try to answer the following SAQs.

SAQ 3

Indicate the nucleophiles in the following reactions.

a) $CH_3CH_2Cl + KOH \longrightarrow CH_3CH_2OH + KCl$

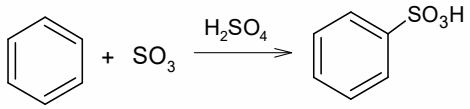
b) 

c) $CH_3CH_2Cl + NaSCH_3 \longrightarrow CH_3CH_2SCH_3 + NaCl$

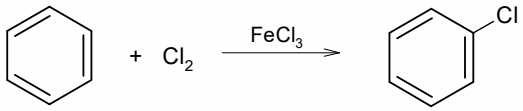
d) $CH_3Cl + NaSH \longrightarrow CH_3SH + NaCl$

SAQ 4

Indicate the electrophiles in the following reactions.

a) 

b) $CH_4 + H^+ \longrightarrow CH_3^+ + H_2$

c) 

d) $CH_3MgI + I_2 \longrightarrow CH_3I + MgI_2$

14.4 TYPES OF REACTIONS

You must have studied classification of organic compounds in your School Chemistry course. You would have learnt that it becomes very easy to understand the nature of organic compounds by categorising them according to the structural types and functional groups. Similarly, it becomes very easy to understand organic reactions if these are categorised into different types, which also helps to frame a series of rules pertaining to each type. However, you should remember that products obtained in a reaction depend upon conditions under which the reaction is carried out. Depending upon the substrate, reagent and reaction conditions, sometimes very different and unexpected products are formed.

Let us study the four main types of organic reactions which essentially involve bond making and bond breaking processes at carbon atoms of a substrate. Each of these types will be dealt in detail in the units of this and other courses. We start with the substitution reactions in the next subsection.

14.4.1 Substitution Reactions

When an atom or a group provided by the reagent replaces an atom or a group of the substrate molecule, the reaction is called a **substitution reaction**. It can take place in a number of ways.

Consider the following reaction as a general case of substitution reaction:

$$Y + R - X \longrightarrow Y - R + X$$

A type of attacking species (nucleophilic), electrophilic or free radical) will substitute the species of similar type in a substitution reaction.

Where R–X and Y–R are both covalent molecules.

i) This reaction may involve homolytic fission as shown below.

$$R - X \longrightarrow R\cdot + X\cdot$$

$$X^{\cdot} + Y \longrightarrow Y^{\cdot} + X$$

$$Y\cdot + R\cdot \longrightarrow R - Y$$

or $$Y\cdot + R - X \longrightarrow Y - R + X\cdot$$

Here the free radicals are produced first and later they combine with other free radicals to give substitution products. This is called a **free radical substitution,** which takes place in a number of steps**.** Photochemical chlorination of methane is an example, which is given below.

$$I_2 \xrightarrow{h\nu} 2Cl\cdot$$

$$Cl\cdot + CH_4 \longrightarrow CH_3\cdot + HCl$$

$$CH_3\cdot + Cl_2 \longrightarrow CH_3Cl + Cl\cdot \ldots \text{ etc.}$$

ii) Another way in which the above substitution reaction can take place is represented as:

$$R-X \longrightarrow R^+ + X^-$$

$$Y^- - R^+ \longrightarrow Y-R$$

or $$Y^- - R - X \longrightarrow Y-R+X^-$$

$$X^- + Y \longrightarrow Y^- - X$$

This occurs when the reaction involves heterolytic fission. The reagent Y is a nucleophile (nucleus-loving) and it seeks a centre of electron deficiency or an electrophilic (electron-loving) centre. The electrophilic centre here is a carbocation. Since the attacking reagent is a nucleophile, the substitution is called **nucleophilic substitution**. You are familiar with nucleophilic substitution reactions of alkyl halides like, hydrolysis of 2-bromo-2-methylpropane given below.

$$(CH_3)_3CBr \longrightarrow (CH_3)_3C^+ + Br^-$$

$$(CH_3)_3C^+ + H_2O \longrightarrow (CH_3)_3COH + H^+$$

Nucleophilic substitution reactions can proceed by more than one type of mechanism. The mechanistic details of these would be discussed in the units of other courses.

iii) There is yet another way in which a substitution reaction can take place. Here also the heterolytic fission of the molecule R – X takes place.

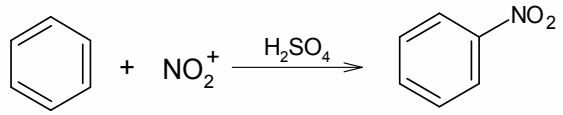
$$R-X \longrightarrow R^- + X^+$$

$$Y^+ - R^- \longrightarrow Y+R$$

or $$Y^+ + R - X \longrightarrow Y-R+X^+$$

The reagent Y^+ is an electrophile. It seeks a reaction centre which has high electron density, a carbanion here. Attacking reagent being an electrophile in this case, the substitution is called **electrophillic substitution**. This type of substitution is most common in aromatic compounds, like, nitration of benzene.

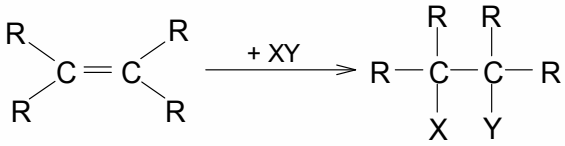
$$HNO_3 + H_2SO_4 \leftrightharpoons H_3O^+ + 2HSO_4^- + NO_2^+$$

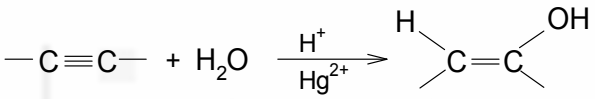


You will study this type of substitution in detail in the units of other courses. Let us now discuss the type of reactions shown by unsaturated organic compounds in the next subsection.

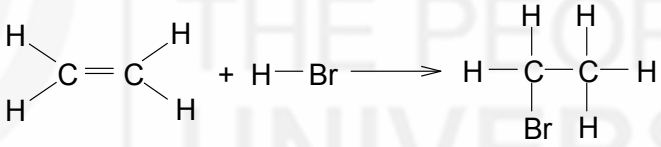
14.4.2 Addition Reactions

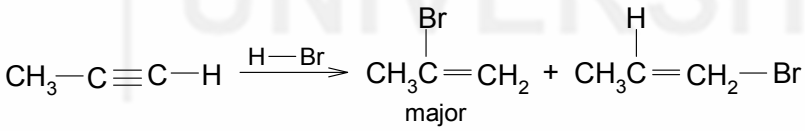
Addition is the most characteristic reaction of alkenes and alkynes. In addition reactions, two atoms or groups are added to a molecule containing a double or a triple bond.



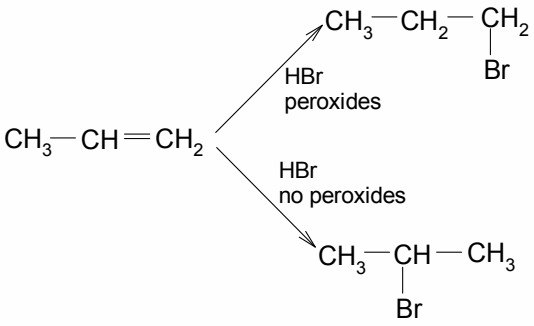


In most of these reactions, the addendum is an electrophile and the alkene, a nucleophile. The reactions are called **electrophilic addition reactions.** A simple example of an addition reaction is the addition of HBr to ethene to give bromoethane in the case of alkenes and addition of HBr to propyne to give bromopropene in case of alkynes.

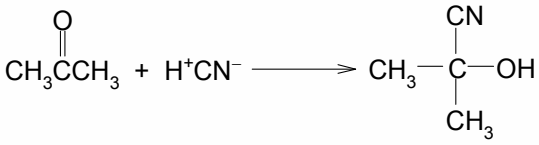




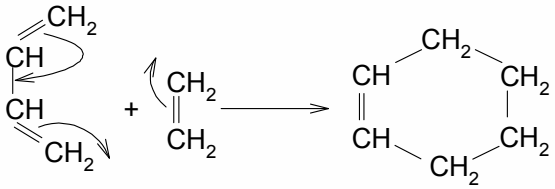
When addition takes place in presence of peroxides, it follows a **free radical addition** mechanism. The product is different in free radical and electrophilic addition. Free radicals being electron deficient species, even free radical additions can be classified as eletrophilic attacks. Propene forms two different products under different reaction conditions as shown below.



As mentioned above electrophilic and free radical addition reactions are common with alkenes and alkynes while **nucleophilic addition reactions** are encountered in double bonds with hetero atoms e.g., with carbonyl compounds. The formation of cyanohydrins by the reaction between propanone and HCN is a common example.



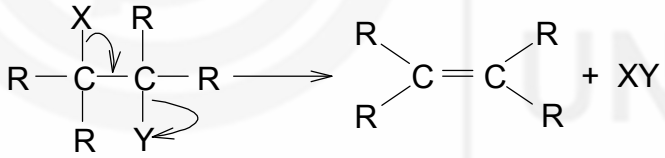
When bond breaking and addition to the double bond take place simultaneously, as shown below, it is referred to as **pericyclic addition**.



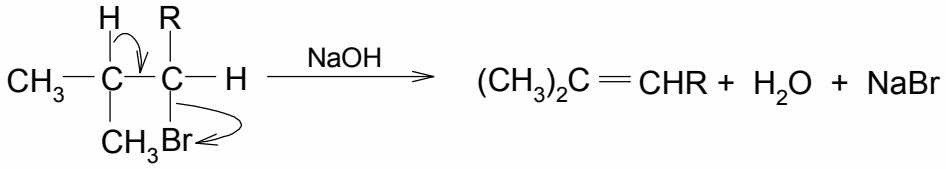
The next type of reactions are opposite to the addition reactions. These are discussed below.

14.4.3 Elimination Reactions

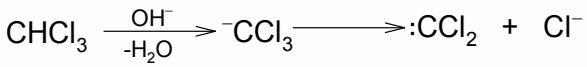
These are reactions that involve the loss of two groups or atoms, commonly from adjacent carbon atoms, introducing a double bond. Thus these are opposite to the addition reactions in which atoms or groups are added to a double bond to form a saturated compound. A general case of the reaction can be represented as follows.



For Example:



Since the above elimination involves two groups (or atoms) on adjacent carbon atoms, it is called **a 1, 2** or ***β*-elimination**. When elimination involves loss of two atoms or groups from the same atom, it is called **(1, 1) or *α*-elimination**. For example,



Trichloromethane **Dichlorocarbene**

The hypovalent neutral species,:CCl_2 in the above reaction is called **carbene**. It is an unstable intermediate about which you will study in detail in the units of other courses.

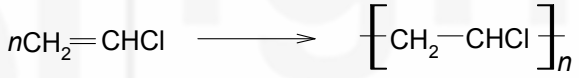
The next and the last type of reactions discussed have a lot of applicability in our day to day life as it is responsible for the formation of a number of polymeric products, which have become a part and parcel of every day activity.

14.4.4 Polymerisation Reactions

Polymerisation is the process of formation of **polymers** by joining of small molecules called **monomers**. The term polymer is derived from Greek words '*poly*' and '*meros*' meaning many parts. Thus a polymer is a large molecule (macromolecule) built up by the repetition of small simple chemical units. The repeat unit of the polymer is usually equivalent or nearly equivalent to the starting material from which the polymer is formed. The monomers can undergo an **addition** or a **condensation** reaction. Accordingly, the reaction is named as addition polymerisation or **condensation polymerisation**.

In contrast to small molecules, polymeric molecules can have essentially the same chemical composition.

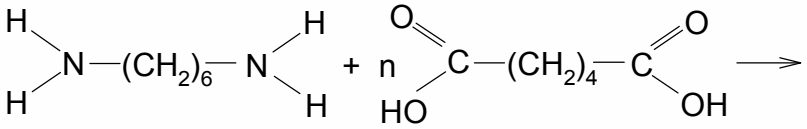
Addition polymerisation involves chain reaction in which the chain carrier may be an ion or a reactive substance with one unpaired electron called a free radical. For example, the polymerisation of chloroethene (vinyl chloride) takes place by addition reaction to form poly(chloroethene) or polyvinylchloride (PVC).



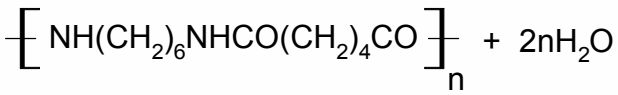
chloroethene **poly(chloroethene)**

The ***n*** in the above reaction represents a large number, usually several thousands.

Condensation polymerisation takes place between two polyfunctional molecules to produce one larger polyfunctional molecule, with the possible elimination of a small molecule such as water. The reaction continues until almost whole of one of the reagents is used up. For example, in producing polyamide 6, 6 two monomers, hexamethylene diamine and adipic acid are used as given below.



1,6-diaminohexane **hexanedioic**



polyamide 6,6

There are more mechanisms involved in polymerisation reactions. The details will be discussed in other elective courses. We will now proceed to the study

of very important components of organic reactions that are part of the study of organic reaction mechanism. These are called reactive intermediates as discussed in the following section. Before proceeding, try to answer the following SAQ.

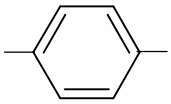
SAQ 5

Write the products of the following reactions and categorise them as substitution, elimination, addition or polymerisation reactions.

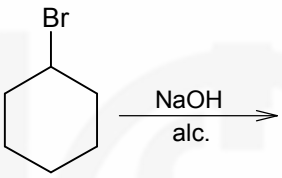
a) $CH_4 + Cl_2 \longrightarrow$

b) $CH_3CH_2OH + PCl_5 \longrightarrow$

c) $H_2C{=}CH_2 + HBr \longrightarrow$

d) CH_3OOC  $COOCH_3 + HOCH_2CH_2OH \longrightarrow$

(dimethyl terphthelate) ethanediol (ethyleneglycol)

e) 

14.5 REACTIVE INTERMEDIATES

Most of the organic reactions take place in a number of steps in which the steps between the initial and final proceed with the formation of products which may vary in their stability and also the reactive nature. A chemical species that is the product of one step of a reaction and is the reactant for the next step is called an **intermediate**. Generally, the intermediates are not very stable compounds. Mostly it is difficult to isolate these however in some cases these are isolated and analysed too. Due to instability these are very reactive. Therefore the intermediates are called the **reactive intermediates**.

It will be appropriate to know a related term called the **transition state**. When the reactants change into products they pass through an unstable state of maximum energy called the **transition state**. We can take the reaction between CH_3I and NaOH as an example to understand the transition state. The reaction can be written as follows.

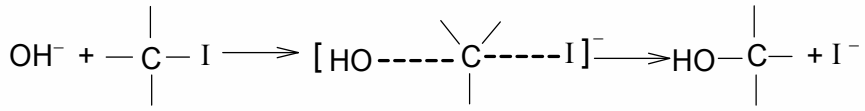
Never confuse transition states with intermediates: Transition states have partially formed bonds, whereas intermediates have fully formed bonds.

$$NaOH \longrightarrow Na^+ + OH^-$$

$$CH_3{-}I + OH^- \longrightarrow CH_3{-}OH^- + I^-$$

An energetic OH^- approaches the $CH_3{-}I$ molecule from a direction opposite to that of the C–I bond. As the two come closer, the energy increases and

continues to increase as the molecule "spreads out". The C–I bond weakens and the C–O bond begins to form as shown below.



Transition state

The energy becomes maximum when the C–I bond is "half broken" and C–O bond is "half formed". The high energy complex is called the transition state or the **activated complex.** The transition state can never be isolated.

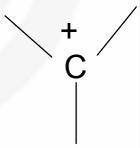
In this section we will discuss three important intermediates formed during the course of an organic reaction. These are carbocations, carbanions and free radicals. We will start with the carbocations in the next subsection.

14.5.1 Carbocations

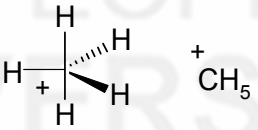
Carbocations serve as electrophiles in reactions. They attract electrons easily as the carbon is deficient in electrons and therefore act as Lewis acids.

You have studied in subsection 14.2.1 that heterolytic cleavage of a C–C bond produces a carbocation. A carbocation is an intermediate species in which a carbon atom bears three bonds, six electrons in the outermost orbital and a positive charge. Carbocations are generally unstable because they do not have eight electrons to satisfy the octet rule. Carbocations were earlier named as **carbonium ions,** which have a higher covalency than the covalency of the neutral atom. Thus the carbonium ions are pentacoordinated ions. For example, methanonium ion is a carbonium ion, which is analogous to ammonium ion. Another term in use is analogous in nature to carbocation called **carbenium** ion. The term **carbocation** is used for both carbonium ion and carbenium ion.

The simplest carbocation and carbonium ion can be represented as follows:



Carbocation

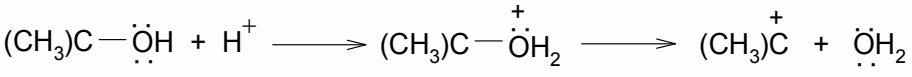


Methanonium ion

Formation of Carbocations

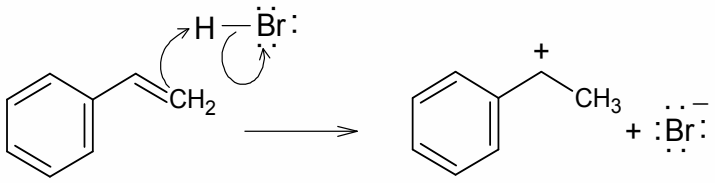
One of the ways of carbocation formation is a **heterolytic cleavage** or an **ionisation reaction**. For example, the reaction of tertiary butanol with a halogen in presence of an acid leads to the formation of a carbocation as the first step. The formation of a carbocation in this way is generally observed during the substitution and elimination reactions taking place by S_N1 and E1 mechanisms respectively. An example is given below.

Electrophilic addition to a π bond occurs in many reactions of alkenes, alkynes and benzene rings.



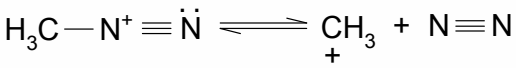
Another way carbocations are formed is when an electrophile attacks a π bond i.e., **electrophilic addition** reaction. The π electron pair may form a new σ bond to the electron-deficient atom of the electrophile. The other carbon of the π bond now does not share the π electron pair, resulting in a carbocation.

Electrophilic addition to a π bond is illustrated by the reaction of HBr (an electrophile) with styrene ($PhCH{=}CH_2$) as given below.



Styrene

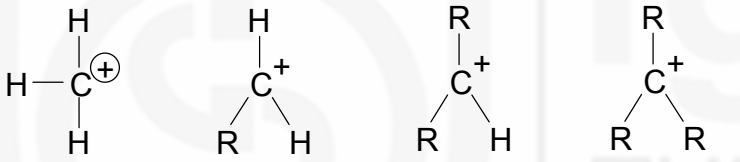
Decomposition reaction also leads to the formation of carbocation, e.g. decomposition of diazomethane as follows:



Diazomethane

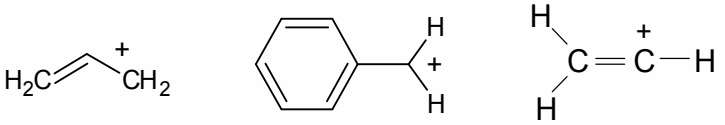
Types of Carbocations

Carbocations are classified according to the number of alkyl substituents that are bonded to the positively charged carbon. A **primary carbocation** has one or no alkyl substituent, a **secondary carbocation** has two, and a **tertiary carbocation** has three alkyl substituents. Their structures are written below.



Methyl carbocation | Primary carbocation | Secondary carbocation | Tertiary carbocation

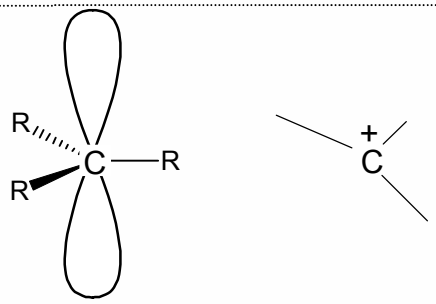
If the carbon bearing the positive charge is adjacent to a carbon-carbon double bond, the carbocation is termed an **allylic carbocation**. If the carbon bearing the positive charge is adjacent to a benzene ring, the carbocation is termed a **benzylic carbocation**. If the carbon bearing the positive charge is part of an alkene, the carbocation is termed a **vinylic carbocation.**



Allyl carbocation **Benzyl carbocation** **Vinyl carbocation**

Structure of Carbocations

Alkyl carbocations are sp^2 hybridised, represented by the equilateral triangle arrangement and therefore are planar. The sp^2 orbitals are directed towards corners of equilateral triangle as these lie in the same plane with electron deficient carbon atom. The *p*-orbital that is not utilised in the hybridisation is empty and is generally shown bearing the positive charge. This orbital is available to accept electrons by overlap with the nearby orbitals.



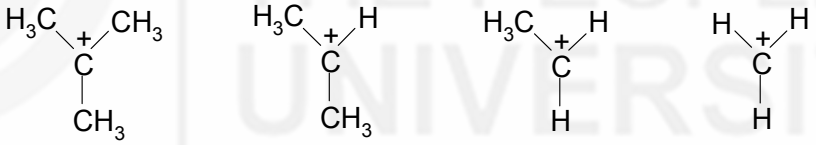
Trigonal planar structure of carbocation

Stability of Carbocations

The stability of a carbocation affects the rate of the reaction in which it is formed. We can say that the increase in stability of a carbocation increases the rate of a reaction. The carbocation stability is affected by the following factors.

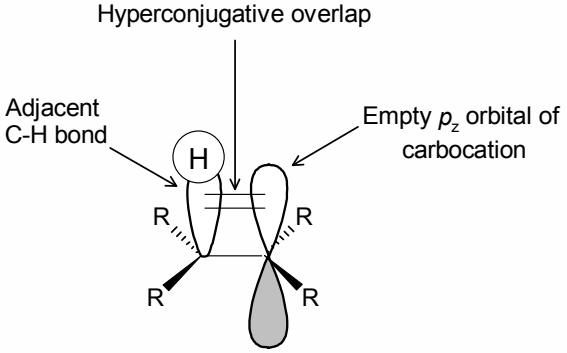
i) Inductive effect; ii) Hyperconjugative effect; iii) Resonance

As mentioned before, being positively charged species a carbocation is electron-poor, and atom or a group, which donates electron or has a +I effect helps to stabilise it. We may also say that a carbocation will be destabilised by an electron withdrawing group due to –I effect. Alkyl groups i.e. methyl, ethyl, etc. are weak electron donating groups, and thus stabilise nearby carbocations. In general, ***more substituted carbocations are more stable***. For example, a tertiary butyl carbocation with three methyl groups is more stable than a secondary propyl carbocation with two methyl groups. Primary carbocations like, ethyl carbocation are highly unstable and not often observed as reaction intermediates; methyl carbocations are even less stable. Thus the order of decreasing stability for methyl, primary, secondary and tertiary carbocations is as given below.

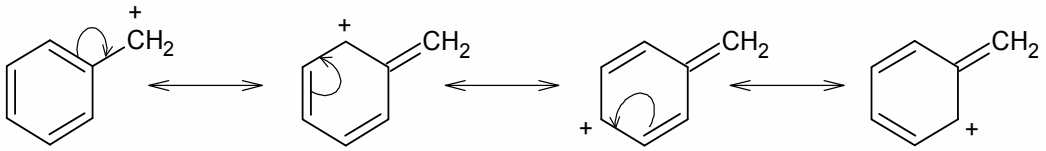


(**Most stable**) $3^o > 2^o > 1^o >$ methyl (**Least stable**)

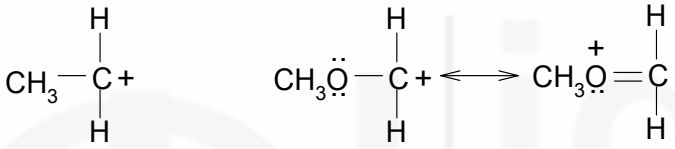
The alkyl groups attached to carbon bearing a positive charge also stabilise it by **hyperconjugation** (Unit 13)**.** The bonding electrons from adjacent *σ* bonds may overlap with the unoccupied *p* orbital of the carbocation as shown below:



Resonance effects can further stabilise carbocations. You would recall from Unit 13 that the phenomenon of resonance explains the delocalization of electrons in a molecule when depicted by their Lewis structures. In a carbocation resonance is responsible for delocalisation of the positive charge that creates additional bonding between adjacent atoms. Decreasing the electron deficiency increases the stability, therefore allyl or benzyl carbocations are more stable than simple primary carbocations. Consider the simple case of a **benzylic** carbocation and try to understand the delocalization of positive charge over other carbon atoms in the ring.



Similarly, an ethyl cation can be compared to the methoxymethyl cation. The ethyl cation does not have any resonance contributors while the latter has an oxygen atom with lone pair that can delocalise the positive charge giving it stability.



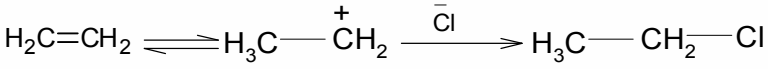
Ethyl cation
(No resonance)

Methoxymethyl cation
(Resonating structures)

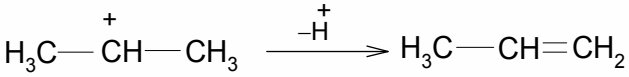
Reactivity of Carbocations

The carbocations have to complete the octet to achieve stability for which they react with nucleophiles as excellent electrophiles. The reactions depicted by carbocations include substitution, elimination, addition and Friedel Craft alkylation etc. Thus there are three common pathways by which carbocations undergo reactions. These are given below.

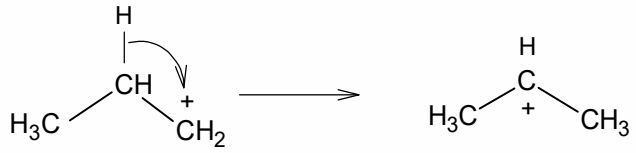
(a) **Capture a nucleophile**, for example, addition of hydrogen chloride to ethylene, which is depicted below.



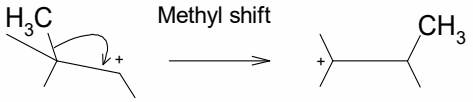
(b) **Lose a proton** to form a π bond e.g. propyl cation losing a proton to form propene as given below.



(c) **Rearrange:** Carbocations are prone to rearrangement via 1, 2-hyride or 1, 2-alkyl shifts in order to form a more stable carbocation. For example, shifting of hydride in 1-propyl cation (a primary cation) leads to a more stable 2- propyl cation (a secondary cation) as shown below:



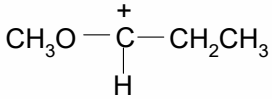
A methyl shift can similarly be shown in case of a secondary carbocation rearranging to a more stable tertiary carbocation.

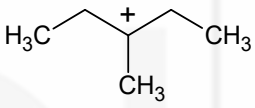


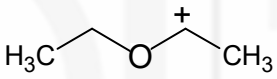
You will learn about another important intermediate in the next subsection. Before proceeding, try to answer the following SAQ.

SAQ 6

Identify the following carbocations as primary, secondary or tertiary.

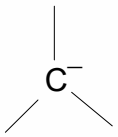
a) 

b) 

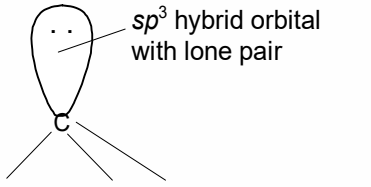
c) 

14.5.2 Carbanions

Carbanions are also generated as a result of heterolytic cleavage of a bond retaining the shared pair of electrons and giving rise to a negative ion. The carbon bearing a negative charge has eight electrons with three bond pairs and one lone pair. It has a trigonal pyramidal geometry due to the sp^3 hybridisation. The carbanion and its geometry can be represented as given below.



Simple representation of carbanion



Trigonal pyramidal geometry of carbanion

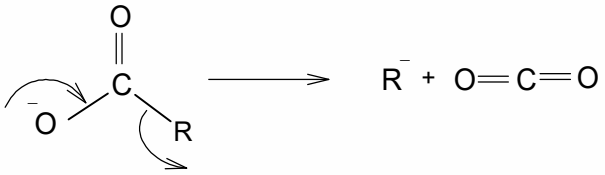
Formation of Carbanions

Carbanions can be formed by the following ways:

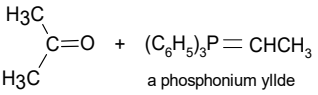
i) Abstraction of an atom generally a positive species,

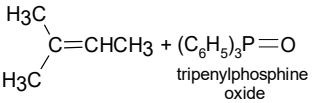
ii) Decomposition of an anion, like a carboxylate ion,

iii) During the rearrangement reactions like Wittig rearrangement. The decomposition of carboxylate ion is shown below.



The reaction of an aldehyde or a ketone with a phosphonium ylide to form an alkene is called **Wittig reaction or rearrangement.**





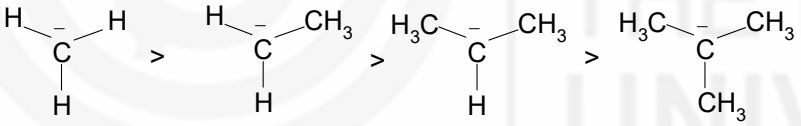
Stability of Carbanions

The stability of carbanionic carbon depends upon how well the negative charge is shared or delocalised by the adjacent groups. It also depends on the electronegativity of the bonded orbitals which is directly proportional to its percent *s*-character. The *s* character increases with the increase in multiplicity of the bond as shown below.

$H_3C—$ $H_2C=$ $HC\equiv$

sp^3 hybridised *sp*^{2} hybridised *sp* hybridised

The carbanion with a triple bond is more stable as compared to a double bonded carbanion and the single bonded carbanion is the least stable. The stability depends upon the **inductive** and the **conjugative** effects of the adjacent atoms or the groups. Electron donating atoms or groups decrease the stability and electron attracting groups increase the stability of carbanions due to +I and –I effect, respectively. The stability decreases with increase in number of alkyl groups on the central carbon atom because the electron density on it is increased due to the +I effect. The negative charge on tertiary carbanion is more as it has three alkyl groups compared to the methyl anion. As a result the stability in the decreasing order is given as below.

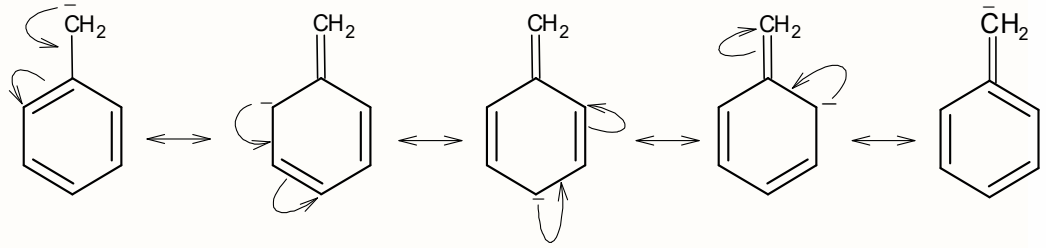


(**Most stable**) methyl > 1^o > 2^o > 3^o (**Least stable**) the +I effect is in the increasing order.

The stability of different type of carbanions in decreasing order is given as:

Aromatic carbanion > Benzyl carbanion > Allyl carbanion > Vinyl carbanion > Alkyl carbanion

In case of allyl and benzyl carbanions the stability is explained by resonance effect. The resonating structures in case of benzyl anion can be written as follows.



The stability of the allyl and benzyl anions in the increasing order can be given as follows.

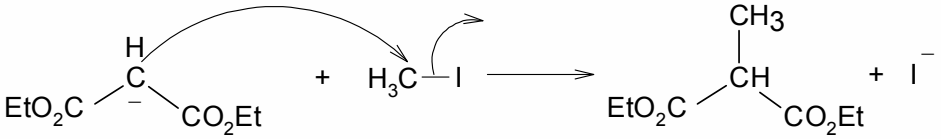
$$CH_2=CH-CH_2^- < C_6H_5-CH_2^- < (C_6H_5)_2-CH_2^- < (C_6H_5)_3-CH_2^-$$

Reactions of Carbanions

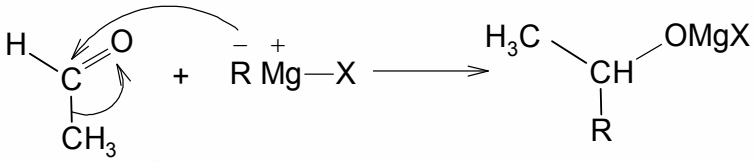
Carbanions are capable of donating a lone pair of electrons hence they may be called Lewis bases. These behave as nucleophiles in reactions.

Some of the reactions which involve the formation of carbanions as reaction intermediates are displacement reactions, addition reactions, elimination reactions and condensation reactions of carbonyl compounds e.g., aldol condensation, Perkin reaction etc. Let us look into examples for a few of these.

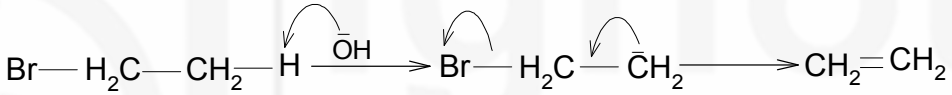
Displacement reaction: The alkylated product is formed by displacement of halogen from an alkyl halide.



Addition to multiple bonds: This involves addition of Grignard's reagent to carbonyl group.



Elimination reaction: Formation of alkene by alkyl halide in presence of alcoholic alkali is an example.



Before proceeding further, try to answer the following SAQ.

SAQ 7

Which carbanion is more stable in each of the following pairs and why?

a) $H_2C{=}CH^-$ and $HC{\equiv}C^-$

b) $H_2C{=}CH^-$ and $H_2C{=}CH{-}CH_2^-$

c) $(Ph){-}CH_2$ and $(Ph){-}CH^-$

14.5.3 Free Radicals

Two types of intermediates that we discussed earlier, i.e., carbocations and carbanions, are formed by the heterolytic cleavage of bonds. **Free radicals**, the third type of intermediates, are produced as a result of homolytic cleavage of a covalent bond in presence of heat or light, Section 14.2. A free radical is any atom or group that possesses one or more unpaired electrons. It is because of this unpaired electron and an incomplete octet that it is highly reactive. You would recall from your previous classes that use barbed, curved, single-headed or **fishhook arrows** to show the change in position of single electrons and to indicate a homolytic mechanism. This will be clear when we write the reaction in which a free radical is formed.

An example is the formation of alkoxyl radical from dialkyl peroxide.

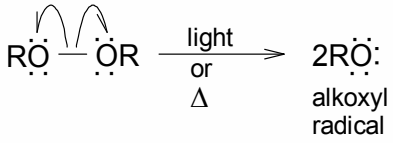


Table 14.4 gives a list of some free radicals.

Table 14.4: List of some free radicals

Atom/Group	Free radical
Hydrogen	H·
Chlorine	Cl·
Silver	Ag·
Sodium	Na·
Oxygen	·O—O·
Carbon	—C·
Alkoxy	—C—O·
Nitroxide	N—O·

Structure of Free Radicals

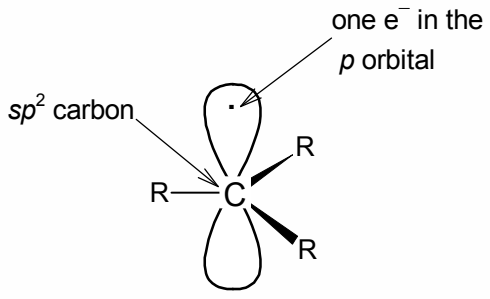
You would like to recall that the carbocation intermediate is sp^2 hybridised and carbanion is sp^3 hybridised with a trigonal planar and pyramidal geometry respectively.

It is difficult to predict whether a carbon free radical would be sp^2 hybridised with trigonal planar geometry (with the odd electron in a *p* orbital) or sp^3 hybridised with tetrahedral geometry or somewhere in between. Experimental evidence indicates that they are either planar or, if they are pyramidal, inversion is very rapid. Thus their shapes can be explained by the following two types.

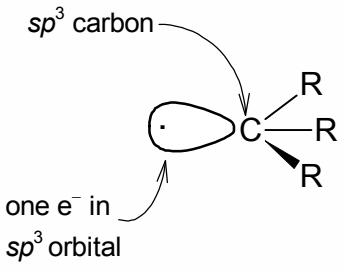
i) **Planar shape**, i.e. the unpaired electron is in a *p*-orbital and the paired electrons in sp^2 orbitals.

ii) **Pyramidal shape**, i.e. the unpaired electron is in sp^3 orbital.

The two types of shapes can be represented as follows:



Planar shape of free radical

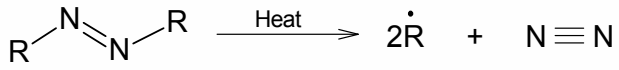


Pyramidal shape of free radical

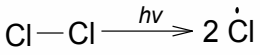
Formation of Free Radicals

Three ways of radical generation are given below.

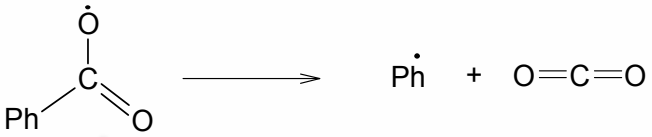
1. **Thermolysis**: The molecules in gas phase cleave homolytically at high temperature, e.g. a diazo compound.



2. **Photolysis**: The molecule gets cleaved in presence of light, e.g. cleavage of chlorine molecule.

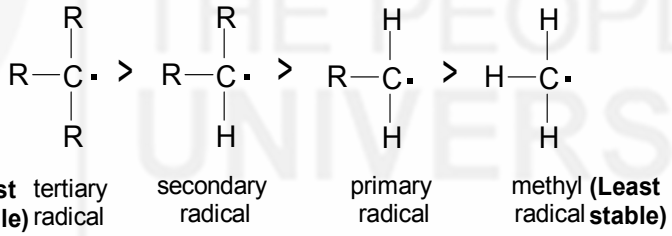


3. **Decomposition reaction**: A free radical gets cleaved during a reaction to form a product and another radical, e.g. decomposition of benzoxy radical can be shown as follows.



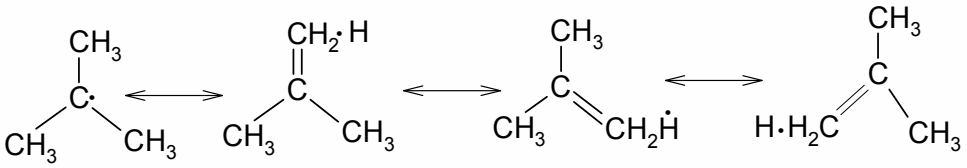
Stability of Free Radicals

The stability of free radicals is related with the group attached to the radical centre and its ability to delocalise the unpaired electron. Like carbocations, radicals are stabilised by electron-donating alkyl groups, so a **tertiary alkyl radical** is more stable than a **secondary alkyl radical**, which in turn is more stable than a **primary alkyl radical**.



Stability of Free Radicals: Tertiary > Secondary > Primary > Methyl

The order of stability can be explained on the basis of hyperconjugation also. The larger the number of alkyl groups attached to the carbon carrying the unpaired electron, higher would be the stability of the radical, e.g. the tertiary butyl radical stability can be shown as below.



The difference in stabilities of primary, secondary and tertiary radicals is small as compared to that of carbocation. This order is explained on the basis of bond dissociation energy (C-H bonds) of primary, secondary and tertiary alkyl radicals. The **bond dissociation energy** may be defined as the energy

required for homolytic cleavage of the covalent bond in the particular molecule to form two radicals. In general, the smaller the amount of energy required for bond rupture, the more stable is the radical.

Allyl and benzyl radicals show stability due to the delocalisation of the unpaired electron.

Reactions of Free Radicals

Free radicals act as intermediates in three types of reactions, *viz.*, substitution, addition and rearrangement. These reactions are catalysed by light or by substances like peroxides, which undergo decomposition easily to produce free radicals. A characteristics of free radical reactions is that once a radical reaction has been started, it usually proceeds at a great rapidity due to the establishment of fast **chain reactions**. These chain reactions arise as a result of the reaction of the first formed radical to generate another radical on reaction with a molecule. The new radical being able to repeat the process, the reaction is carried on. The reaction is terminated when the radicals start reacting with each other to form neutral molecules. This happens when most of the reactants have been consumed.

Thus, there are three distinct phases of a radical reaction; **initiation**, **propagation** and **termination** as we shall see in the following types.

1. Substitution Reactions

Photochemical chlorination of methane is a typical example of substitution by free radical formation as an intermediate. The three phases can be depicted in the following manner.

i) **Initiation**

$$Cl_2 \xrightarrow{h\nu} Cl\cdot + Cl\cdot$$

ii) **Propagation**

$$Cl\cdot + H-CH_3 \longrightarrow HCl + \cdot CH_3$$

$$\cdot CH_3 + Cl-Cl \longrightarrow CH_3Cl$$

iii) **Termination**

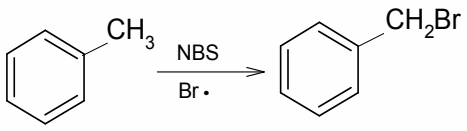
$$\cdot CH_3 + \cdot CH_3 \longrightarrow CH_3-CH_3$$

$$Cl\cdot + \cdot CH_3 \longrightarrow CH_3Cl + \cdot CH_3$$

$$Cl\cdot + Cl \longrightarrow Cl_2$$

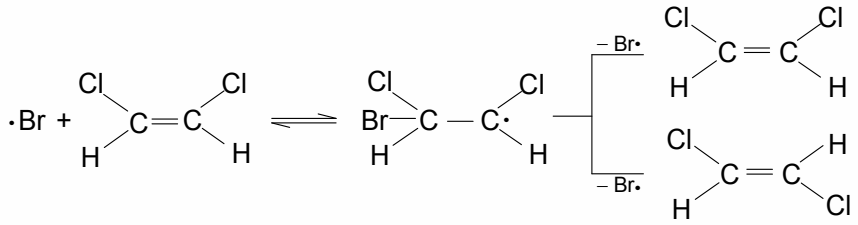
Bromination also takes place in a similar manner but it is a slow process. N-Bromosuccinimide (NBS) is a specific reagent for bromination at allylic and benzylic positions. 1

$$CH_2=CH-CH_3 \xrightarrow[Br\cdot]{NBS} CH_2=CH-CH_2Br$$



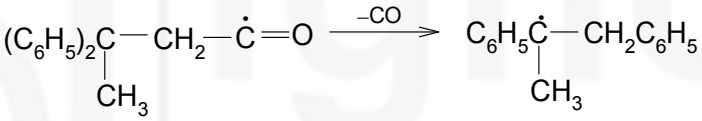
2. Addition Reactions

Addition of halogens to carbon-carbon double bond can proceed through free radical mechanism in the vapour phase or in a non-polar solvent like carbon tetrachloride under the catalytic influence of light.



3. Rearrangement Reactions

Though alkyl radicals show the same order of stability in terms of structure as carbocations, radical rearrangements are not very common. The few known rearrangement reactions of radicals nearly always involve migration of the aryl group, e.g. migration of phenyl group in the following reaction.



You can try to answer the following SAQ to assess the understanding of the free radicals.

SAQ 8

Triphenylmethyl radical is stabilised due to extensive delocalisation. Write the possible resonance structures of this radical.

14.6 SUMMARY

Let us summarise the important fundamental aspects of organic reactions we have discussed in this unit.

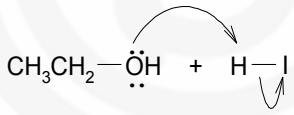
- The organic reactions involve bond breaking and bond making. Depending upon the way a bond is broken, mechanism of organic reactions can be broadly classified into homolytic and heterolytic types.
- The reagents generally used in organic reactions are of two types; nucleophiles, which are attracted towards a positive centre, and electrophiles, which are attracted towards a negative centre.
- It becomes easy to understand the large number of organic reactions if categorised into different types. When a group or atom in an organic

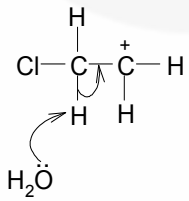
molecule is replaced by another group or atom, it is called a substitution reaction. Depending upon the reagent, substitution reactions can be nucleophilic, electrophilic or free radical type. When two atoms or groups are added to a double or a triple bond, it is called an addition reaction. This can also be classified into nucleophilic, electrophilic and free radical type. Elimination reactions are those in which two atoms or groups are removed from a molecule, usually from adjacent carbon atoms leading to unsaturation in the molecule. The polymerisation reactions involve formation of large molecules called polymers with repeating units of smaller molecules called monomers.

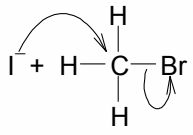
- The organic reactions undergo completion in more than one step via the formation of intermediates. These intermediates are called reactive intermediates as these are generally short lived in nature and therefore are very reactive in nature. Three types of most common intermediates are carbocation, carbanions and free radicals. Carbocations are formed by a heterolytic cleavage, are electron deficient and react with an electron rich species. Carbanions are also formed by the heterolytic cleavage of bonds but are electron rich species and react at the electron deficient centre. Free radicals are formed by homolytic cleavage of bonds, have a single unpaired electron and are neutral in nature. Free radical reactions take place in presence of heat or light or a peroxide molecule.

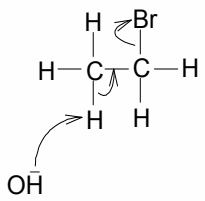
14.7 TERMINAL QUESTIONS

1. In the following reaction, reactants and arrows showing the flow of electrons are indicated. Write the products of the reactions and mention the type of reaction involved.

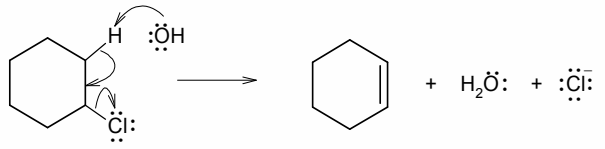
a) 

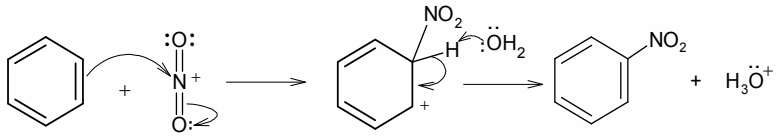
b) 

c) 

d) 

2. Identify the nucleophile and the electrophile in the following reactions

a) 

b) 

3. Why is iodide ion a good nucleophile but a weak base?

4. Categorise the following species into electrophiles and nucleophiles.

   CH_3O^-, PH_3, H^+, $CH_3CO{-}Cl$, CH_3NH_2, H^-,

   $AlCl_3$, $H_2C{=}O$, I^-, $CH_3CH_2S^-$, Hg^{2+}.

5. What type of reaction must be carried for the following conversions.

   a) An alkene to an alkyl halide

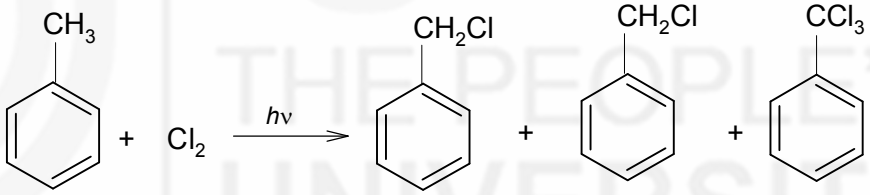
   b) An alkyl chloride to an alkyl bromide

   c) An alkene to an alkane

   d) A haloalkane to an alkene

   e) Ethylene to polyethylene

6. Indicate the probable mechanism type- ionic or radical for the following reactions.

   a) 

   b) $HBr + CH_3CH_2{=}CH_2 + (CH_3)_3C{-}O{-}O{-}C(CH_3)_3 \xrightarrow{\Delta} CH_3CH_2CH_2Br$

   c) $CH_3Br + NaOH \longrightarrow CH_3OH + NaBr$

   d) $CH_3CH_2Br + KCN \longrightarrow CH_3CH_2CN + KBr$

   e) $(CH_3)-C-Br \xrightarrow{+NaOH} (CH_3)C-OH + NaBr$

7. Which out of the two ions; ethylenic anion and cyclopentadienyl anion will be more stable and why?

14.8 ANSWERS

Self-Assessment Questions

1. The correct option is a).

2. The correct answer is c).

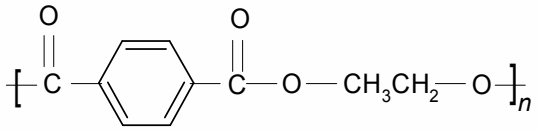
3. Nucleophiles– OH^- , CN^-, $^-SCH_3$, SH^-

4. Electrophiles– SO_3, H^+, Cl^+, I^+

5. a) $CH_3Cl + HCl$ – Substitution

   b) CH_3CH_2Cl– Substitution

   c) CH_3CH_2Br– Addition

   d) CH_3OH + 

   Polyethylenertphthalate- Polymerisation

   e)  + NaBr

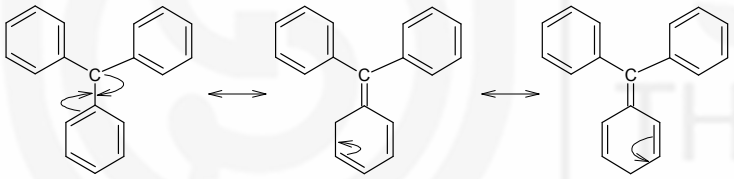
   Elimination

6. a) Secondary b) Tertiary c) Primary

7. a) $CH \equiv C^-$ (more *s* character and more electronegative in nature)

   b) $CH_2 = CH - CH_2^-$ (has a resonance structure)

   c) $(Ph)_2CH^-$ (more resonating structures due to extra Ph group)

8. 

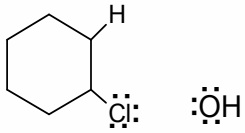
Terminal Questions

1. a) $CH_3CH_2 - I + H_2O$

   b) $CHCl=CH_2 + H_3O^+$

   c) $CH_3I + Br^-$

   d) $H_2C=CH_2 + H_2O + Br^-$

2. a) 

   Electrophile Nucleophile

   b) 

   Nucleophile Electrophile

3. Iodine has a large atom and the outer electrons in it being farther from the nucleus are less tightly held. The outer electrons are, therefore, more easily attracted to a positive centre and can attack a partially positive carbon atom readily. However, it does not easily accept a proton from an alkyl halide and thus act as a good nucleophile and a weak base.

4. Nucleophiles: CH_3O^-, PH_3, H^-, I^-, $CH_3CH_2S^-$, CH_3NH_2

   Electrophiles: H^+, $CH_3CO{-}Cl$, $AlCl_3$, $H_2C^+ - O^-$, Hg^{2+}

5. a) Electrophilic addition reaction
   b) Substitution reaction
   c) Addition reaction
   d) Elemination reaction
   e) Polymerisation reaction

6. a) Radical b) Radical c) Ionic d) Ionic e) Ionic

7. Cyclopentadienyl anion will be more stable as it can give rise to resonance structures adding to the stability of the ion.

Further Reading

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